Application of Cordon Congestion Pricing for Urban Network with Integrated Model

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1. Introduction

Congestion pricing has been discussed as a practical traffic management on urban transport networks, for example, in Norway, in Singapore, in Korea (Seoul).... Traffic congestion is defined as an external diseconomy on the network in transport economics. It has been proposed that congestion pricing would be applicable to reduce traffic on the network. This system calls for a congestion toll to the links on the overall network. However, link-based charging may not be realized practically because of technical problems. Therefore, cordon congestion pricing should be considered. The optimal combination of cordon tolls would be determined in order to maximize social benefit. As the set of cordon congestion tolls is obtained, the evaluation of congestion pricing can be done in terms of social benefit analysis as well as reduction in traffic congestion.

2. The Theory of Congestion Pricing

2.1 Theoretical out line of congestion pricing

A single road between origin and destination is often assumed to formulate congestion pricing in transport economics. The core parts in this theory are summarized here to demonstrate its basic economic background. The congestion mechanism is illustrated by Figure 1.

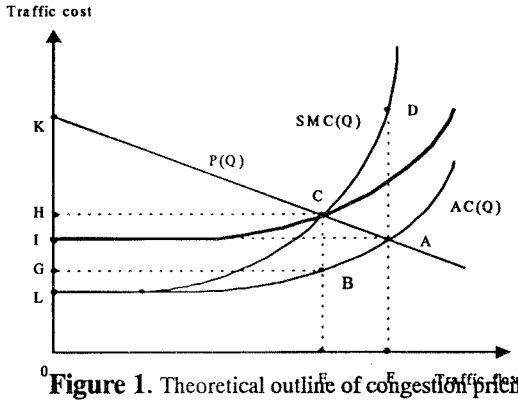

Figure 1. Theoretical outline of congestion pricing

AC(Q): Travel cost for an individual driver, average cost
SMC(Q): The social marginal cost.
P(Q): The traffic demand between origin and destination
BC: The value of congestion pricing that should be charged.

Traffic on the road is reduced with congestion pricing as indicated from F to E. Economic benefits constructed to congestion pricing can be considered. The social net benefit (SNB) consists of consumer's surplus and supplier's surplus. Therefore, the social net benefit is obtained corresponding to the area of KCL when an optimal congestion toll is charged. The dead weight loss is counted as the difference of SNB in market equilibrium from that in optimal congestion pricing.

2.2 Congestion pricing and traffic assignment:

The traffic assignment can be connected to congestion pricing theoretically. The market equilibrium flows on the network is equivalent to the user equilibrium (UE) in traffic assignment. The travel cost is measured by the link performance function $t_a(w)$. The demand function is defined as $q_{rs} = D_{rs}(c_{rs})$.

subject to

$$\min Z_{UE} = \sum_{a\in A}\int_0^{x_a} t_a(w)dw - \sum_{r\in R}\sum_{s\in S}\int_0^{q_{rs}^{max}} \left(\frac{1}{\theta}\ln\left(\frac{w}{q_{rs}-w}\right) + c_{rs}^{mass}\right)dw + \sum_{a\in A}\alpha x_a R$$

$$\sum_{k\in K_{rs}} f_k^{rs} = q_{rs}, \quad \forall r\in R, s\in S$$

$$f_k^{rs} \geq 0, \quad \forall k\in K_{rs}, r\in R, s\in S$$

$$x_a = \sum_{r\in R}\sum_{s\in S}\sum_{k\in K_{rs}} \delta_{a,k}^{rs} f_k^{rs}, \quad \forall a\in A$$

$$q_{rs} \geq 0, \quad \forall r\in R, s\in S$$

$$\sigma = 1/0 \quad \text{Exit/ not exit toll gate for Congestion Pricing}$$

This formulation is a modal split and traffic assignment integrated model with UE principle. It corresponds to the market equilibrium according to the average cost (AC). Next, the modal split and traffic assignment integrated model can also be applied to compute all the travel times, travel flows, ...of all links and all paths of a target urban network- Gifu city urban network as shown in figure 3.

The objective function in case of integrated model with SO principle is:

$$\min Z_{SO} = \sum_{a\in A} x_a t_a(x_a) - \sum_{r\in R}\sum_{s\in S}\int_0^{q_{rs}^{max}} \left(\frac{1}{\theta}\ln\left(\frac{w}{q_{rs}-w}\right) + c_{rs}^{mass}\right)dw + \sum_{a\in A} x_a R_a$$

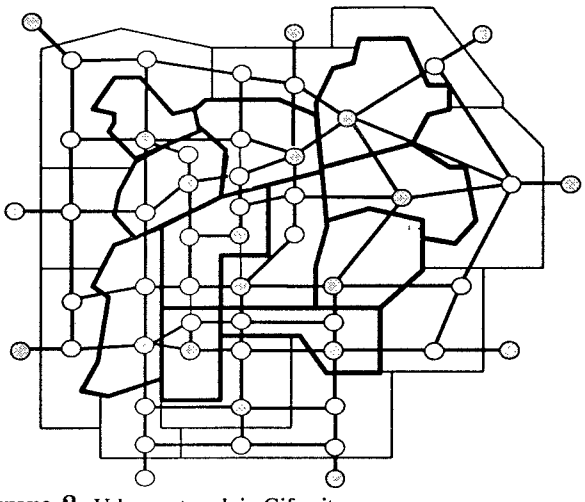

Figure 2. Urban network in Gifu city

Link cost can be determined from BPR function as (JSCE,1998):

$$t_a(x_a) = t_a^0\left[1 + 0.15\left(\frac{x}{Q_c}\right)^4\right]$$

In this paper, congestion pricing is considered in these two cases: + Case 1: Link-based Congestion pricing

+ Case 2: Cordon congestion pricing.

In case 2, first, just zone number 1, then only the combined area of zone numbers 1, 2, 5, 6 is applied to congestion pricing, respectively named "Narrow area Cordon Congestion Pricing" and " Wide area Cordon Congestion Pricing". All the results of travel time, travel flow, of all links, can be computed. Then some other involved features of economic effect may be accrued, such as social benefit, social net benefit, social surplus, user surplus, number of car users, number of mass transit users, increase of mass transit income and so on, after a congestion pricing application has been computed and analyzed.

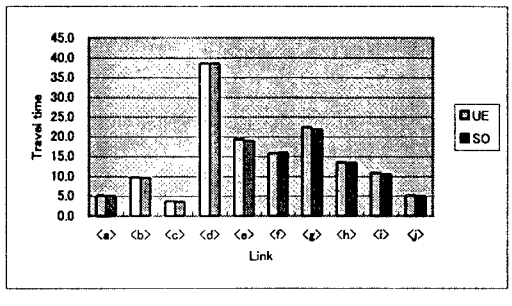

Figure 3. Link travel time

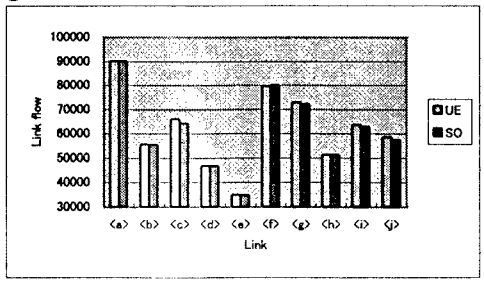

Figure 4. Link flow

The social net benefits in the case of " Narrow area Cordon Congestion Pricing" and in the case of "Wide area Cordon Congestion Pricing" are shown as figure 5.

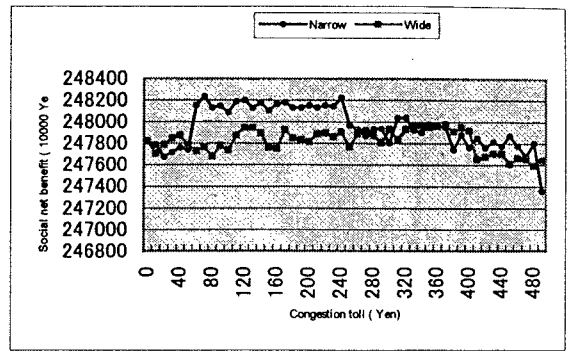

Figure 5. Social net benefit

Table 1 and table 2 show the two sets of results that are obtained with a congestion toll of 50 Yen, and a congestion toll of 100 Yen. The range in the charges of congestion pricing is from 0 Yen to 490 Yen.

Toll = 50 Yen	Narrow area	Wide area
Social total benefit	360916	360947
Social total cost	113175	113166
Income by road pricing	94	131
Social net benefit	247741	247781
User surplus	110163	110115

Table 1. Evaluation of Cordon Pricing (Unit: 10000 Yen)

Toll =100 Yen	Narrow area	Wide area
Social total benefit	360916	360947
Social total cost	113175	113166
Income by road pricing	94	131
Social net benefit	247741	247781
User surplus	110163	110115

Table 2. Evaluation of Cordon Pricing (Unit: 10000 Yen)

3. Conclusions

The cordon congestion pricing system is proposed as a combined optimization problem in this study. It might be the practical application of the congestion pricing for an urban transport network. The congestion pricing on urban transport network can be formulated via a combined model of modal split and traffic assignment. The cordon congestion pricing system may work well to ease traffic congestion in central area of a city.

By application of congestion pricing, the number of car users decreases, and the mass transit users increases. The income coming from congestion pricing should be used not only to improve vehicle networks services but also public network services. This could be a positive solution on environmental problems.

References

1. Akiyama T, Takahiro N. (2002), *Analysis of Zonal Congestion Pricing on Urban network.*

2. Sheffi, Y. (1985) *Urban Transportation Networks*: Equilibrium Analysis with Mathematical Programming Methods, Prentice-Hall