Optimal Pricing Policy in a Transport Network with both Scale Economies and Congestion

--Case Study of Nagoya Metropolitan Area

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ABSTRACT

Transport pricing depends largely on the cost structure of transport system, which is characterized by three most relevant properties: economies of scale, congestion, and capacity constraint. In this paper we investigate in particular the economies of scale in railway transport. And by combining the railway cost functions with increasing returns into a network equilibrium model, we compute the effects of marginal cost pricing schemes on roads and railways. These results suggest that while the effects of marginal cost pricing restricted on railways may be limited, road marginal cost pricing has outstanding effects of driving car users to railways in the long run.

Keywords: Optimal Pricing, Network, Scale Economies, Congestion

1. INTRODUCTION

Pricing is a fundamental policy tool for achieving the efficient and fair use of transport network systems. For efficiency, the marginal cost pricing scheme (MCP) by which the prices are set equal to the marginal social costs for the marginal use of transport infrastructure or service is an ideal scheme under some ideal circumstances. MCP implies that a system with economies of scale should be subsidized and a system with congestion should be taxed. In this paper by congestion we mean the economic property of transport that the average cost increases with the increase of usage of the network system.

While MCP is advocated in EU (European Communities White Paper, 2001), there is still doubt about its effectiveness due to the lack of sufficient consideration of fairness and fiscal affairs, and other institutional constraints (Rothengatter, 2003). A practical approach is the so-called MCP-based pricing which aims to shrink the gap of efficiency between actual pricing scheme and MCP (Nash C. And Matthews B. eds., 2006).

In practice, transport pricing indeed seems to lie between marginal cost and average cost pricing. In fact, most railways in Europe and American, and most underground railways in Japan are subsidized. There are more and more cities which have implemented congestion pricing on urban road network. This reflects the spread of application of marginal cost pricing in road network management.

It is then of great importance to establish a method that can analyze and design flexible pricing schemes of transport networks with both economies of scale and congestion, with various kind of constraints.

In this paper we present a network equilibrium approach for analyzing pricing schemes in a network with both economies of scale and congestions, and report findings of our empirical study on the pricing system for railway and road network in Nagoya metropolitan area of Japan.

In the following section, economies of scale in particular in railways will be examined. In Section 3 congestion in transport will be briefly addressed. In section 4 some theoretical aspects of transport pricing will be reviewed, and practical transport pricing will be examined based on evidence from Japan. A network equilibrium based model for analyzing transport pricing policies will be presented in Section 5. In Section 6 this model will be applied to the Bi-modal transport network of Nagoya metropolitan area in central Japan. In particular, the effects of marginal cost pricing on roads and railways will be investigated.

2. ECONOMIES OF SCALE IN TRANSPORT SYSTEMS

In this section we examine economies of scale in railway and road transport.

2.1 Railway

It is widely recognized that railway transport exhibits strong *economies of density* because the fixed investment on rail tracks, rolling stocks, stations and other equipments are huge compared with the variable costs. Here we examine the case of some Japanese firms.

There are currently three categories of main railway companies: the Japan Railway (JR) companies which were established by the privatization of the former Japan National Railway; the private companies which have been developed accompanying to Japan's industrialization and urbanization since the early 20th century; underground railways in large cities operated by municipalities with one exception: the Tokyo Metro company with limited shares owned jointly by Japanese central government and the Tokyo Metropolitan Government.

In Figure 1 is shown the average operating cost (including depreciation) of 62 private railway companies (excluding some small ones; data source: Railway Statistical Year Book of 2001, Ministry of Land, Infrastructure, and Tourism, Japan) plotted with respect to their transport densities (passengers per track). Since most Japanese private firms are also doing businesses such as real estate and retail, it is difficult to identify the capital cost of investment on railways and therefore difficult to identify their true total costs. However, the fares of Japanese railways are regulated by the average cost pricing principle (cf. Okabe 2004), it may be assumed that fare reflects the average total costs of railways. Economies of density can also be observed by using fare as a measure of cost (see Figure 2).

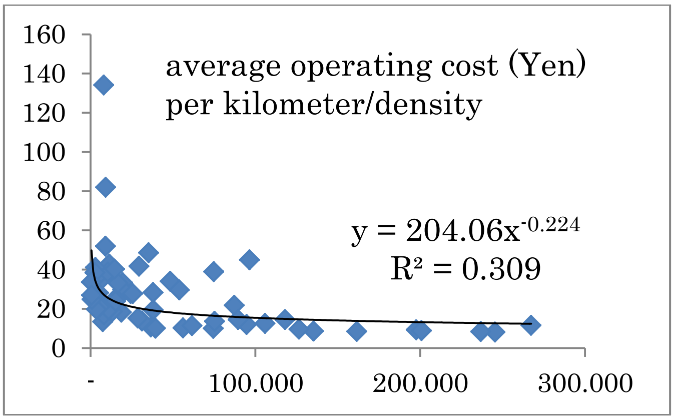

Figure 1 – Decreasing per passenger-km cost of Japanese railways with increasing density

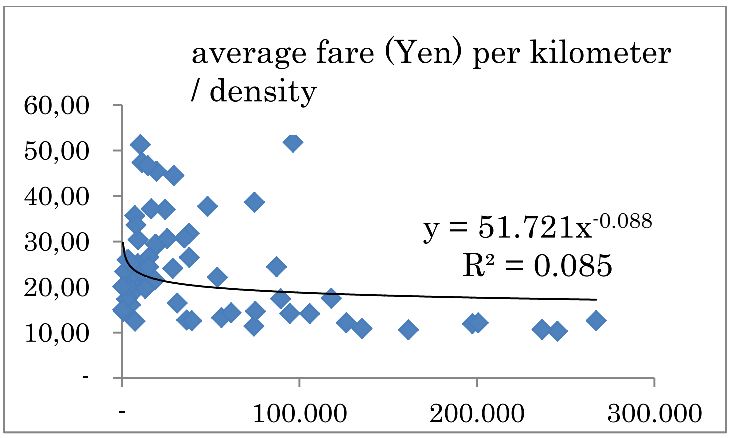

Figure 2 – Decreasing per passenger-km fare of Japanese railways with increasing density

We have actually also observed outstanding *economies of scale* in passenger railway transport. In Figure 3 and 4 are shown the graphs for the relationship of per passenger kilometer operating cost and fare with passenger kilometers traveled, for the 62 railway firms in Japan, respectively. Given fixed lengths of rail tracks, scale is proportional to density, therefore economies of density and scale are the same thing in this case. However, there may exist complementary effect between spatially complementary routes that ride passengers to each other, this may be a reason for the exhibition of economies of scale with a different nature than density. Furthermore, the existence of optimal size of firm may also be a general factor explaining economies of scale of railway.

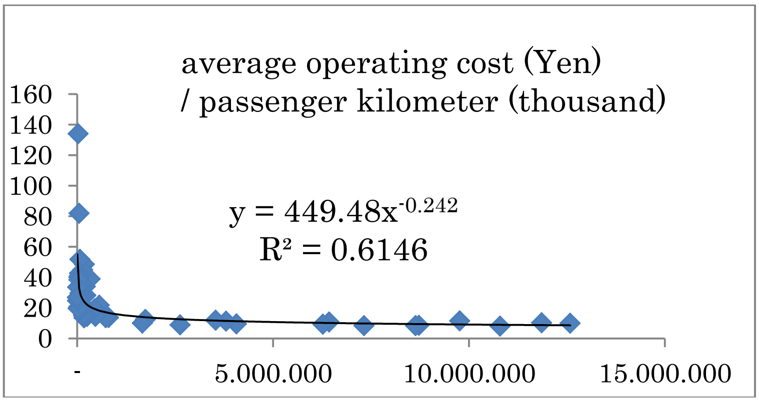

Figure 3 – Decreasing per passenger-km cost of Japanese railways with increasing scale

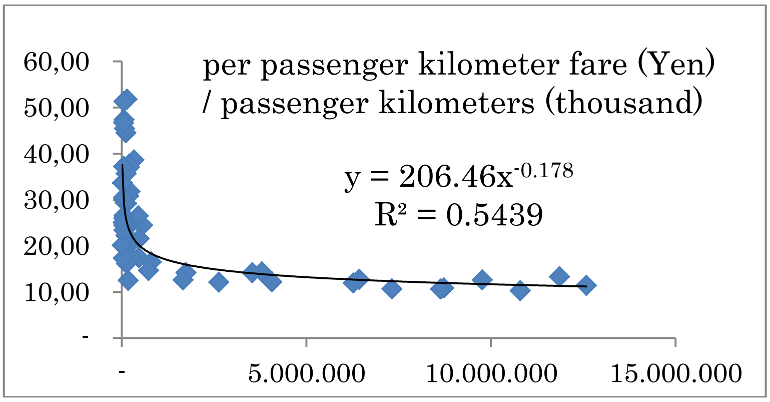

Figure 4 – Decreasing per passenger-km fare with increasing scale

A passenger's cost depends also on waiting time, travel time and comfortableness, along with fare. In general, for dense and large scale railway system, the frequency and speed of trains are usually high, and passengers have less cost in term of travel time. This is also an effect of economies of scale and density of railway transport.

For a single trip, economies of scale also exist. That is, a longer trip by railway usually has smaller average cost than a shorter one. This is mainly because the cost at stations is considerably large. Due to this reason, Japanese railway fares contain a starting fare plus a variable part depending on the length of trip. A two variable cost function will be identified In order to reflect this effect in the modeling of pricing policy analysis in Section 6.2.

2.2 Road Transport

Since roads also need fixed investment for construction, there may exist economies of density and scale. In Figure 5 is shown an approximately linear relationship between operating cost and vehicle kilometers in urban highways in Tokyo, Osaka-Kobe and Nagoya. Taking into consideration the fixed investment cost of construction, economies of scale may be expected to exist. Actually, Nagoya has a smaller highway network than Tokyo and Osaka, and has higher tolls.

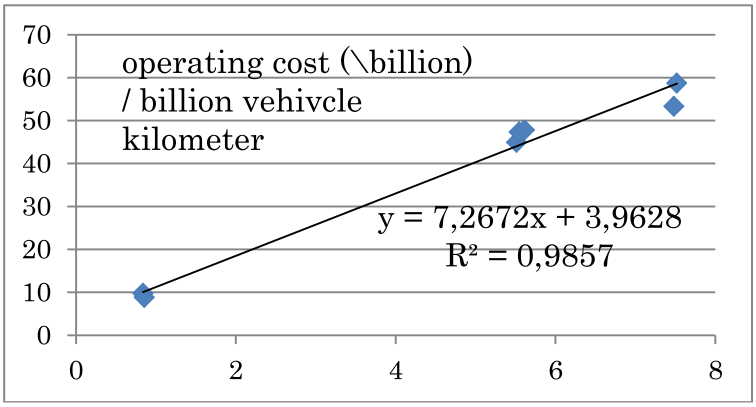

Figure 5– Operating cost and traffic volume of Japanese urban highways.

Source of data: financial reports and IR documents.

3. CONGESTION

As defined in the Introduction section, by congestion we mean the economic property of transport that average transport cost increases with traffic volume. Here we analyze several kind of congestions in railway and road transport.

Railway Transport

Given the capacity of a railway route, large volume of passengers may generate queues and cause longer waiting time, and cause congestion and injure comfortableness in train and increases passenger’s cost (Maruyama *et al*. 2002). From these observations, it may be concluded that economies of scale exists in the long run and congestion may exist in the short run for railway transport.

Road Transport

Perhaps the most well known formula expressing the congestion effect of road transport is the U.S. Bureau of Public Road function for the road travel time

$$t = C_0(1 + b\left(\frac{x}{Cap}\right)^a),$$

where a and b are positive parameters, C_0 is the free flow travel time and Cap the capacity of a road. Cars that travel with low speed also consume more fuels than high speed within an appropriate range. Comfortableness will also be injured due to congestion. These effects also reflect the cost of congestion: the average cost by driver increases with traffic volume.

4. THEORY AND PRACTICE IN TRANSPORT PRICING

4.1 Monopoly, Average Cost and Marginal Cost Pricing

When unregulated, a natural monopolistic railway company's profit maximizing behavior results in a pricing regime where the marginal cost equals the marginal revenue. Traditional regulation policy requires that the price is set equal to the average cost, which contains a certain fair rate of return of capital invested in the transport system (the average cost pricing principle, ACP). However, under some conditions, the best pricing regime that maximizes the social welfare (consumer's surplus plus producer's surplus) is the marginal cost pricing (MCP) which sets the price equal to marginal cost.

4.2 Ramsey Pricing, Non-linear Pricing

In the case where economies of scale exist, the MCP is lower than ACP thus brings about a deficit to the transport service provider. Given a budget constraint, a mark-up inversely proportional to the elasticity of demand should be added to the price beside marginal cost. This is the well-known Ramsey pricing principle (Baumol *et al*. 1970).

The origin of economies of scale in transport systems can be attributed to the huge initial investment in the construction of infrastructures. A simple pricing regime for achieving same efficiency as MCP while collecting sufficient revenue covering the full cost is the two-part pricing which levies a fixed part of tariff and collects another part of tariff according the usage of the transport system. This can be extended to general nonlinear pricing schedules according to the characteristics of the system.

4.3 Congestion Pricing, Peak Load Pricing and Scarcity Pricing

The marginal cost pricing, as applied to the case where congestion is dominating, is equivalent to the so called congestion pricing, which charges the user the average cost plus a congestion tax equal to the difference of marginal cost and average cost. The utilization of a transport system is changing across different seasons, different days of the week and different time of the day. The capacity of the transport system largely depends on the travel demands at the peak times. From this fact an idea arises to collect a capacity investment cost from the peak time users. Peak load pricing may also be looked at as a scarcity pricing principle in the sense that capacity may be considered as a kind of scarce resource and its use should be properly priced. In general, scarcity in transport system means a kind of opportunity cost caused by the exclusive use of the system by a particular user. In the case of road traffic, excess demand can be queued up and the scarcity cost can be measured by the increase of waiting time cost to the rest of users. However, if we consider the cost of operating a particular train in a particular slot, then the scarcity cost is actually determined as the competing auction price for exclusively using this slot (Nilsson 2002).

4.4 Practical Transport Pricing

There are basically two forces determining fares charged to passengers. The first is the government regulation and subsidization policy, the second is the pricing strategy by individual private or public train operating companies.

Japan's railway system is operated based on the average cost pricing principle. There are currently three categories of main railway companies: the Japan Railway (JR) companies which were established by the privatization of the former Japan National Railway; the private companies which have been developed accompanying to Japan's industrialization and urbanization since the early 20th century; underground railways in large cities operated by municipalities with one exception: the Tokyo Metro company with limited shares owned jointly by Japanese central government and the Tokyo Metropolitan Government (Ying 2009).

The Japanese government regulates the fares by the so-called yardstick competition within each of these categories. For each category, reference formulas for calculating various operating costs are derived from the average performance of the railway companies in the category. For each category a cap price is set based on these formulas and a certain admitted rate of return for capitals invested in railways (Okabe 2004). Therefore Japan's railway transport pricing may be considered as very close to average cost pricing as a whole.

However, the pricing regimes are different among different passenger groups: the regular passengers (commuters and students) usually use monthly passes and the irregular passengers use normal tickets. The former is actually a two-part pricing with the variable part being zero. All fares are almost fixed across both peak and off-peak periods.

5. EQUILIBRIUM BASED DESIGN OF TRANSPORT PRICING

In order to design pricing in a multi-modal transport network, a natural choice (perhaps the only choice) is to apply traffic network equilibrium model for modeling the effect of various pricing policies and optimizing such policies under various constraints. It will be ideal to use a dynamic traffic equilibrium model for analysis pricing policies because of the time dependent nature of travel demand within a day. Indeed there has already been research which applies dynamic models for analysis transport pricing policy (see Kanamori et al. 2007). However, this kind of detailed models is currently difficult to be applied to analyze pricing policies involving the long term financial structure of railways. Furthermore, day time can be divided into several time periods within which travel demands and traffic flows are stable, and peak load period traffic flows contain most commuting travels and reflect the main features of characteristics of an urban network. Therefore it is still possible to use a static traffic equilibrium model to study the effect of various multi-modal pricing policies on the network. In this work a bi-modal stochastic user equilibrium (SUE) model is used for analyzing transport policies. As shown in Figure 6, the pricing schedule is input to the bi-modal network equilibrium model, travel time, monetary costs are obtained as outputs of the model.

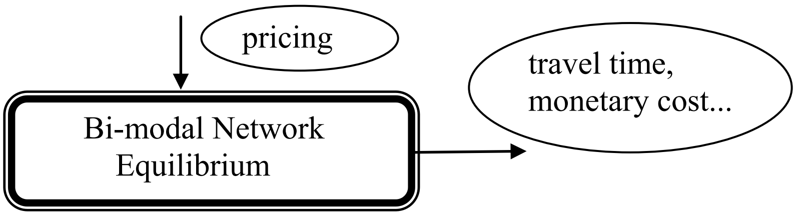

Figure 6. Equilibrium based pricing policy analysis.

The SUE model for a network consisting of railways and roads can be formulated as follows.

Let $\bar{q}_{rs}$ be the travel demand from origin $\boldsymbol{r}$ to destination $\boldsymbol{s}$. The demand using passenger car q_{rs} and the demand for railway $\hat{q}_{rs}$ are given by the following formula

$$q_{rs} = \bar{q}_{rs} \frac{\exp(-\alpha(S_{rs} + G_{rs}))}{\exp(-\alpha(S_{rs} + G_{rs})) + \exp(-\alpha \hat{S}_{rs})} \qquad (1)$$

$$\hat{q}_{rs} = \bar{q}_{rs} - q_{rs}$$

α : parameter

S_{rs} : disutility of using automobile

G_{rs} : relative disutility difference factor of using automobile

$\hat{S}_{rs}$: disutility of using transit

Let $A = \{ij\}$ be the set of road links, road network stochastic user equilibrium is determined by the following equations.

$$F_{ij}(\boldsymbol{x}) = x_{ij} - \sum_{rs} q_{rs} \frac{\sum_k \exp(-\theta c_k^{rs}) \delta_{ij,k}^{rs}}{\sum_l \exp(-\theta c_l^{rs})}$$

$$= x_{ij} - \sum_{rs} q_{rs} \frac{\partial S_{rs}}{\partial t_{ij}} = 0, \quad ij \in A; \qquad (2)$$

$q_{rs} = q_{rs}(S_{rs}, \hat{S}_{rs})$ a function derived from (1)

$S_{rs} = -\dfrac{1}{\theta} \ln(\sum_k \exp(-\theta c_k^{rs}))$: disutility of using automobile

$c_k^{rs} = \sum_{ij} c_{ij} \delta_{ij,k}^{rs}$: route cost

$c_{ij} = t_{ij}(x_{ij})VOT + T_{ij}$: VOT is value of time by car, T_{ij} is the toll on link ij.

$$\hat{F}_{ij}(\hat{x}) = \hat{x}_{ij} - \sum_{rs} \hat{q}_{rs} \frac{\sum_k \exp(-\theta \hat{c}_k^{rs}) \delta_{ij,k}^{rs}}{\sum_l \exp(-\hat{\theta} \hat{c}_l^{rs})}$$

$$= \hat{x}_{ij} - \sum_{rs} \hat{q}_{rs} \frac{\partial \hat{S}_{rs}}{\partial \hat{c}_{ij}} = 0, \quad ij \in \hat{A}; \qquad (3)$$

$\hat{q}_{rs} = \hat{q}_{rs}(S_{rs}, \hat{S}_{rs})$ a function derived from (1)

$\hat{S}_{rs} = -\frac{1}{\hat{\theta}} \ln(\sum_k \exp(-\hat{\theta} \hat{c}_k^{rs}))$: disutility of using railway transit

$\hat{c}_k^{rs} = \sum_{ij} \hat{c}_{ij} \delta_{ij,k}^{rs}$: route cost

$\hat{c}_{ij} = \hat{t}_{ij} + \hat{T}_{ij}(\hat{x})$: $\hat{T}_{ij}$ is the fare for railway link *ij*.

In general, $\hat{T}_{ij}$ depends not only on the passenger flows of a railway link, but also on flows on other links.

In the following empirical studies, *VOT* was set to be 62.86 Yen/Minute for a car. Number of passengers per car was estimated as 1.427826. Therefore *VOT* per person is 62.86/ 1.427826=44.025 (Yen/Minute). We also use this figure as the value of railway travel time. The parameters $\alpha, \theta, \hat{\theta}$ are determined from results of existing research on route choice and modal split in Nagoya area (Kanamori 2007, with modification).

$$\alpha = 0.0033, \theta = 0.0167, \hat{\theta} = 0.01 \qquad (4)$$

6. EMPIRICAL STUDY ON NAGOYA AREA

In this section we investigate the outcome of several marginal cost based pricing schemes applied to the Nagoya metropolitan area. The area is composed of 481 zones (including some zones geographically outside Nagoya area in order to take into account the influence of flows outside Nagoya area).

6.1 Road Network

The road network of the metropolitan area centered at Nagoya has 3,383 nodes and 10,687 (directed) links in total. As shown in Figure 7, there are inter-city expressways (abbreviated as IC) of Central Nihppon Expressway (former Japan Highway) and a ring expressway (abbreviated as RING) in Nagoya, and several routes managed by the Nagoya Expressway Public Corporation (owned by Nagoya City, abbreviated as NE).

The data for the network and for travel demand is from “the Fourth Chukyo (Nagoya Area) Personal Trip Survey” undertaken in 2001.

Modified BPR functions are used as link cost functions.

$$t = t_0\left(1 + \alpha\left(v / C_{ap}\right)^{\beta}\right), \ \alpha = 0.48, \ \beta = 2.82, \qquad (5)$$

where v is link traffic flow, C_{ap} is link capacity, t_0 is free flow link travel time.

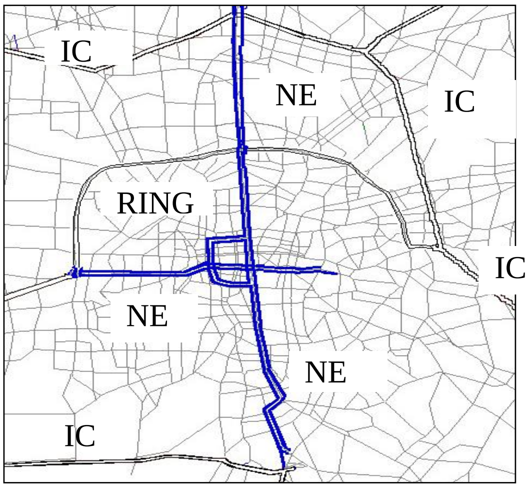

Figure 7. Road network of Nagoya area.

6.2 Railway Network

In Nagoya metropolitan area, there were the following railways: Nagoya Underground, Central Japan Railway, Nagoya Railroad, Kintetsu, Tarumi Railway, Aichi Loop Line, Jouhoku Line, Akechi, Toyotetsu, Sangi, Nagara Railway, Peach Line, Ise Railway, Guideway Bus,Gifu Street Car, and Toyotetsu Street Car.

By examining the cost structures of main railways of Japan, underground railways were found to have distinct features from over-ground railways. Operating costs of underground seem to be more relevant to the number of passengers than the total passenger kilometers traveled, while operating costs of over-ground railways depend more strongly on the total passenger kilometers traveled. This may be due to the fact that underground railways have a larger share of station costs than over ground railways.

Therefore we identified two kinds of cost functions: one for underground and the other for over ground railways. Central Japan Railway is a railway company which operates a Shinkansen line and a network of conventional trains centered at Nagoya. Because Shinkansen carries mainly long distance passengers, the effect of traffic volume in Nagoya area has very limited influence on its costs, we assume that Shinkansen has constant average cost.

For over ground railways (excluding Shinkansen high speed rail), using the data of 61 railway firm from Railway Statistical Year Book of 2001 (Ministry of Land, Infrastructure, and Tourism, Japan), we got the following cost function

$$TOC = AX^{0.122146}Y^{0.647607} \qquad (6)$$

where TOC is the total operating cost (Japanese Yen), X (passenger) is the total number of passengers and Y (passenger kilometer) is the total passenger kilometers traveled. The parameter A is determined for each specific firm by equalizing the actual total cost with the value estimated from formula (6).

For the underground, the data set was small (10 Underground Railways). In order to obtain stable estimation of function parameters, we assumed that the ratio of the marginal cost per person and the marginal cost per passenger kilometre is fixed. We also assume that this ratio equals to the ratio of total starting fare with the total fare proportional to the ride distances for the Nagoya Underground railway, which is 4.2873 by applying equilibrium model for the railway network with given railway demands by the Nagoya Area Personal Trip Survey (Aichi Prefecture, 2001). With these assumptions, we got the following cost functions for underground railway

$$TOC = BX^{0.66624}Y^{0.1554} \qquad (7)$$

The parameter B is determined by equalizing the actual total cost for each specific firm with the value estimated from formula (7).

6.3 Results

Table 1 shows results of 4 kinds of pricing schemes applied to the Nagoya metropolitan area. The first is the base case reflecting the actual state in 2001. We compared this case with actual statistical data and found that observed traffic flows are slightly larger than the estimated results (especially for railways), which is caused by omitting the traffic flows within zones; otherwise our model coincides well with the actual case.

The second, third and fourth are the cases applying marginal cost pricing on rail network, road network and both networks, respectively. For the latter two cases, marginal cost of both highways and street roads are only the marginal cost of total link travel time, that is, it does not include maintenance and capital costs of roads.

In the table, *daily* usage of both railway and road and various costs are given for these cases. The column *Rail Users* indicates the daily number of railway passengers moving within, into and out from the Nagoya metropolitan area. *Rail Revenue* and *Rail Cost* indicate respectively the total railway revenue and operating cost. *Road Users*, *Road Time* and *Road Revenue* indicate the number of car users, total car travel time and revenues from roads (including both highway and street roads). *Local Rail Users* and *Local Road Users* indicate the daily number of railway passengers and the number of car users moving within the central part of the Nagoya metropolitan area, respectively.

From the results it can be observed that marginal cost pricing on rail has a slight effect of shifting car drivers from road to railway for the total network (about 5% increase of rail passengers), the increase ratio for the central area is 10%. We think this may reflect the fact that the effect of reducing fare without reducing travel time may be limited, especially for long distance travelers. Applying marginal cost pricing to both railways and roads has significant effect of shifting road users to railways. Total railway passengers increase by 13% and local passengers rise by 20%. Total and local road travelers reduces from 9.88 million to 9.60 million (-2.8%) and from 4.48 million to 4.2 million (-6.3%), respectively. In our previous study (Ying and Ando, 2006), a much smaller effect of marginal cost pricing on road network assuming no modal shifting was observed. This result suggests that marginal cost pricing on road network has much stronger effect if the alternative railways are available.

In Table 2 are shown some results of pricing schemes which treat highway and street roads differently. In the case MCP on Highway, marginal time cost is imposed on highway links. It can be observed that in this case the total highway revenue is even less than the actual case, implying that highways in Nagoya area currently actually exhibit scale economies on the

	Base Case	MCP on Rail	MCP on Road	MCP on both Rail & Road
Rail Users (million)	2.17	2.28	2.36	2.45
Local Rail Users (million)	1.38	1.48	1.56	1.66
Rail Revenue (million Yen)	757.7	651.5	781.4	667.5
Rail Cost (million Yen)	757.7	782.9	781.4	803.7
Road Users (million)	9.88	9.78	9.70	9.60
Local Road Users (million)	4.48	4.38	4.30	4.20
Road Total Time (million Hours)	3.66	3.58	3.07	3.03
Road Revenue (million Yen)	980.2	971.0	2564.0	2445.3

Table 1. Results of four pricing schemes. Figures are values for a single day.

	Base Case	MCP on Highway	MCP on Highway (+Oper Cost)	MCP on Rail&HW (+Oper Cost)	MCP on Street Road
Rail Users (million)	2.17	2.09	2.12	2.22	2.44
Local Rail Users (million)	1.38	1.30	1.32	1.42	1.64
Rail Revenue (million Yen)	757.7	733.9	741.9	636.3	810.6
Rail Cost (million Yen)	757.7	733.9	741.9	763.9	810.6
Road Users (million)	9.88	9.96	9.93	9.83	9.61
Local Road Users (million)	4.48	4.56	4.53	4.43	4.21

Road Total Time (million Hours)	3.66	3.57	3.57	3.53	3.11
Road Revenue (million Yen)	980.2	520.2	859.4	843.0	3033.9

Table 2. Results of pricing schemes focused on urban highways.

average, rather than congestion. In the cases *MCP on Highway (+Oper. Cost)* and *MCP on Rail&HW (+Oper. Cost)*, a marginal highway operating cost (7.276 Yen per vehicle kilometer, see Figure 5) is added to the marginal time cost. We can see that these cases are close to the actual situation with average cost pricing. The last case *MCP on Street Road* shows the result of applying marginal time cost only on street roads, which is similar to the case of *MCP on both Rail and Road* shown in Table 1.

7. CONCLUDING REMARKS

In this paper we have investigated in particular the economies of scale in railway transport. And by combining the railway cost functions with increasing returns into a network equilibrium model, we computed the effects of marginal cost pricing schemes on roads and railways. These results indicate that road marginal cost pricing has outstanding effects of driving car users to railways, while the effects of marginal cost pricing restricted on railways are rather limited. This reveals that there is strong potential for achieving efficient use of the multi-modal network by a combination of various pricing policies both on roads and on railways. We are continuing the search of such kind of optimal pricing combinations by applying the network equilibrium based optimization methods, and will present our findings in due course.

Acknowledgements

This work has been financially supported by the Grant-in-Aid for Scientific Research by Japan Society for the Promotion of Science (C 20510133), The Asahi Glass Foundation Research Grant and a fund by Gifu University for short term over-sea research. We are grateful to the Council for Integrated Urban Transportation Planning of Chyukyo Metropolitan Area for providing us with person trip data. We would also like to thank Dr. R. Ando for discussion at an early stage of this research.

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