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Under the conventional road planning in Japan, arterial road network standard or density has been determined in an “engineered” way, aiming to adequately deal with the future transportation demand. The “engineered” methods might be most appropriate during the high economic growth period, when no one doubts continuous transportation demand growth requiring capacity expansion. In depopulating era that Japan is now facing, however, it is noteworthy to analyze the “economic” aspect of road demand and supply. Economic theory indicates that road transportation demand is determined by price of road use (fuel tax, toll, etc.). It is necessary to inform the road users of the price or actual cost of road use, based on the estimation of road construction, maintenance, renewal costs and external costs including congestion costs, so that it is possible to supply optimal road capacity through a new planning and financing scheme (a distance-based and social marginal cost pricing).

The purpose of this study is to propose a new road planning and financing scheme based on short-term social marginal cost pricing that enables to lead optimal road capacity in the long term. If road is congested or the capacity does not meet the transportation demand, short-term social marginal cost pricing (congestion pricing) brings more revenue than the necessary fund to maintain and renew the existing road. Then we can increase the capacity with the fund, which improves the congestion and then results in the reduction of the road prices. On the contrary non-congested road can be optimized by not replacing all old roads with limited revenue. This study aims to demonstrate this new planning and financing scheme by conducting simulation analysis assuming arterial roads in Japan.

Key Words　Marginal cost pricing, Road planning, Road Financing, Distance-based charges

1 Introduction

Under the conventional road planning in Japan, arterial road network standard or density has been determined in an "engineered" way, with the aim of adequately dealing with the future transportation demand. For example, the "national coefficient theory" has been applied for the determination of the intercity arterial road network standard, which determines the necessary network density by population, land area, etc. (Imai *et al.,* 1971). For the urban arterial road network, necessary network density and the number of lanes have been determined based on the land use and trip generation density (City Bureau of the former Japanese Ministry of Construction, 1992). These "engineered" methods might be most appropriate during the high-growth period, when no one doubts the continuous growth of transportation demand requiring capacity expansion.

However, in the depopulating era that Japan is now facing, it is noteworthy to analyze the "economic" aspect of road demand and supply. Economic theory indicates that road transportation demand is determined by the price of road use (fuel tax, toll, etc.). Based on the beneficiaries-pay principle, the price must be set considering the road supply cost. The price of road use would be high on a costly section of roads, and the higher price leads to lower transportation demand and to more revenue and investment as well. It is necessary to inform the road users of the price or actual cost of road use, based on the estimation of road construction, maintenance, renewal costs and external costs including congestion cost, so that it is possible to provide an optimal road capacity through a new planning and financing scheme (a distance-based and social marginal cost pricing).

Road pricing has attracted academic curiosity for decades. Since the early works on the subject in the 1960s, such as Walters (1961), Vickrey (1963), and the UK Ministry of Transport (1964), the interest has grown largely especially due to practical needs. Thus, there have been a number of applications of road pricing. These examples are comprehensively organized in Small and Gomez-Ibanez (1998).

The theory of road pricing was first developed as the method of relieving traffic congestion, which is one of the social costs, by charging a toll equal to the social marginal cost. Most of the studies on road pricing have focused not on capacity management but only on transportation demand management. In other words, the road capacity has usually been treated as "fixed" in the past studies. Thereafter, Mohring (1976) first expanded the theory to consider how capacities are optimized in the long term. Our paper is also based on the assumption of road capacity as "variable."

Since the optimal toll differs with the extent of congestion, the optimal toll must be differentiated by area, time period, distance driven, etc. This type of differentiation is now possible through technical innovations in ICT and ITS (Intelligent Transportation System), such as DSRC (Dedicated Short Range Communication), GPS, digital tachograph, and automatic identification of license plate. These innovations make it possible to obtain information about the location of a vehicle at a reasonable cost that is necessary for road pricing. The conventional road planning is now required to be restructured with the help of new technology.

The purpose of this study is to propose a new arterial road planning and financing scheme based on short-term social marginal cost pricing that facilitates the establishment of optimal arterial road capacity in the long term. If the road is congested or the capacity does not meet the transportation demand, short-term social marginal cost pricing brings more revenue than is necessary to maintain and renew the existing road. Then, we can increase the capacity using the funds, which improves the congestion and subsequently results in the reduction of the road prices. On the contrary, a non-congested road can be optimized by not replacing all old roads with limited revenue based on marginal cost pricing. This study aims to demonstrate this new planning scheme by conducting simulation analysis based on arterial roads in Japan.

2 Road Planning Scheme Based on Beneficiaries-Pay Principle

2.1 Average Cost Pricing and Marginal Cost Pricing under Fixed Road Capacity

The road price is defined as the total of the taxes and charges paid by the user upon purchase, possession and use of an automobile, including vehicle holding taxes, gasoline taxes and road tolls, although the user has to bear vehicle cost and time cost additionally when driving. These taxes and charges are transferred from the users to the government, which appropriates them for maintenance and renewal of the roads (Table 1). There exist a variety of empirical studies on the classification of road costs. Levinson and Gillen (1998) deal with the feature of cost on road administrators in the U.S., and Misui (2005) studies the same issue in Japan. With regard to external costs, there exist more studies such as Greene, Jones, and Delucchi (1997), which surveys and refines the previous studies.

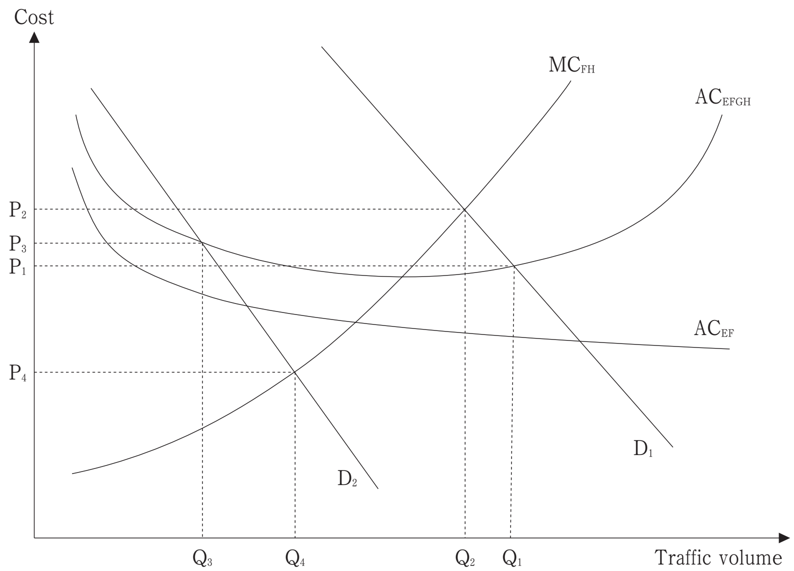
The traditional way to finance roads has been to collect taxes amounting to the total fixed cost E (in Table 1) for constructing the roads plus the variable cost F (i.e., E and F make the total expenses of road administrators). This principle is called average cost pricing because the average cost multiplied by the traffic volume makes the total cost. However, it is theoretically understood that charging social marginal costs, which include the external costs (e.g. congestion and air pollution), is the way to obtain the optimal distribution of resources in short term. This approach synchronizes the marginal costs with the users' willingness to pay (marginal benefits).

Table 1　Road Costs

		Fixed costs	Variable costs
Internal costs	Road users	A: Vehicle costs and maintenance	B: Time cost, travel cost
	Transferred	C: Vehicle acquisition tax, license fee	D: Gasoline tax, expressway fee, congestion charge, distance-based fee
	Road administrators	E: Construction cost, maintenance cost (lighting, etc.)	F: Maintenance cost (painting, etc.)
External costs		G: Landscape destruction, redundancy	H: Congestion, air pollution, noise, traffic accidents

The principles of average cost pricing and marginal cost pricing are illustrated in Figure 1. The maintenance costs F increases with traffic volume, but the rate of increase slows down with the traffic volume, so the average cost curve of road administrators (AC_{EF}) is concave upward. The average cost curve including external effects (AC_{EFGH}) begins to increase once the traffic volume exceeds the road capacity and traffic speed drops. Previous research on estimating externalities indicates that congestion cost is the dominant portion of the marginal cost curve (MC_{FH}) (Quinet and Vickerman (2004)). If the demand for a given road is D_1, the average cost pricing results in a price of P_1 and the traffic volume at this price is Q_1. Marginal cost pricing indicates correspond-

Figure 1　Average Cost Pricing and Marginal Cost Pricing



ing values of P_2 and Q_2. At a lower demand D_2, the prices predicted by the average cost and marginal cost pricing are P_3 and P_4 respectively.

The revenue and expenditure of the road administrators is balanced under average cost pricing, but they are not able to make any preparations against congestion or environmental problems. In addition, the users' burdens are higher in regions where the demand is low. In contrast, marginal cost pricing internalizes the externalities that are caused by congestion and environmental problems. These prices can reduce the traffic volume to the optimal level, but when no congestion occurs, an insufficient price is collected since the price has been set lower than the average cost. The administrators are then unable to afford maintenance and renewal, and they have to make up the shortfall from the general revenue, or abandon some of the renewal works.

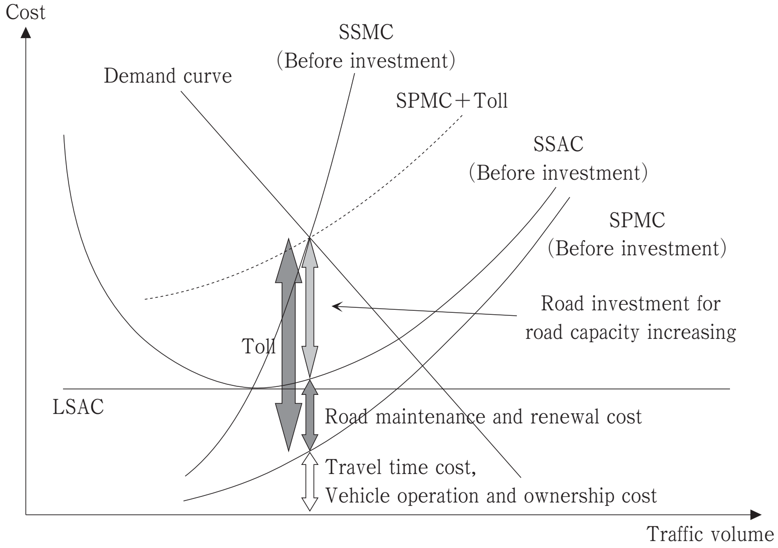
Which is more important objective, financing with average cost pricing or efficient management with marginal cost pricing? In reality, road administrators in Japan are regarded to maintain an even balance with respect to financing road network as a whole by average cost pricing under earmarking fuel fund with the same tax rate throughout Japan. It still remains for them, however, to introduce Transportation Demand Management (TDM) in a limited road sections, i.e., to institute fee structures using marginal cost pricing that places relatively higher tolls on congested sections and lower tolls on less-congested sections.

2.2 Optimal Road Capacity Building through Social Marginal Cost Pricing

Generally, the arguments on road pricing have so far postulated that the road capacity is given and fixed and have focused on whether it is more adequate to adopt short-term marginal cost pricing or short-term average cost pricing. However, in order to manage road network efficiently, it is more desirable to increase the road capacity if demand exceeds supply, and by the same token, road capacity should be decreased if supply exceeds demand. It is possible to change the capacity of roads for some length of time, since road stock has a life or a certain number of years for which it is durable.

Mohring (1976) proved that under constant returns to scale of road service, in other words, given that the long-term average cost curve of road service is horizontal, "the optimal road investment is realized when the price is set at short-term marginal cost." We applied this concept to propose a new road planning scheme with distance-based pricing. Under the new planning scheme, when a road is congested, the road administrator levies a congestion charge to make the excess revenue and invest it in increasing the road capacity. On non-congested sections, on the other hand, since the toll set by marginal cost pricing is relatively low, the road administrator

Figure 2 Optimal toll and its allocation for capacity expansion



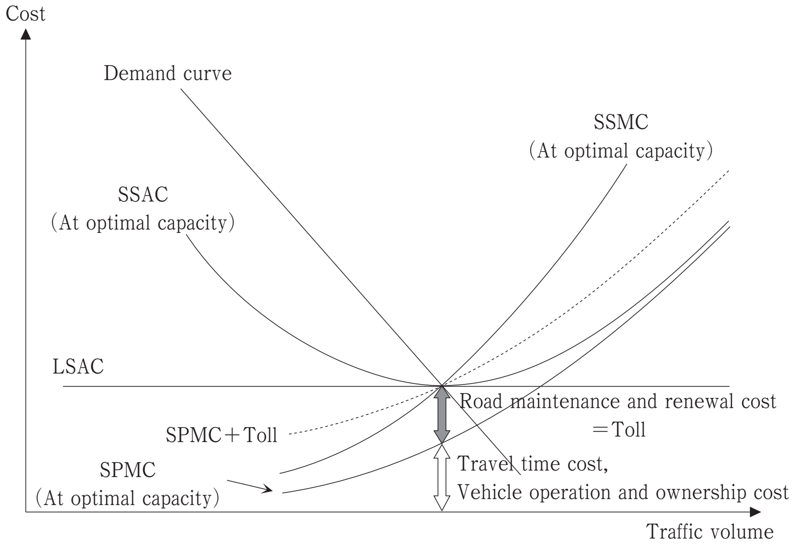
must reduce the road capacity.

More specifically, we propose a new scheme, under which the long-term optimization of road capacity can be realized through the short-term marginal cost pricing. Here we need to examine road related costs in detail. In the following sections, we assume that the road costs consist of the road infrastructure cost and the time cost of road users. Short-term Social Average Cost (SSAC) is calculated as the road costs divided by traffic volume. Short-term Social Marginal Cost (SSMC) is expressed as the derivative of the road cost function with respect to traffic volume. Short-term Private Marginal Cost (SPMC), which is equal to a Short-term Private Average Cost (SPAC), is a time cost at a certain traffic volume (Figure 2).

Under the new planning scheme based on the beneficiaries-pay principle, as with the other congestion pricing scheme, the short-term optimal toll is determined as the difference between SSMC and SPMC where the SSMC curve intersects the demand curve. The difference between SSAC and SPMC is the necessary amount for the maintenance and renewal of road capacity during the period. When the road capacity is relatively small, SSMC is higher than SSAC. In that case, toll revenue exceeds maintenance/renewal cost. The road administrator then invests the excess amount on increasing the road capacity (lane-widening, network development, etc). In the next period, the road capacity is larger than in the previous period, as a result of the investment in the previous period.

Over repeated pricing and investments, long-term optimal road capacity for the road is realized

Figure 3　Toll at optimal capacity

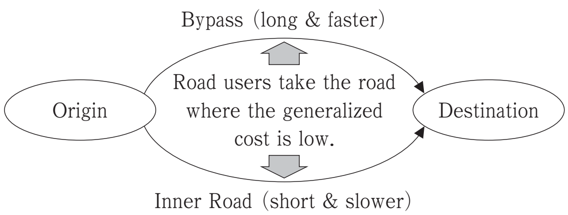


where the SSMC curve intersects the SSAC curve and also the demand curve (Figure 3). In addition, when demand is low, the optimal road capacity is realized by decreasing the road capacity (lane narrowing, network density decreasing, etc.). Under the newly proposed scheme, by increasing or by decreasing the road capacity, the road capacity will converge to an optimal level where the toll equals the necessary amount for road maintenance and renewal, in both cases.

2.3　An Optimization Problem under "Two-Route Model"

In order to demonstrate the new planning scheme, this paper examines a "two-route model" in which we assume one pair of origin and destination is connected by two routes; one is a long-distance, high-speed arterial road ("bypass") and the other is a short-distance, low-speed arterial road ("inner road") (Figure 4). Road users choose either route to minimize their generalized cost, a sum of travel time cost and toll (Both routes are toll roads based on distance-based pricing.

Figure 4　"two-route model"



Fuel taxes are eliminated). For simplification, we assumed the total transportation demand as fixed.

If the bypass has relatively small capacity, then through the mechanism of optimization of capacity based on marginal cost pricing, the capacity will increase by investing the toll revenue. On the other hand, if the inner road has relatively large capacity then toll revenue based on marginal cost pricing will not be enough to cover the maintenance and renewal cost. In this case, road administrator must give up renewal of the road partly and therefore the road capacity will decrease. Through the repetition of these processes, capacity of both bypass and inner road shall converge into an optimal level.

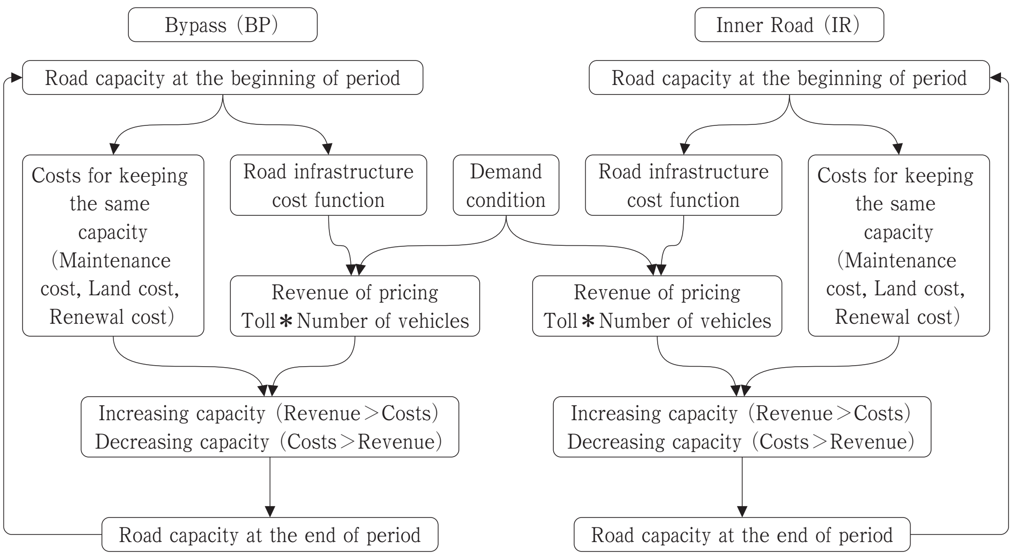
3　Simulation of Optimal Road Capacity Building through Social Marginal Cost Pricing

3.1　Simulation Framework

This section considers the simulation framework of optimal road capacity building. The purpose of this simulation is to demonstrate a planning scheme to reach the optimal level of road capacity, supposing that there exist two different routes connecting the same origin and destination and both routes are tolled based on short-term social marginal cost pricing, and that the revenues are to be allocated to maintain, renew the routes and to invest in capacity expansion when excess revenue arises.

The framework of simulation is shown in Figure 5 and the conditions are shown in Table 2 be-

Figure 5　Framework of road capacity equilibrium simulation



low. First, we set the initial road capacity for each route. The initial capacity and the total traffic volume determine the travel speed, traffic volume and toll revenue on each route. On the other hand, the road capacity also determines the necessary amount of expenditure for leased land, maintenance and renewal of the routes as explained in Table 2. If the toll revenue excesses the necessary expenditure for maintenance and renewal, then the surplus will be invested to increase capacity. If the toll revenue falls below the necessary expenditure for maintenance and renewal, then the capacity will decrease. At the end of each period, the capacity for each route is calculated and that will be the initial capacity for the next period.

Table 2 Conditions of simulation

	Bypass (BP)	Inner Road (IR)
Road length	12 km	10 km
Free flow speed	66.7 km/h	50 km/h
Link performance function	$V_{BP}=\dfrac{66.7}{1+0.15\cdot\left(\dfrac{N_{BP}}{1000\cdot N_{BP}}\right)^4}$	$V_{IR}=\dfrac{50}{1+0.15\cdot\left(\dfrac{N_{IR}}{750\cdot L_{IR}}\right)^4}$
	V: speed (km/h), N: traffic volume (vehicle), L: the number of lanes	
Initial lane number	3 lanes (each way)	3 lanes (each way)
Traffic volume	4,200 ($N_{BP}+N_{IR}=4200$)	
Time cost	Time value (3771.6 yen/h)*length (km)/speed (km/h)	
Land cost	1.34 bn. yen/lane/km/40 years	0.89 bn. yen/lane/km/40 years
Maintenance cost	20 mil. yen/lane/km	14 mil. yen/lane/km
Renewal cost	1.32 bn. yen/lane/km/40 years	0.88 bn. yen/lane/km/40 years

The result of simulation shows that on the bypass, which offers relatively high level of service, the investment to increase capacity will go on. On the other hand, on the inner road, which offers lower level of service, the capacity will decrease. And both capacities will converge to a certain level respectively.

The road cost consists of travel time cost and infrastructure costs (leased land, maintenance and renewal). The unit cost of travel time cost are assumed based on the cost-benefit manual (Ministry of Land, Infrastructure and Transport (2003)) and the unit cost of infrastructure are determined by the recent road works in Japan. The number of lanes calculated is the proxy variable of road capacity. The simulation assumes the total transportation demand between origin and destination as 4,200 vehicles per hour 24-hours a day (assumption of no hourly variation pattern of demand).

Based on the framework and conditions explained above, we conducted a simulation analysis of distance-based pricing. As explained, toll rate is determined as the difference between SSMC and

SPMC where SSMC curve crosses with demand curve. In this simulation, however, since the total transportation demand is assumed as fixed, efficient traffic allocation between two routes is achieved at the intersection of two short-term marginal cost curves. For example, for the 1st period, the traffic volume on each routes is determined at the intersection (bypass: 2,518 vehicles/hour, inner road: 1,682 vehicles/hour) and the toll rate on each route is determined as the difference between SSMC and SPMC.

3.2 Simulation Results

Simulation results are summarized in Figures 6 and 7. These results show that, concerning the bypass, the traffic volume will increase, toll rate will gradually decrease and the number of lanes of the bypass will increase gradually from 3 to 4.56 for 50 years. Concerning the inner road, the traffic volume will decrease, toll rate also will decrease and therefore the number of lanes of inner road will decrease gradually from 3 to 1.16 for 50 years.

Although in this simulation each year's toll revenue is to be invested in the same year, in reality the revenue could be accumulated to make investment at the right time. The result indicates that the bypass could be widened to 4 lanes at the 12th period and to 5 lanes at the 47th period and the inner road could be narrowed to 2 lanes at the 14th period and to 1 lane at the 39th period.

When we repeated this process until 200th period, the number of lanes of the inner road falls below 1 at the 56th period and finally vanishes at the 180th period. This result indicates that in

Figure 6 Toll revenue and its expenditure (Bypass)

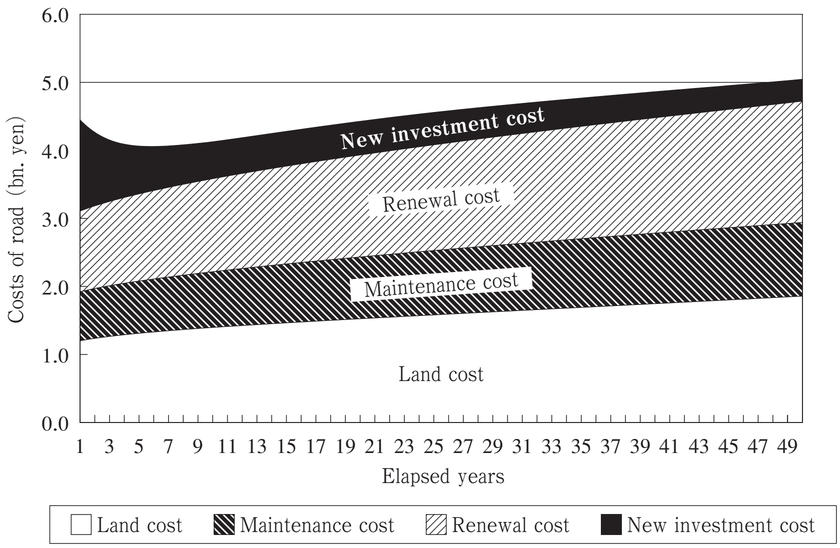
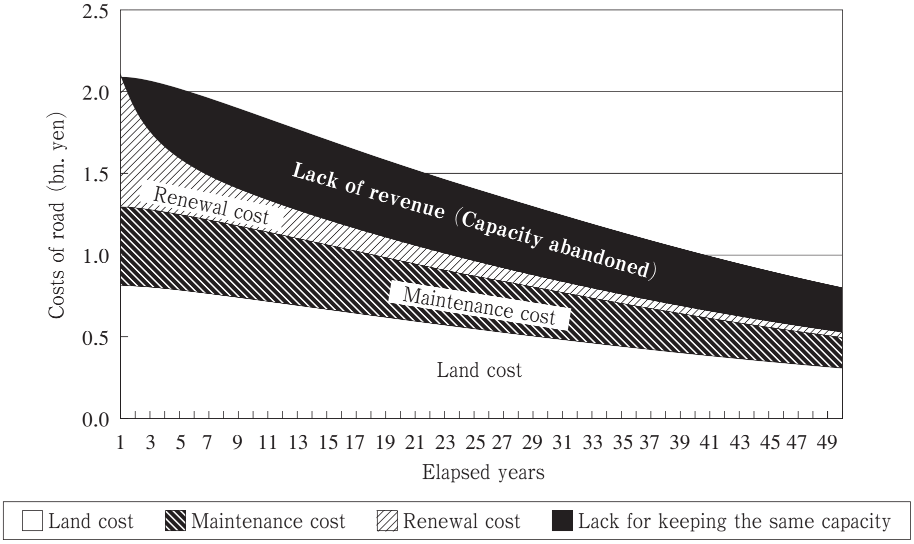


Figure 7 Toll revenue and its expenditure (Inner Road)



this simplified situation where one pair of origin and destination is connected by two routes, it is desirable to use only one route relatively efficient if we assume constant returns to scale of road service. In the simulation the bypass has lower long-term average cost curve of road service, then increases its capacity, while the inner road disappears. Verhoef (2008) conducted a similar simulation analysis under the same assumption of constant returns to scale, showing the capacity of relatively efficient route increases.

3.3 Sensitivity analysis

The situation with a couple of routes without the condition of constant returns to scale has not been analyzed so far. Although we could expect an efficient solution theoretically at the intersection of long-term marginal cost curves of two routes, it is not easy to forecast the dynamic process to reach the efficient solution. This is why we conducted sensitivity analyses with different conditions in addition to the base case.

In this analysis we assume economy of scale of infrastructure cost of bypass and diseconomy of scale of infrastructure cost of inner road. When we increase the road capacity by one lane, we have to purchase or lease the land just outside the existing road and to construct roadbed there. Concerning inner road it seems difficult to purchase the land and we need compensation payment for residents' relocation resulting in diseconomy of scale, while concerning bypass we can expect cheaper construction cost in adding new roadbed resulting in economy of scale. Figure 8 shows

Figure 8 Conditions of sensitivity analysis

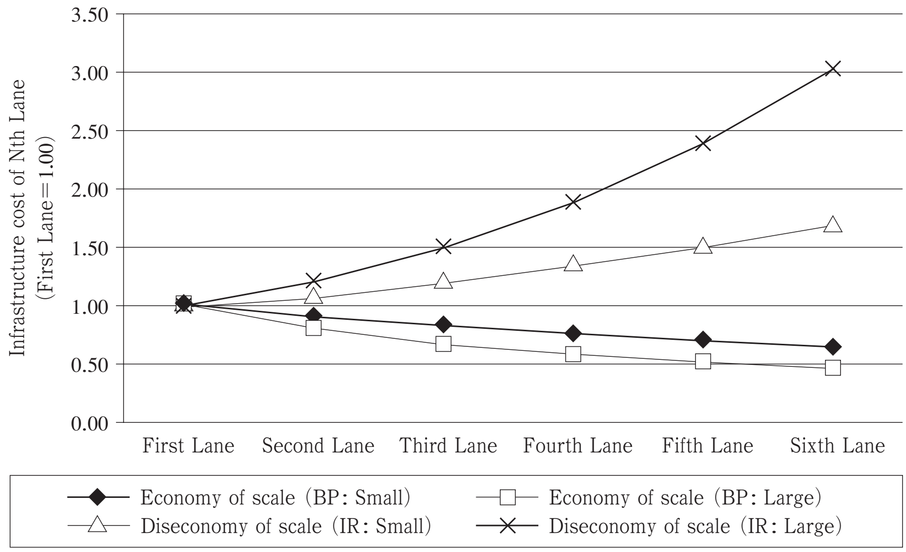


Table 3 Results of sensibility analysis

	Economy of scale of bypass	Diseconomy of scale of inner road	Number of lanes of bypass at period 50	Number of lanes of inner road at period 50
Base Case	—	—	4.56	1.16
Alternative 1	—	Small	4.76	0.85
Alternative 2	Small	—	5.02	0.77
Alternative 3	Small	Small	5.16	0.58
Alternative 4	—	Large	4.92	0.62
Alternative 5	Large	—	5.37	0.54
Alternative 6	Small	Large	5.26	0.43
Alternative 7	Large	Small	5.46	0.42
Alternative 8	Large	Large	5.53	0.32

the rates of additional infrastructure cost (including land cost) of Nth lane to that of the first lane. For example, infrastructure cost of third lane of inner road is 1.5 times higher than that of the first lane of inner road when we assume "Large" diseconomy of scale.

The results are summarized in Table 3. The results of all the 8 scenarios show that the number of lanes of the bypass will increase to 5-6 and the number of lanes of the inner road decrease to 0-1. We assumed economy of scale in the cheaper route in terms of long-term marginal cost and diseconomy of scale in more expensive route, so that convergence speed is more accelerated than the base case, particularly in the case of Alternative 8 with 'Large' economy of scale and 'Large' diseconomy of scale.

4 Conclusion

In this study, we proposed a new road planning scheme to build optimal road capacity through social marginal cost pricing, by applying the concept introduced by Mohring (1976) to the step-by-step optimization process. The traditional argument has been focusing on the trade-off between "marginal cost pricing theory" and "average cost pricing theory." While the former insists that the toll should be optimal for efficient resource allocation, the latter insists that the toll is necessary for financing if it maintains the current capacity, in both cases considering current road capacity as given and fixed. This study, on the other hand, proposed a planning scheme for building an optimal road capacity in the long term through the distance-based social marginal cost pricing.

Furthermore, we developed a "two-route model" and conducted simulations in order to see how the optimal toll and road capacity would be realized throughout the periods. Through the simulations, we found that the new planning scheme works under the assumption of plural routes and thus proved the scheme is feasible, having policy implication that we need not forecast uncertain demand any more but we could adjust the capacity to the demand with distance-based charges almost within 30 years.

We recognize, however, that this model contains further issues to be solved. First, we need more simulation analyses by applying other conditions (especially economy of scale regarding travel speed function on roads with different capacity). Second, we need more and detailed examples of road cost and other external costs including accident cost and environmental cost. Third, we need to analyze price elasticity of transportation demand, and introduce an elastic demand function. Finally, we need to extend the simplified "two-route model" to network model with multiple pairs of origin and destination.

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