PRACTICAL MANAGEMENT OF DISTANCE BASED TOLL SYSTEM FOR URBAN EXPRESSWAY

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ABSTRACT

According to the extension of Electronic Toll Collection System (ETC), the distance based toll system has been recently introduced to realize the effective traffic management for urban transport networks. However, the particular type of distance based toll should be specified from the empirical study. Even though the step function is applied in the real world, many types of function can be assumed between the distance and the price of toll. The optimization technique with intelligent information processing is proposed as well to specify the parameters in the particular distance based toll function. In the study, urban road network in Keihanshin area is analyzed as an empirical study. The traffic assignment technique is modified to estimate the traffic conditions on the network with describing the individual route charging as well as diversion traffic in case of distance based toll system. The impact of implementation of distance based toll onto the real scale transport network can be evaluated to discuss the social benefit of road users. The advanced technique with intelligent information processing can be proposed to determine the optimal combination of parameters in distance based toll function. In the study, the reduction of total travel time of road users is regarded as the index of the social benefit on urban network. Therefore, the estimation model of total travel time is created by neural network without the estimation process for large scale network. After the optimal combination of parameters is determined, practical road pricing policy on the urban network can be analyzed. Therefore, the toll system of urban expressway is investigated in terms of empirical study. Finally, the optimal function form of distance based toll is recommended in practical implementation.

Keywords: Urban Expressways, Distance Based Toll, Traffic Assignment, Neural Networks,

INTRODUCTION

The proper form of distance based toll has been discussed for basic idea of pricing policy of urban road networks. The traffic assignment as a fundamental technique in the field of traffic engineering can be applied to demonstrate the user equilibrium situation on the road network. In the study, the urban expressway toll system is analyzed to realize the second best toll for urban transport network which consists of urban streets and expressways. According to the extension of Electronic Toll Collection System (ETC), the distance based toll system has been recently introduced to realize the effective traffic management for urban transport networks (Akiyama, 2008). However, the particular type of distance based toll should be determined from the empirical study. Many types of function can be assumed between the distance and the price of toll. Even though the type of toll function is determined, there are some parameters in the function. The modified traffic assignment technique is proposed in the study to evaluate the social benefit in introducing the distance based toll system (Mun, S. and et. Al.,.2007). The optimization technique with intelligent information processing is proposed as well to specify the parameters in the particular distance based toll function.

The urban road network in Keihanshin area is analyzed as an empirical study. The traffic assignment technique is revised to estimate the traffic conditions on the network with describing the individual route charging as well as diversion traffic in case of distance toll system. The impact of implementation of distance based toll onto the real scale transport network can be evaluated to discuss the benefit of road users. On the other hand, the advanced technique with intelligent information processing can be proposed to determine the optimal combination of parameters in distance based toll function. In the study, reduction of total travel time of road users is regarded as the index of the social benefit on urban network. Therefore, the estimation model of total travel time can be created by neural network without traffic assignment process with large scale network.

After the optimal combination of parameters for the distance based toll function is determined, practical road pricing policy on the urban network can be analyzed. Therefore, the toll system of urban expressway is investigated in terms of empirical study. The optimal form of distance based toll system of urban expressway is confirmed with travel time reduction. Finally, the optimal function form of distance based toll is recommended in practical implementation.

THE NETWORK ANALYSIS FOR URBAN EXPRESSWAY

The distance based toll of urban expressways

The urban transport network consists of urban expressways and urban streets. The urban network of Keihanshin area is illustrated in Figure 1. The toll road system has been introduced in Japanese urban expressway. As four different zones are shown in the expressway, the distance based toll is applied for central three zones and the uniform toll is applied only for Kyoto district (Akiyama & Okushima, 2004, Okuhsima & Akiyama, 2006).

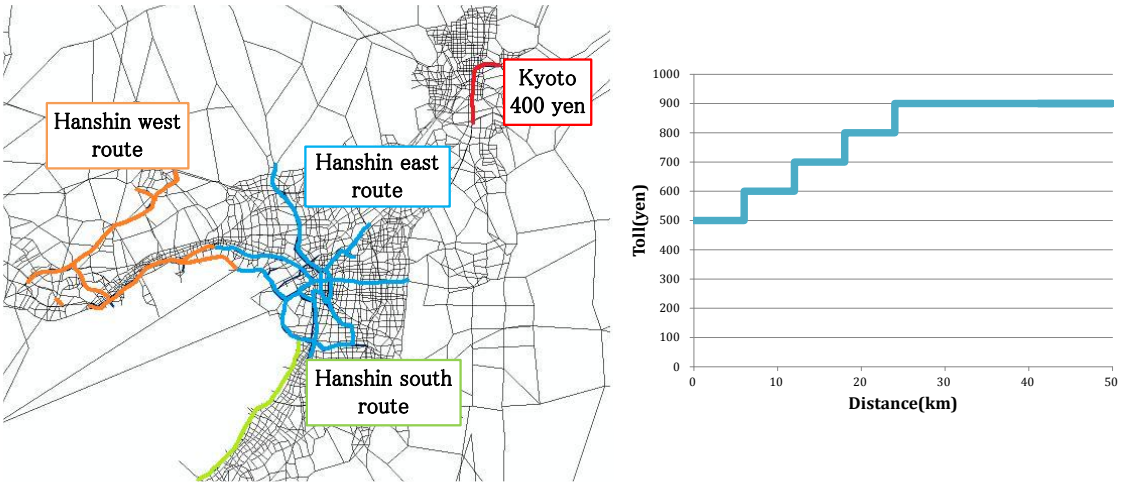

Figure-1 Urban expressways with distance based toll system

The proper form of distance based toll has been discussed for basic idea of pricing policy of urban road networks. The traffic assignment as a fundamental technique can be applied to demonstrate the user equilibrium situation on the urban road network. In the study, the urban expressway toll system is analyzed to realize the second best toll for urban transport network which consists of urban streets and expressways. The uniform toll system had been applied in urban expressways for a long time. According to the recent traffic network extension and requirement of proper traffic management, the distance based toll system has been introduced as an advanced toll system for urban expressway (Akiyama & Okushima, 2004). The step function form of distance based toll has been applied in Hanshin Expressway since January, 2012 as shown in Figure 1.

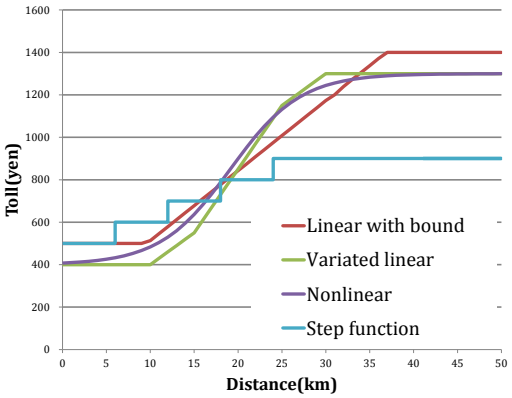

Figure-2 Several fuctions of distance based toll

Several different form of distance based toll can be proposed as shown in Figure 2. The step function form corresponds to the practical distance based toll in the expressway. In the study, the linear distance based toll is discussed for alternatives of toll system. In particular, the linear function with upper and lower limits should be regarded as a fundamental form. The slope of the linear function indicates the proportion of pricing to the travel distance. Therefore, the linear function can be often applied for basic analysis of function form. The toll with the combination of variable linear functions might be a generalized form to formulate the different

proportions of pricing to the travel distance. Furthermore, a monotonically continuous function form of toll can be determined with a few of parameters. Therefore, the nonlinear functional form of toll can be easily handled mathematically to determine the alternative toll systems.

Representation of toll roads as urban expressway

As mentioned previously, urban transport network are assumed to consist of streets and urban expressways. The algorithm of user equilibrium traffic assignment can be applied with modification to estimate traffic condition with distance based toll in urban expressway. The impedance of toll between on-ramp and off-ramp for route choice behaviour should be formulated corresponding to the distance based toll system. The different toll should be charged according to the distance between on-ramp and off-ramp. Therefore, representation of toll charge is required in the user equilibrium traffic assignment algorithm (Okushima &Akiyama, 2006). Figure 3 illustrates the mechanism of route choice in the network with toll roads for urban expressways.

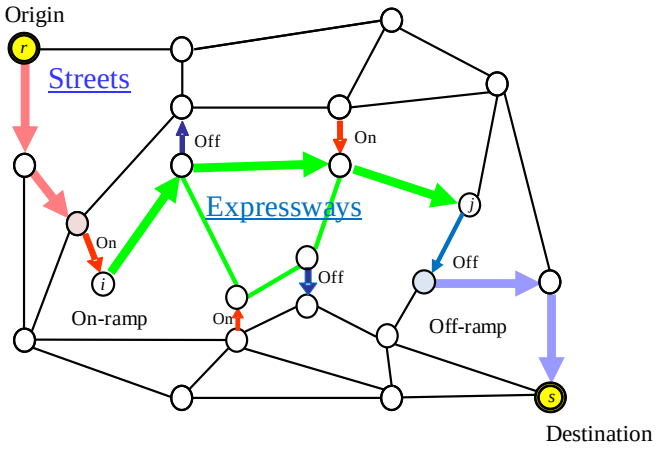

Figure-3 Representation of Urban Networks

Let us assume the urban expressway route existing between origin *r* and destination *s*. The road network between the origin and the destination is divided by three sub networks assuming on-ramp and off-ramp for urban expressway as *(i, j)*. The networks are determined origin to on-ramp for *r-i*, on-ramp to off-ramp for *i-j*, and off-ramp to destination for *j-s*. The shortest path for each network is determined separately. The value of toll should be taken into account for the generalized travel cost for the expressway path. The value of time is applied to determine the equivalent value of travel time of toll. Therefore, the shortest path for the origin to destination is determined by generalized travel time with combining the shortest paths such the origin to on-ramp for *r-i*, on-ramp to off-ramp for *i-j*, and off-ramp to destination for *j-s*. According to the algorithm and network representations, the impedance of toll for travel is formulated mathematically to solve the user equilibrium (UE) condition for traffic flow analysis.

Another important of traffic assignment technique is to describe the diversion traffic in case of introduction of distance based toll. The travel behaviour of drivers may change under the distance based toll system because the route choice opportunity should be increased comparing to the uniform toll system as previous conditions. The algorithm should be modified to describe the travel behaviour such as origin-street-expressway-street-expressway-street-destination.

Representation of diversion traffic

Therefore, the algorithm should be improved to estimate the diversion traffic on urban expressway. In particular, the modified algorithm is required for shortest path search by OD traffic. The algorithm with four stages is proposed shown in Figure 4. The shortest path is searched between the on-ramps and off-ramps in step 1. The shortest path between the on-ramp and off-ramps can be represented with equivalent value of toll corresponding to the travel distance. The imaginary links are determined as the representation of path travel time and value of toll for the expressway in step 2. The shortest path is searched on the imaginary network including the representation of the diversion travel in step3. After the shortest path is found in the imaginary network, the shortest path on the original network can be determined in step 4.

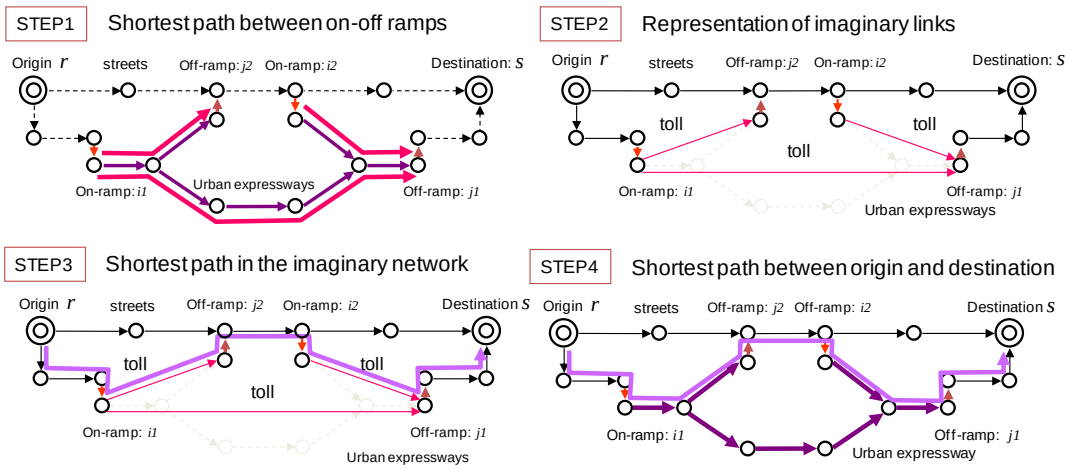

Figure-4 Modified Algorithm for representation of diversion

This modified algorithm of traffic assignment would describe the behaviour of drivers who may use the expressway sections for two times or more. The imaginary path representation process is required to demonstrate the situations in the algorithm. The modified shortest path algorithm can be introduced into the original algorithm for determination of user equilibrium condition on the network. Therefore, realistic traffic flows on the network can be estimated referring to the diversion traffic under the distance based toll system.

The determination of distance based toll

The particular form of distance based toll can be determined from the comparison of possible form of toll functions. In the study, the linear function with upper and lower limit can be proposed. The value of toll is counted as 760 yen corresponding to the average distance of travel of expressway as 15 km. The slope of function should be determined as 33 yen/km. Therefore, it is assumed that the function should cross the point as (15km, 760 yen) with slope of 33 yen/km. As a fundamental case, the upper limit is to be 1,200 yen and the lower limit is to be 400 yen.

All installation cases would be determined according to the fundamental case as shown above. The values of upper limit and lower limit are discussed. The level of overall toll is discussed as well. Figure 5 illustrates the example of installation of toll function. The standard function is shown as (400, 1200, 0) = (lower limit, upper limit, overall level).

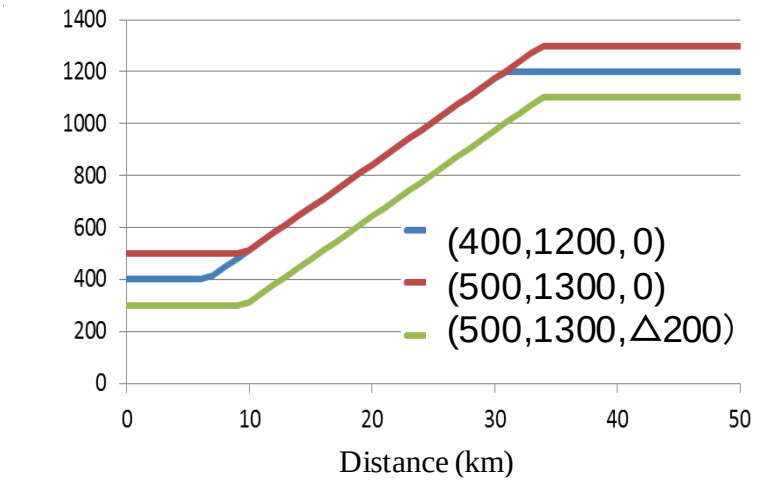

Figure 5 The installation of distance based toll

It is assumed that the lower limit and upper limit are 500 and 1,300 respectively. This corresponds to the function as (500, 1300, 0). Furthermore, the overall level of toll would be discussed as well. The function as (500, 1300, ▵200) is the same form as the function as (500, 1300, 0) with 200 yen discount. The bottom linear line corresponds to the function. Therefore, three parameters should be determined to install particular form of toll function.
It is known that lower limit and upper limit of the function as (500, 1300, ▵200) is equivalent to 300 and 1100 respectively. Four values are assumed for lower limit and upper limit respectively. At the same time, five cases for level of toll are assumed. Therefore, eighty cases (=4×4×5) are considered totally. The results for all cases cannot be required to discuss the proper form of distance based toll. Thirty cases are taken out to investigate the form of distance based toll. The cases with circle are shown in Table 1.

Table-1. Combination of Parameters for Distance Based Toll Form

Lower (yen)	Upper (yen)	The value of discount(yen)				
		▵ 200	▵ 100	0	100	200
300	1200	○				○
	1300		○			
	1400		○		○	
	1500	○				○
400	1200			○		○
	1300	○			○	
	1400		○			○
	1500			○	○	
500	1200	○		○		
	1300		○		○	
	1400	○				○
	1500		○	○		
600	1200	○				○
	1300				○	
	1400		○		○	
	1500	○				○

The urban network is represented by 7826 links and 5264 nodes. The link flows on urban expressways and urban streets are calculated by traffic assignment techniques as previously mentioned. The revenue of toll and diversion traffic can be estimated from the results of traffic assignment. Therefore, the estimation results for total travel time and the revenue of toll are illustrated in Figure 6.

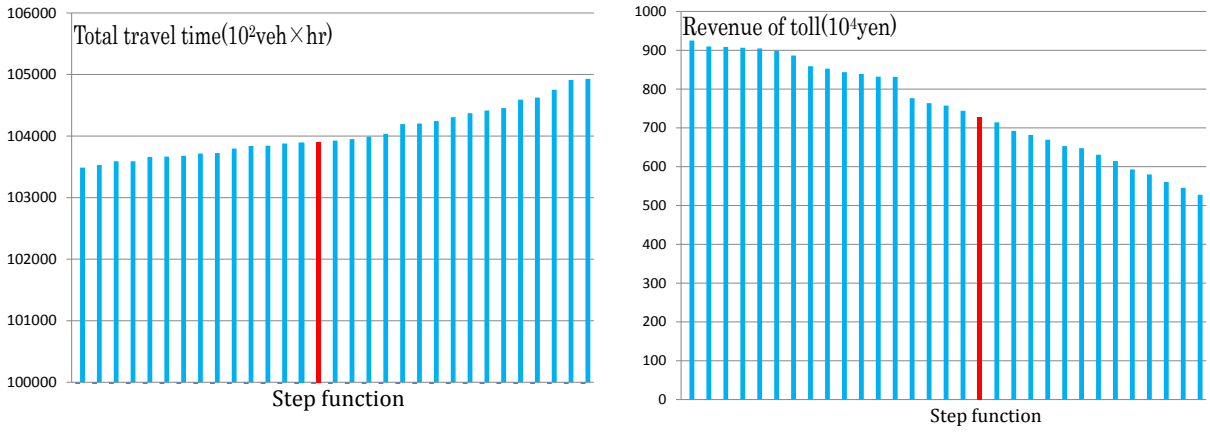

Figure-6 Estimation Results of Evaluation Values

The distance based toll with step function is determined as standard form of toll. It corresponds to the present distance based toll in the real world. The value of total travel time for each case is demonstrated in increasing order. The total travel time under the step function toll is indicated in the middle of diagram. The value of total travel time is smaller for fourteen cases comparing to the step function toll system. These cases are coloured in the Table 1. It can be found that lower level of overall toll may provide the benefit of travel time reduction to the step function toll as traffic demand for urban network is fixed.
On the contrary, the revenue of toll for the expressway can be estimated for each case at the same time. The revenue of toll for each case is shown in decreasing order in Figure 6.
The case of step function toll is shown in the middle of the diagram. The larger values of toll revenue are observed in seventeen cases to the step function toll. This reflects on the increase of traffic volume on urban network. It is known that the introduction of proper distance based toll system may increase the revenue of toll.
The comparison of different forms of distance based toll has been discussed with small number of parameter combination. The evaluation results for even small number of cases may provide the significant comparison of different forms of distance based toll.

THE EVALUATION WITH NEURAL NETWORK MODEL

The intelligent information technique is applied to estimate the evaluation values for the different forms of distance based toll. A large number of parameter combinations are assumed such as the lower limit, the upper limit and the discount level of toll even in the linear function. Theoretically, it is possible to determine the optimal form of distance based toll among many alternative combinations of parameters. The MPEC problem can be formulated that the user benefit of reduction of travel time on urban network is maximized subject to user equilibrium condition (Akiyama and et. al., 2011). The problem can be formulated as follows:

$$\min Z_S = \sum_{a \in A} x_a \cdot t_a(w) \tag{1}$$

s.t.

$$\begin{cases} \min Z_U = \sum_{a \in A} \int_0^{x_a} t_a(w)dw + \sum_{ij \in \Omega_h} \frac{p_{ij}}{\gamma} f_{(i,j)}^{rs} & (2) \\ s.t. \\ \sum_{k \in K_{rs}} f_k^{rs} - Q_{rs} = 0, \quad \forall rs \in \Omega & (3) \\ x_a = \sum_{k \in K_{rs}} \sum_{rs \in \Omega} \delta_{a,k}^{rs} f_k^{rs}, \quad \forall a \in A & (4) \\ f_k^{rs} \geq 0, \quad x_a \geq 0 & (5) \end{cases}$$

where x_a is traffic flow on link a, f_k^{rs} is traffic flow on path k for OD pair $r-s$, $t_a(x_a)$ is the performance function for link a, Q_{rs} is traffic demand for OD pair $r-s$, p_{ij} is price of toll for ramp pair $i-j$, and γ is the value of time. The objective function is formulated as minimizing the total travel cost for urban networks. The constraint should be formulated as user equilibrium condition with referring to the price of toll for travel on the urban expressway.

As the large time consuming effort is required in the traffic assignment for large scale network, it seems to be difficult to apply the traffic assignment technique to realize the user equilibrium condition for every evaluation times in the previous formulation. Therefore, the practical optimization approach would be required.
In the study, the approximation of evaluation values would be calculated without the traffic assignment process. The intelligent information technique can be applied to create the estimation model of approximation value of traffic condition.

The estimation model is created according to the procedure (Akiyama and et. al., 2011a, 2011b). 1) The form of distance based toll is determined with parameters of linear function. 2) Traffic flows on the urban network are estimated with traffic assignment techniques. 3) The indices of evaluation values are calculated from the estimation results of traffic flow. Neural network model is proposed to develop the approximation model. The neural network can describe the complex interaction between the independent variables and the objective variables. As the upper limit, the lower limit and the discount level are determined, the total travel time and revenue of toll can be estimated approximately. The structure of neural network for approximation model of evaluation values can be shown in Figure 7.

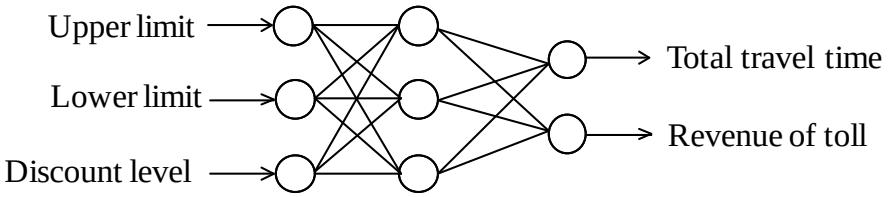

Figure-7 Representation of neural network model

The neural network consists of 3-3-2 neurons for each layer. The estimation results for thirty cases in previous section are applied as training data for parameter determination of neural network. According to the formulation of the problem in equation (1) to (5), it is known that the total travel time can be counted by vehicles × hour and the revenue of toll can be counted as 10^4 *yen* . Both values for evaluation can be determined from the network traffic flows on the urban networks as results of UE traffic assignment in equation (2) to (5). In the estimation, the process of back propagation for training is iterated at most 10,000 times. It is basic estimation procedure to determine the connecting weights between neurons.

The approximation model for the evaluation value is created with neural network representation. The total travel time and revenue of toll can be estimated approximately without traffic assignment process. The relation between the approximation of neural network and the estimation from traffic assignment can be illustrated. The relation for total travel time is illustrated in left diagram of Figure 8. The root mean square error (RMSE) for total travel time is counted as 9981 (veh・hour).

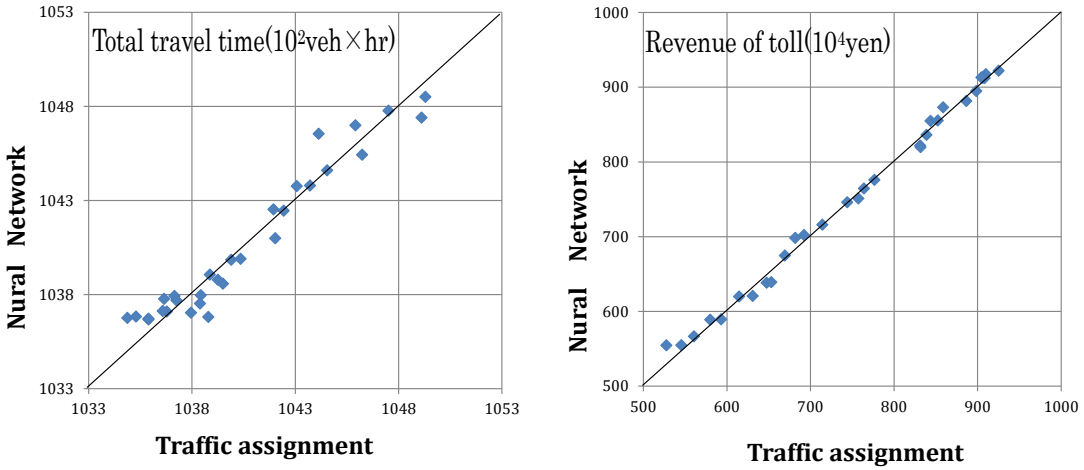

Figure- 8. The Estimation Results of Neural Network

The approximation value of total travel time by NN is quite similar to the value from the traffic flow estimation by UE traffic assignment. On the other hands, the revenue of toll is estimated as well simultaneously by NN model. Therefore, the relation between the estimation of traffic assignment and approximation of NN is shown in the right diagram in Figure 8. The RMSE is counted as 931 $\times 10^4$ yen

According to both estimation results, the strong correlation can be observed from the figure between estimation of NN model and results if traffic flow analysis. Therefore, the approximation of NN model can be applicable to the practical evaluation. In terms of the revenue of toll for another evaluation value, the similar result can be confirmed with small error. Therefore, the estimation of NN model is practically applied in the evaluation of distance based toll installation without the estimation of traffic assignment procedures.

The Installation of Proposed Distance Based Toll

The optimal form of linear distance based toll would be determined according to approximation of the evaluation values. The user benefit of total travel time reduction for urban road networks is applied as a measure of effective form of distance based toll. The parameters of distance based toll such as lower limit, upper limit and discount level are determined by 10 yen as unit cost. The lower limit is varied between 300 yen to 600 yen for 31 cases. The upper limit is varied between 900 yen to 1500 yen for 61 cases. Similarly, the discount level is varied between -200 and 200 for 41 cases. Therefore, the number of combination for parameters is counted as 77,531 (=61×31×41). It seems to be difficult to estimate the traffic flow conditions for urban network with traffic assignment techniques because of large number of combination. The approximation model with neural network is applied to estimate the evaluation values as total travel time and revenue of toll.

According to the estimation of total travel time for all cases from the NN model, the optimal case is pointed out with the minimum value of total travel time. At the same time, the revenue of toll is estimated for the case. The optimal case can be indicated as (lower limit, upper limit, discount level) = (300, 900, Δ110). The form of the function is illustrated with the original case as (400, 1200, 0) and step function form as current. As the discount level is equal to 110 yen, the real lower limit and upper limit are determined as 190 yen and 790 yen respectively. The overall form of the distance based toll is similar to the original installation as (400, 1200, 0). The smaller lower limit is recommended according to the optimization of the combination of parameters.

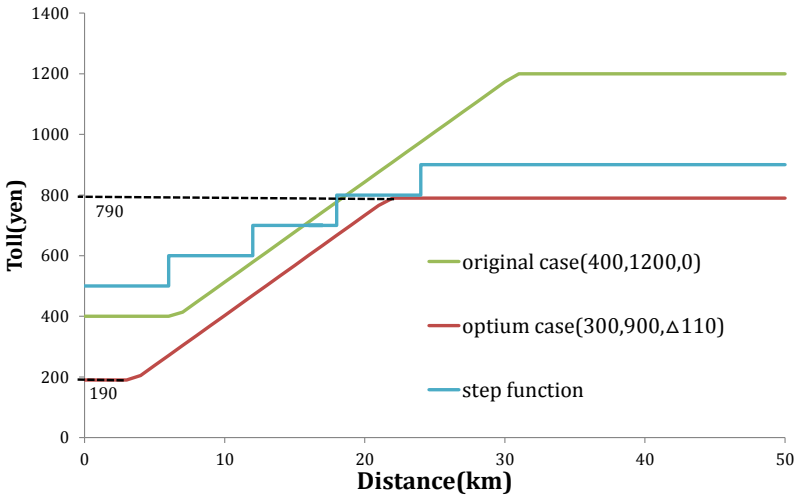

Figure-9. The Optimal Form of Distance Based Toll

The proposed approximation model by neural network seems to be profitable to find the optimal case among the large number of alternative cases. The optimal distance based toll is recommended with the discount level of 110 yen to the linear function with lower and upper limit as (300, 900) for the distance based toll. This effective modification of toll function can be regarded as an advantage of distance toll system. Actually, the NN model can be applied not only for the linear function toll but also for the nonlinear function with several determined parameters with the same manner.

The traffic flow on the network with the optimal distance based toll as (300, 900, Δ110) can be estimated through the traffic assignment previously mentioned. Table 2 summarizes the essential evaluation values from the traffic flow estimation.

Table- 2. Evaluation of The Optimal Distance Based Toll

Toll	Urban Expressways						Urban Networks	
	Revenue (10000yen)	Vehicles (vehs)	Average (yen/veh)	Average (km)	Diversion (vehs)	Travel Time (veh×hr)	Travel Time (veh×hr)	User Benefit (10000yen)
Step function	72,797	1,052,124	692	16.2	22,609	364,841	10,390,510	
Original case	74,402	1,127,500	660	14.7	29,818	350,044	10,384,260	2,625
Optimum case	58,626	1,245,661	471	13.9	42,877	372,121	10,360,610	12,558

The total travel time for urban expressways is increased by proposed distance based toll comparing to the step function toll. On the contrary, the total travel time for urban network involving the ordinal streets is reduced. It causes of inflow traffic increase for urban expressway with lower level of toll charge. The average travel distance is decrease as well. It can be concluded that the distance based toll may provides the user benefit with optimal form determination.
The requirements should be mentioned to determine the proper form of the distance based toll. The linear distance based toll should be recommended mainly because of improvement of traffic efficiency on urban network. Therefore, total travel time for urban network should be reduced
On the other hand, the daily refund cost for construction of urban expressway should be required in the definition of toll. The requirement of revenue is determined as about 540,000 thousand yen from long term traffic estimation.

Traffic flow change between linear function toll and step function on the network can be estimated as well. Figure 10 illustrates the link traffic flow change on the Hanshinn expressway.

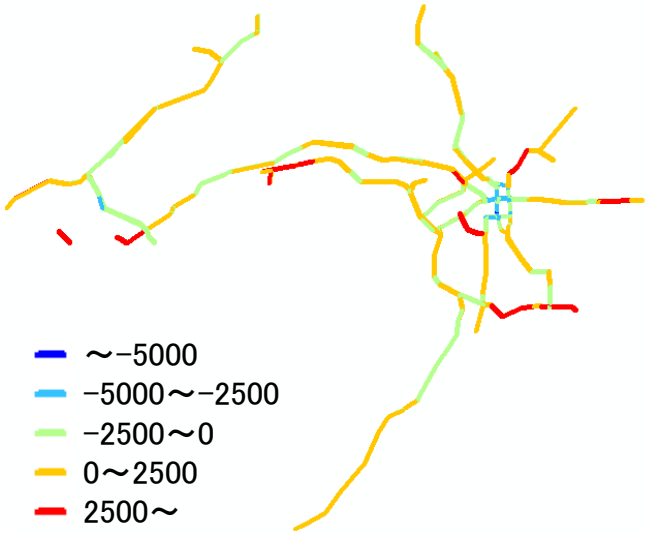

Figure-10 The Traffic Flow Change on The Proposed Distance Based Toll

As the lower price of toll is introduced comparing to the step function toll, traffic flow is reduced on the loop road in the city centre. On the contrary, traffic flow in the surroundings should be increased.

CONCLUDING REMARKS

The practical distance based toll system for urban expressway is discussed. In particular, the proper form of toll can be determined among many alternatives. The main findings are summarized as follows:

1) Many values of toll for travel between on-off ramps can be determined in distance based toll system. It is realized that the proper form of distance based toll can be determined in terms of the efficiency of urban traffic. It can be summarized that the optimization problem of the distance based toll with different forms can be formulated as MPEC according to user benefit of travel time reduction.
2) Even though the user equilibrium analysis is effective to estimate the traffic flows on urban network, the effort of estimation must be too much to evaluate all alternative cases concerning with the distance based toll system. The approximation model to estimate the evaluation values is proposed with neural network representation. The evaluation values such as total travel time and revenue of toll can be determined from the NN model with significant level of estimation.
3) Since the evaluation of feasible alternatives of the distance based toll can be estimated by the NN model rather instantly, the optimal form of the distance based toll is easily determined among many alternatives. In particular, it is useful to determine the several parameters in the distance based toll. The approximation model with NN is easily applicable in the practical problem. Finally, the optimal linear function is derived to produce the effective traffic flow on the urban expressways.

The approximation of evaluation values for distance based toll can be applied to the large scale expressway networks. For further study, the interaction between user benefit as reduction of travel time and the revenue of toll for management sector of urban expressway should be discussed for the comprehensive traffic management with pricing policy on urban expressways. Furthermore, the nonlinear function tolls with several parameters would be discussed as well for the proper distance based toll determination.

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