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POLICY ISSUES ASSOCIATED WITH ROAD CAPACITY OPTIMIZATION THROUGH SOCIAL MARGINAL COST CHARGING

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Abstract

Economic theories demonstrate that when roads are congested, the social optimal traffic volume for addressing road capacity can be achieved through social marginal cost charging. Moreover, based on the study by Mohring (1976), in the neutral economies of scale, optimization of road capacity can, theoretically, be achieved by appropriating the excess revenue derived from social marginal cost charging to additional investment in road capacity. To apply this approach to actual road investment, however, we need to address the issues that impede the shift to optimal road capacity.

In this study, we enhanced the simulation analysis conducted in Misui and Nemoto (2010, 2011), and evaluated the SMC charging through the examination of the relationship between the road capacity of the network and the traffic environment road users faced. As a result, we pointed out three policy issues: (1) modification of SMC charges considering public acceptance, (2) feasibility of the optimal road capacity under cost-benefit criterion, and (3) long-term relationship between the urban structure and the road network.

I. *Introduction*

When the road is congested, the revenue obtained through social marginal cost charging exceeds the cost of the road. Therefore, road capacity can be optimized by using the excess revenue derived from social marginal cost charging. Conversely, when roads are not congested, the revenue derived through social marginal cost charging is insufficient to cover road costs.

In Misui and Nemoto (2010, 2011) simulation analysis, a four-route road network was used; through repeated application of the short-run and long-run social marginal cost charging methods, optimal road capacity was achieved. The results demonstrated policy changes that resolve road-use financial problems.

By calculating the revenue derived from social marginal cost charging and the needed road costs on the basis of the neutral economies of scale for the numbers of lanes, Misui and Nemoto were able to estimate the optimal road capacity. In this situation, one of the most important policy issues was how to evaluate the road capacity increase, compared to the optimal road capacity.

In Japan, all road investment projects are subject to a cost-benefit analysis. Briefly, this cost benefit analysis compares benefits (e.g., time cost saving effect) and costs (e.g., road investment costs) using a "Cost-benefit ratio" (Benefits/Costs) mainly to objectively evaluate efficiency of any road project. With increasing financial constraints, the most beneficial road investment is the one that most effectively addresses social needs and requirements; hence, implementing an independent project assessment is advantageous to all parties. The project assessment alternatives, however, do not take into consideration the optimal road capacity. It is required to introduce the scheme facilitating optimization of road capacity to the existing road project assessment now.

In this study, we expanded the simulation analysis performed by Misui and Nemoto (2010, 2011). Misui and Nemoto (2010, 2011) used the road network, with all four routes having a one-lane minimum (this will be described in detail later in this paper). However, a road is considered a social capital with durability, so we can, in the long-run, define it as variable capital. On the basis of this hypothesis, in this study, a zero lane is assumed in three routes, excluding the lowest specific route. This expansion lends greater flexibility to the study's simulation analysis.

In the next section, on the basis of the discussion mentioned above, we show the optimal method of road capacity building through short-run marginal cost (SMC) charging. In Section III, we undertake simulation analysis to introduce the policy implications of road capacity optimization.

II. *Optimal Road Capacity Building through SMC Charging*

This section summarizes the theory of optimal road capacity building through SMC charging, on the basis of Misui and Nemoto (2010).

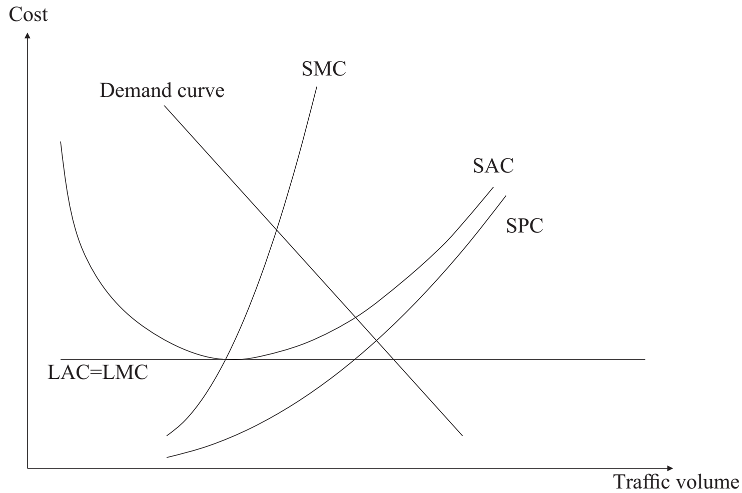
As CE Delft (2002) has shown, "self-financing" is a standard result of microeconomics under constant returns to scale. This principle was applied by Mohring (1976) and some studies have refined it (e.g., CE Delft [2002] and Nemoto, Misui, and Kajiwara [2009]). In this section, we briefly discuss this principle, as understood by Nemoto, Misui, and Kajiwara (2009).

Generally, arguments on road pricing, thus far, have postulated that road capacity is given and fixed; the discussions have also focused on whether it is more appropriate to adopt SMC charging or short-run average cost (SAC) charging. The former focuses on the economical optimum (i.e., maximization of social welfare), of which congestion pricing is a typical example. The weakness of this pricing principle, however, is that, since most sections of highways (except urban networks) are not congested, the revenue from marginal charging is relatively low and is insufficient to cover the necessary road maintenance and renewal costs. Because of budget constraints, general budget financing would not always be available to cover the decreased revenue stream.

Thus far, in Japan, fuel tax rates and expressway tolls are uniform, nationally, and the revenues are used to develop the national arterial highway network. This funding system can be understood as a type of average-cost charging, whereby road users are charged the full cost of road use. Using the average-cost charging scheme as a base, the Japanese government has recently introduced marginal-cost charging schemes in which congestion charges, or environmental road pricing, are being implemented in order to address urban problems, such as congestion and air pollution.

However, both charging theories lack the perspective that considers road capacity as a variable. In order to manage the road network efficiently, it is more desirable to increase the

FIG. 1. ROAD COSTS BEFORE INVESTMENT



road capacity, if demand exceeds supply; similarly, road capacity should be decreased, if supply exceeds demand. It is possible to change the capacity of a road for some length of time, since road stock has a life (i.e., a certain number of years for which it is durable).

Mohring (1976) proved that under constant returns to scale, in other words, given that the long-run average cost (LAC) curve of a road is horizontal, "the optimal road level is realized when the price is set at SMC." Nemoto, Misui, and Kajiwara (2009) applied this concept in proposing a new road-planning scheme with mile-based charging. Under the new planning scheme, when a road is congested, the road administrator levies a congestion charge to bring in excess revenue and invests the revenue in order to increase road capacity. On non-congested sections, on the other hand, since the charge set by marginal-cost charging is relatively low, the road administrator must "give up" on maintaining the capacity, and reduce the road capacity to the revenue-shortage level.

More specifically, Nemoto, Misui, and Kajiwara (2009) propose a new scheme under which the long-run optimization of road capacity can be realized through SMC charging, determined according to the transportation demand. Road-related costs are a major issue, as well. Nemoto, Misui, and Kajiwara (2009) assume that road costs consist of the infrastructure cost for the road and the total time cost of road users. SAC is calculated as the road costs divided by traffic demand, and SMC is expressed as the derivative of the road-cost function, with respect to traffic volume. Short-run private marginal cost (SPC), which is equal to short-run averaged private cost, is a time cost at a certain traffic volume (see Figure 1).

Under the proposed scheme, on the basis of the beneficiaries-pay principle, as with the other congestion pricing scheme, the short-run optimal charge is determined as the difference between SMC and SPC, where the SMC curve intersects the demand curve. The difference between SAC and SPC is the amount necessary for the maintenance and renewal of road capacity during the pre-determined period. When the road capacity is lower, SMC is higher than SAC. In that case, charged revenue exceeds maintenance and renewal costs. The road

FIG. 2. CHARGE FOR ROAD BEFORE INVESTMENT

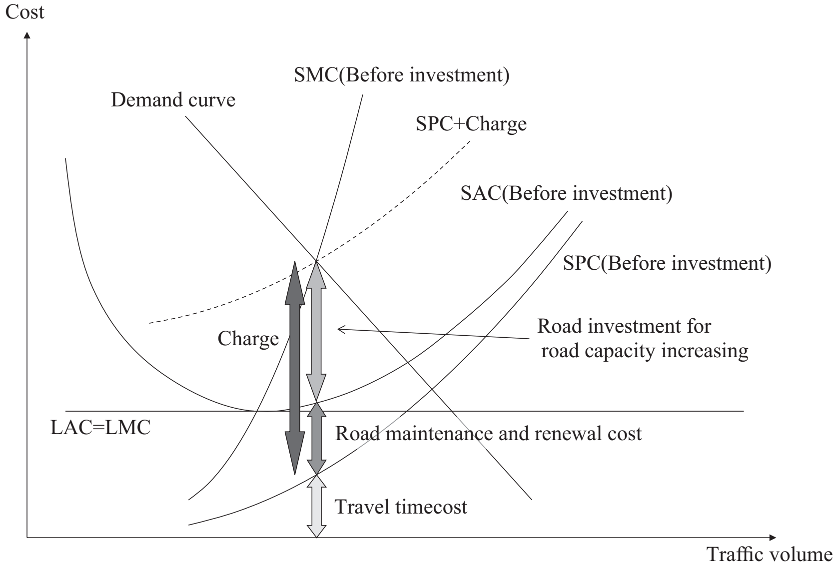
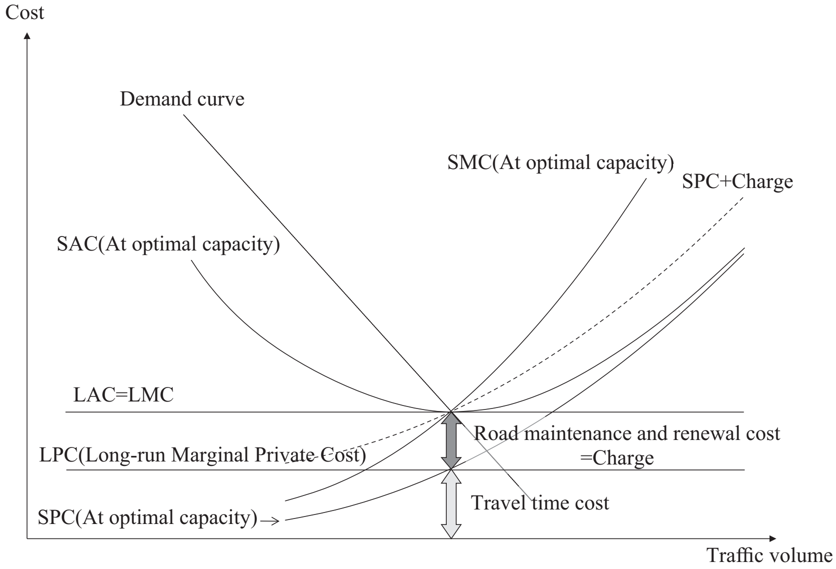


FIG. 3. ROAD COSTS AND CHARGES FOR ROAD AT OPTIMAL CAPACITY



administrator then invests the excess amount in increased road capacity (lane-widening, network development, etc.). In the next period, as a result of the investment in the previous period (Figure 2), the road capacity increases.

With repeated charging and investments, long-run optimal road capacity is realized where the SMC curve intersects the SAC curve, as well as the demand curve. In addition, when demand is low, the optimal road capacity is realized by decreasing the road capacity (lane narrowing, network density decreasing, etc.). Under this proposed scheme, by increasing or decreasing the road capacity, the road capacity will be induced to converge to an optimal level where, in both cases, the charge equals the necessary amount for road maintenance (Figure 3).

III. *Simulation Analysis*

1. Purpose of Simulation Analysis

In Section II, we demonstrated the theoretical framework of SMC charging. However, Figures 1-3 present theoretical situations, so it is important to discuss real-cost situations. For example, the shapes of the SAC curve, short-run marginal cost curve, and short-run private cost curve change the impact of policy implications.

In this section, using the simulation analysis results, we expand the simulation analysis of Misui and Nemoto (2011) and consider the situation surrounding the shift to optimal road capacity and the significance of the time cost saving effect mentioned in Section I.

2. Simulation Analysis Elements

(1) Network

In this simulation analysis, we assume a ladder network, which consists of four east-west routes (expressway, main arterial highway, arterial highway, and sub-arterial highway), as well as access roads that run in a north-south direction. This network has nodes placed every 5 km on four east-west routes, with access roads connecting each node. The length of each east-west

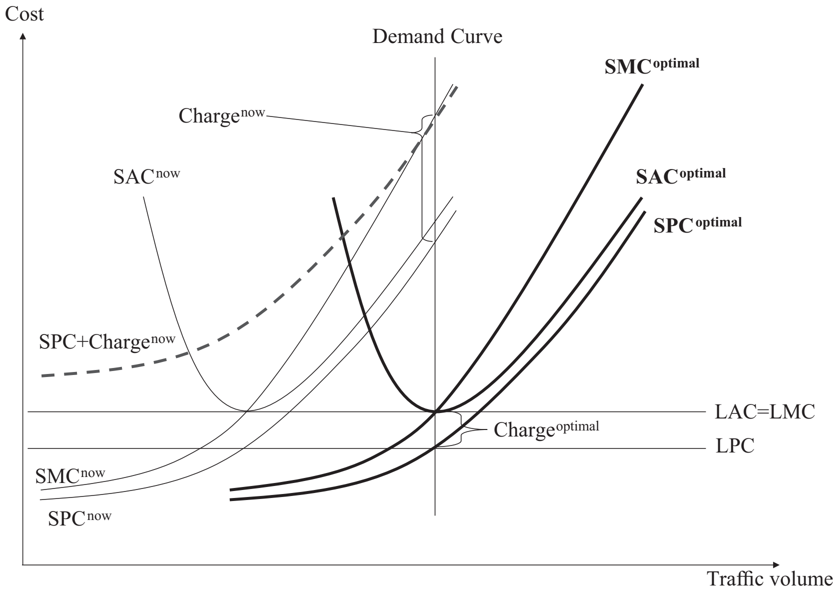
TABLE 1. CHARACTERISTICS OF FOUR ROUTES CONSTITUTING THE NETWORK

	Free flow speed (km/hour)	Road capacity per lane (vehicles/hour)	Renewal cost (million yen/km)	Land cost (million yen/km)	Maintenance cost (million yen/km)
Expressway (east-west)	100	2,000	1,200 / 40 years	3% of 400	27
Main arterial highway (east-west)	70	1,500	600 / 40 years	3% of 200	13.5
Arterial highway (east-west)	50	1,200	600 / 40 years	3% of 200	5.3
Sub-arterial highway (east-west)	30	1,000	600 / 40 years	3% of 200	0.41
Access road (north-south)	30	–	–	–	–

TABLE 2. DISTRIBUTION OF OD TRIP LENGTH

Trip length	Transportation demand	Component ratio
5km	600	40.0%
10km	375	25.0%
20km	300	20.0%
30km	150	10.0%
70km	75	5.0%
Cross traffic volume	4,500 vehicle/hour	−

FIG. 4. SMC CHARGING IN FIXED DEMAND



route is 50 km. The total length of each access road is 6 km, with 3 km between the expressway and the main arterial highway. The length between the main arterial highway and the arterial highway is 2 km and that between the arterial highway and sub-arterial highway is 1 km. This network setting is based on an existing case in the Tokai region of Japan.

The free flow speed and road capacity for each route are shown in Table 1. In this simulation, additionally, on the basis of previous research (e.g., Kanemoto [2007]), we suppose constant returns to scale.

(2) Origin-Destination (OD) trip

Each OD trip commences at each node on the sub arterial highway and terminates at the node on the sub-arterial highway 5 km, 10 km, 20 km, 30 km, and 70 km ahead. The OD trip length distribution is set as shown in Table 2, with reference to the Japanese Road Traffic Census Survey.

Here, the assumption of 4,500 vehicles/hour of cross-traffic volume means that we consider that the demand curve is vertical (Figure 4).

(3) Link performance function

In this section, the user-cost function (link performance function) is specified in order to analyze the simulation model. In this simulation analysis, we adopt the Bureau of Public Roads' (BPR) travel-time function as the link-performance function (Equation 1). The BPR function is very similar to the traffic-assignment simulation.

$$SPC = \omega \cdot l_a \cdot t_a(x_a) = \omega \cdot l_a \cdot t_{a0}\left\{1 + \alpha\left(\frac{x_a}{C_a}\right)^{\beta}\right\} \quad (1)$$

Where

SPC: generalized price
ω: the value of time (62.86 yen/minute)
l_a: length of link a (km)
t_a: travel time of link a (minute)
t_{a0}: the free-flow travel time of link a (minute)
α: parameter (0.48)
β: parameter (2.82)
x_a: traffic volume of link a (vehicles/hour)
C_a: road capacity of link a (vehicles/hour)

We set the value of time at 62.86 yen/minute, on the basis of the cost-benefit analysis report presented by the Ministry of Land, Infrastructure, Transport and Tourism, Japan, and use the "JICA STRADA3.5" software to assign traffic within this network.

Additionally, in this simulation analysis, we set the cross-traffic volume at constant, which does not change depending on network size for simplicity. This is the same as assuming that the demand curve is vertical. In addition, the SMC charge with the assumption that the demand curve is vertical is larger, compared to what it would be if we assumed a normal downward-sloping demand curve.

Moreover, this simulation analysis considers the fact that the road administrator invests in each route in a range of zero-lane to three-lane highways. This range is the simulation setting difference between this study and Misui and Nemoto (2011). We assume, however, that sub-arterial road is in a range of one-lane to three-lane highways. This means that we can consider a total of 192 network sizes (road capacity is between 1, 000 vehicles/hour and 17, 100 vehicles/hour).

Further, as noted above, this stimulation analysis does not consider the economies of scale due to an increase in the number of lanes. For example, the road capacity of a two-lane expressway is 4,000 vehicles/hour. However, there are economies of scale between four routes. For example, the road capacity of a one-lane main arterial highway is 1,500 vehicles/hour, but the road capacity of a one-lane sub-arterial highway is 1,000 vehicles/hour. Additionally, in this simulation analysis, we assume that the road capacity of north-south access roads is 99, 999 vehicles/hour. This assumption means that access roads have infinite capacity (the setting of 99, 999 vehicles/hour is based on the traffic assignment software specifications). Road costs (road renewal cost, land cost, and road maintenance cost) for each route are set on the basis of Nemoto and Misui (2008).

3. Results of Simulation Analysis

At first, we simulate SMC charging. We can introduce the SMC function using the above SPC function (Equation 2).

$$SMC=\frac{dTC}{dx}=\frac{d(SPC\cdot x_a)}{dx}=\omega\cdot l_a\cdot t_{a0}\left\{1+\alpha(\beta+1)\cdot\left(\frac{x_a}{C_a}\right)^{\beta}\right\} \tag{2}$$

For example, if the cross traffic volume is 4,500 vehicles/hour, and the network size is 5, 700 vehicles/hour (expressway; one lane, main arterial highway; one lane, arterial highway; one lane, sub arterial highway; one lane), the result of traffic assignment based on SMC charging is as shown in Table 3. Table 3 shows that traffic is allocated in a manner nearly proportional to the road capacity of each route.

The (weighted base traffic volume) average SMC charge is 41.0 yen/km. The revenue from SMC charging is 40.4 billion yen per year, and the total road cost is 7.7 billion yen per year. From the discussion in Section II, we can allocate the difference between revenue and cost (32.7 billion yen) to expand road capacity.

The most impressive result of this simulation analysis is shown in Figure 5. Figure 5 shows that the larger road capacity is, the smaller the revenue of charging under 4, 500 vehicles/hour of cross traffic volume. In addition, the shape of the curve of revenue of charging is steep under 6,000 vehicles/hour of road capacity but is moderate over 6,000 vehicles/hour of road capacity. In contrast, the larger the road capacity, the larger the road cost. As a result, the curves of revenue of charging and road cost cross at about 9,100 vehicles/hour of road capacity. This result means that the optimal road capacity is approximately 9, 100 vehicles/hour under 4,500 vehicles/hour of cross traffic volume. In other words, we have to increase road capacity using revenue of charging under about 9, 100 vehicles/hour of road capacity, and we must decrease road capacity, because road cost exceeds revenue of charging.

Secondly, Figure 6 shows the relationship between road capacity and time cost of road users and the relationship between road capacity and time cost of road users and road cost. The latter relationship already has been shown in Figure 5. Figure 6 demonstrates that the larger road capacity is, the smaller the time cost of road users under 4, 500 vehicles/hour of cross traffic volume.

TABLE 3. RESULTS OF TRAFFIC ASSIGNMENT AND SMC CHARGE FOR EACH ROUTE

	Road capacity (vehicles/hour)	Traffic volume (vehicles/hour)	Traffic speed (km/hour)	SMC charge (yen/km)
Expressway	2,000	1,680	77.3	31.2
Main arterial highway	1,500	1,324	52.3	51.3
Arterial highway	1,200	896	41.3	44.8
Sub arterial highway	1,000	600	26.9	40.3
Total	5,700	4,500	–	–
Average	–	–	56.1	41.0

FIG. 5. RELATIONSHIP BETWEEN ROAD CAPACITY, REVENUE OF CHARGING AND ROAD COST (Cross traffic volume is 4,500 vehicles/hour)

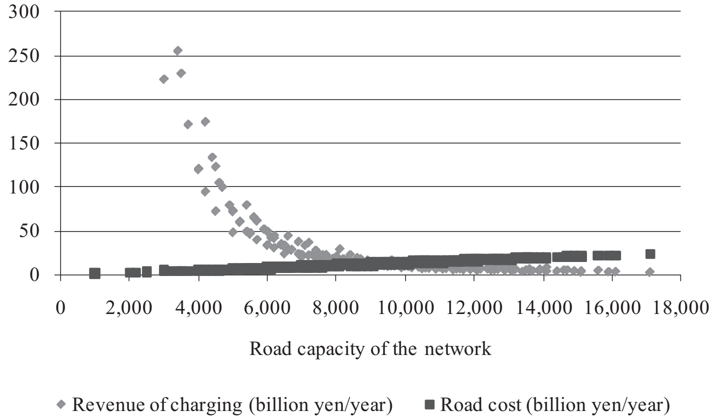
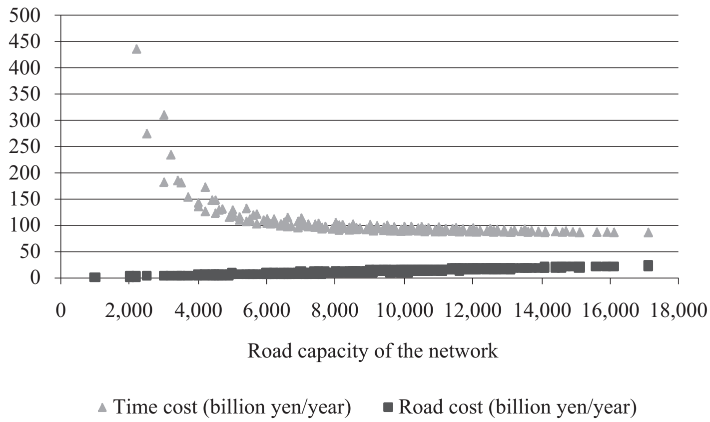


FIG. 6. RELATIONSHIP BETWEEN ROAD CAPACITY, TIME COST OF ROAD USERS AND ROAD COST (Cross traffic volume is 4,500 vehicles/hour)



Figures 7-10 show the relationships between traffic volume and traffic speed or SMC charge in one lane of expressway, main arterial highway, arterial highway, and sub-arterial highway. We can see that the higher standard route has the higher curve of traffic speed and the moderate curve of amount charged.

Fig. 7. Relationship between Traffic Volume and Traffic Speed or SMC Charge in One Lane of Expressway

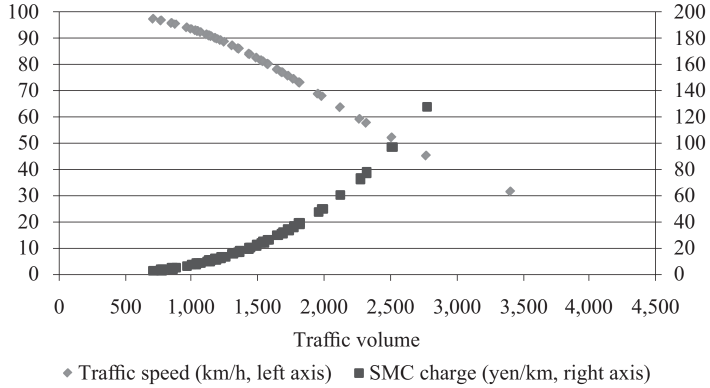


Fig. 8. Relationship between Traffic Volume and Traffic Speed or SMC Charge in One Lane of Main Arterial Highway

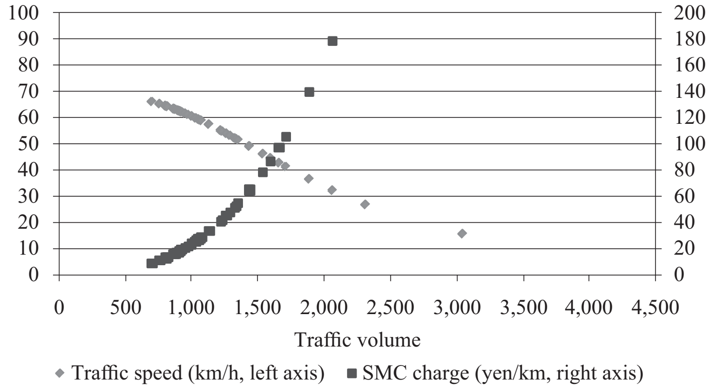


FIG. 9. RELATIONSHIP BETWEEN TRAFFIC VOLUME AND TRAFFIC SPEED OR SMC CHARGE IN ONE LANE OF ARTERIAL HIGHWAY

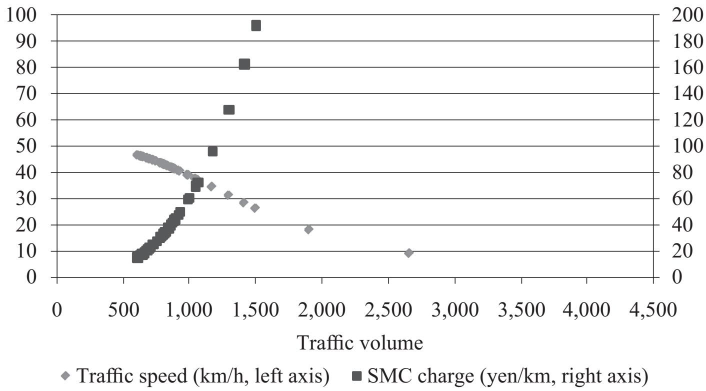
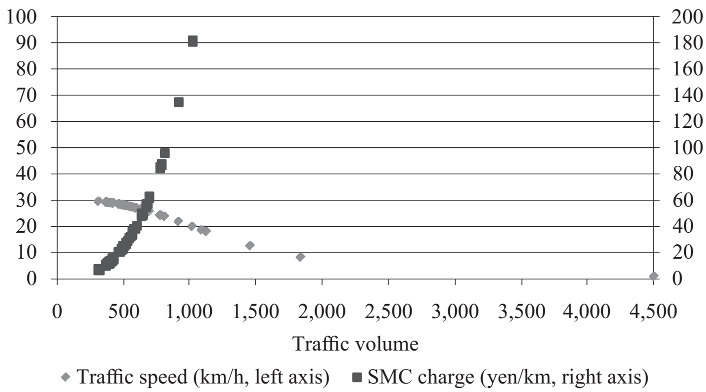


FIG. 10. RELATIONSHIP BETWEEN TRAFFIC VOLUME AND TRAFFIC SPEED OR SMC CHARGE IN ONE LANE OF SUB ARTERIAL HIGHWAY



Additionally, Figures 11-18 show the relationships between traffic volume and traffic speed or SMC charge per route. These figures show that an increase of lanes improves traffic speed and drastically decreases the SMC charge.

FIG. 11. RELATIONSHIP BETWEEN TRAFFIC VOLUME AND EXPRESSWAY TRAFFIC SPEED

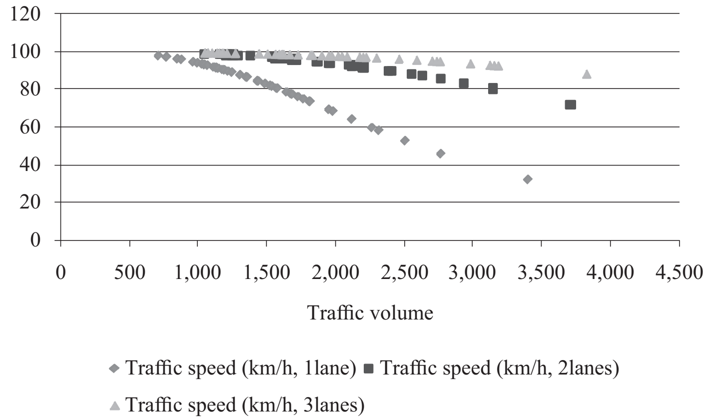


FIG. 12. RELATIONSHIP BETWEEN TRAFFIC VOLUME AND SMC CHARGE IN EXPRESSWAY

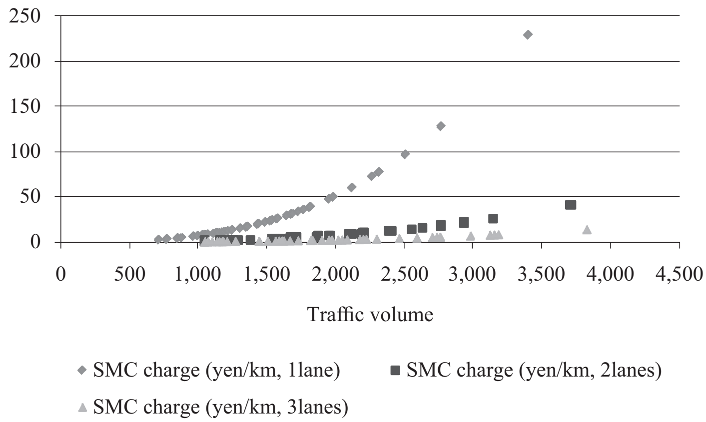


FIG. 13. RELATIONSHIP BETWEEN TRAFFIC VOLUME AND MAIN ARTERIAL HIGHWAY TRAFFIC SPEED

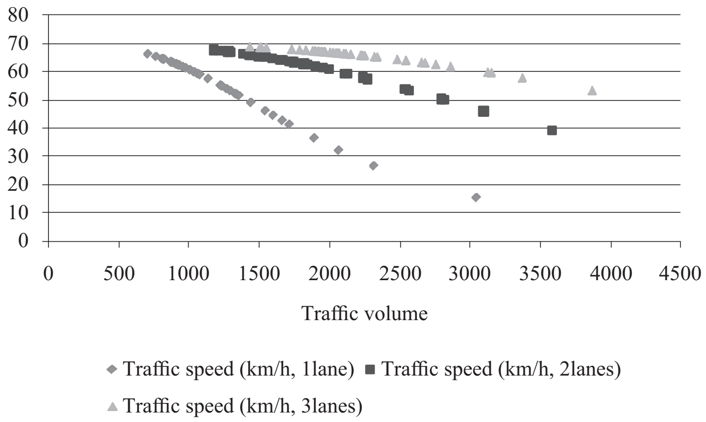


FIG. 14. RELATIONSHIP BETWEEN TRAFFIC VOLUME AND MAIN ARTERIAL HIGHWAY SMC CHARGE

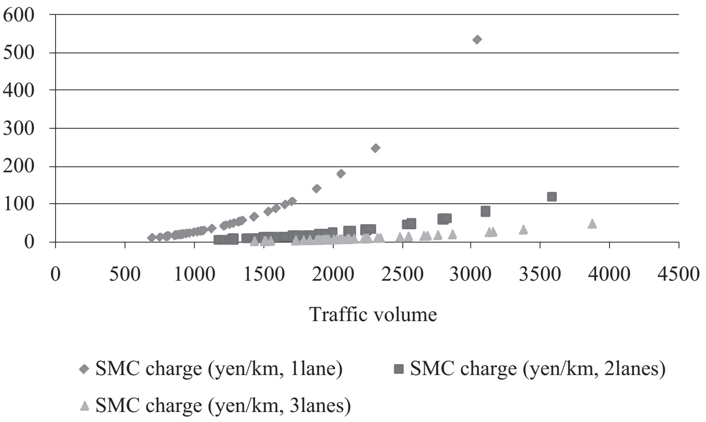


Fig. 15. Relationship between Traffic Volume and Arterial Highway Traffic Speed

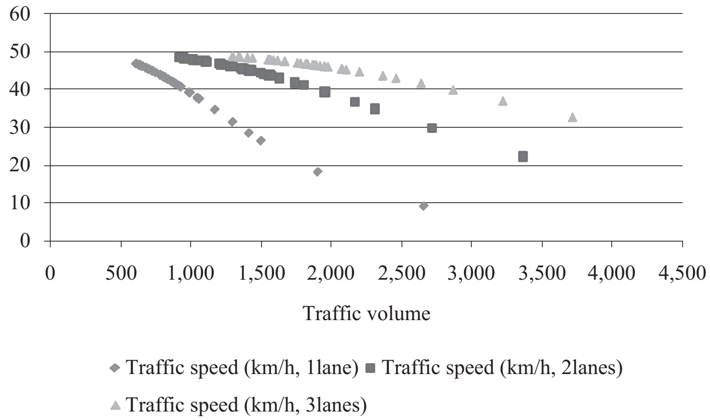


Fig. 16. Relationship between Traffic Volume and SMC Charge in Arterial Highway

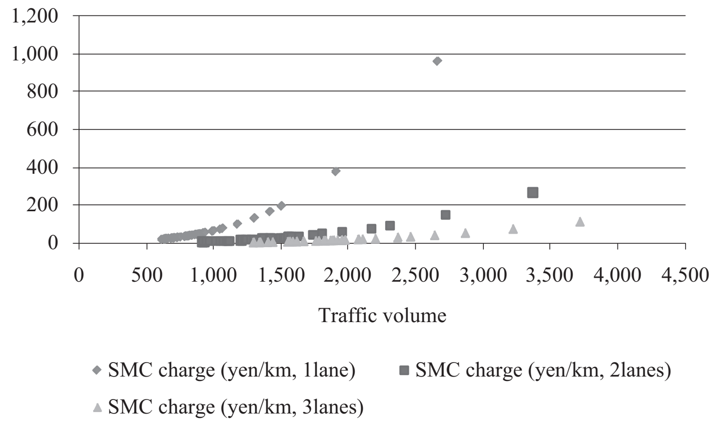


Fig. 17. Relationship between Traffic Volume and Sub-arterial Highway Traffic Speed

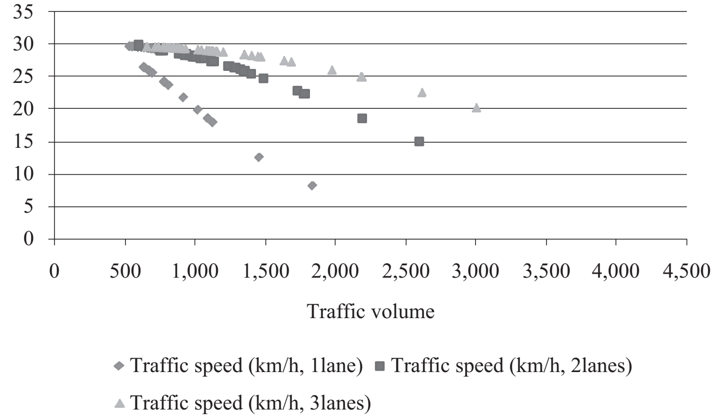


Fig. 18. Relationship between Traffic Volume and SMC Charge in Sub-arterial Highway

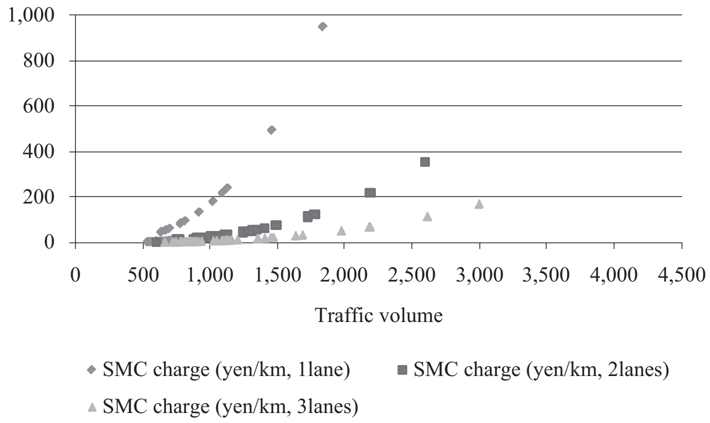
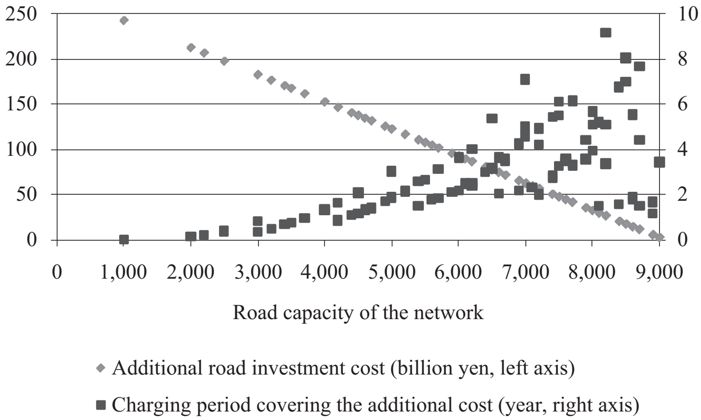


FIG. 19. RELATIONSHIP BETWEEN ADDITIONAL ROAD INVESTMENT COST AND CHARGING PERIOD COVERING THE ADDITIONAL COST



4. Interpretation of Simulation Analysis

(1) Interpretation of simulation results

The results of the above-mentioned simulation analysis are as follows.

The charging revenue decreases by an increase of the road capacity when the traffic volume is constant. The charging revenue, therefore, becomes smaller relatively when the existing road capacity is larger. As a result, the charging period covering the additional investment cost becomes longer (Figure 19).

The road cost to renew and maintain the existing road capacity increases by an increase of the road capacity when the traffic volume is constant. As the road capacity increases, the charging revenue decreases (ever-decreasing curve) and the road cost increases (ever-increasing curve). As a result, both curves intersect at a certain level of road capacity. According to the result of the simulation analysis, the level of road capacity is 9,100 vehicles/hour.

The time cost of the road uses decreases by an increase of the road capacity when the traffic volume is constant. A decrease in time cost according to an increase in road capacity is especially remarkable when the road capacity is less than 6,000 vehicles/hour.

(2) Three policy isuues

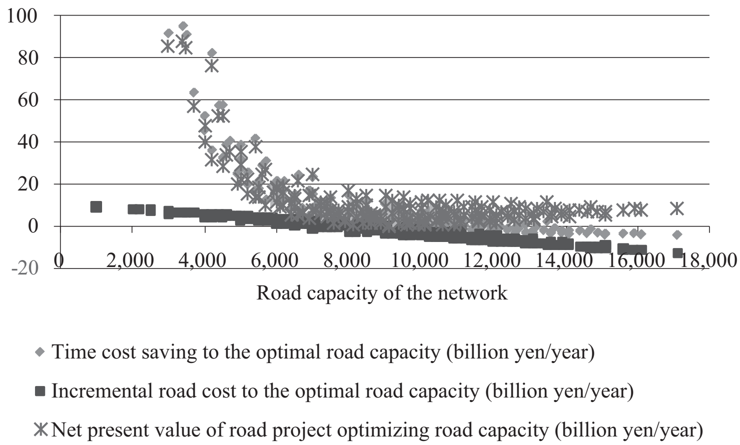
We derived the following policy issues from the simulation results.

1) Modification of SMC charges considering public acceptance

When an existing road capacity is extremely small compared with the optimal road capacity, the marginal cost and then the SMC charges are very high. These high SMC charges become the barrier to build the social consensus or causes congestion in another road links through the detour traffic to evade the high amount in the actual situation. To solve this issue, we could suppress the SMC charges to low.

When an existing road capacity is not small compared with the optimal road capacity, the

FIG. 20. RELATIONSHIP BETWEEN ROAD CAPACITY AND NET PRESENT VALUE OF ROAD PROJECT OPTIMIZING ROAD CAPACITY



SMC charges are low. This results that the charging period covering the additional road investment cost is longer as shown in Figure 19. In this siruation, therefore, an alternative financing scheme could be introduced; for example we invest borrowed money to increase road capacity first and then repay the money afterwards by road user charges with a different principle.

In any case, the SMC charging is not applied to the road users directly. It is necessary to modify the charging in consideration of public acceptance. The simulation analysis in the future could be expanded to consider the advantages and disadvantages with low charges and the alternative financing scheme.

2) Feasibility of the optimal road capacity under the cost-benefit criterion

In the current road planning process requested to apply cost benefit analysis, as mentioned above, the investment cost of a certain road section is compared with the benefit including time cost saving of road users and so on, using the cost benefit ratio (Benefit/Cost) chiefly.

According to the result of simulation analysis, however, the time cost of road users hardly decreases even if the road capacity increases when the capacity is over 6,000 vehicles/hour, as shown in Figure 6. This means the additional benefit of capacity increase is extremely small when the capacity is over 6,000 vehicles/hour. On the other hand, as shown in Figure 6, the cost to increase capacity is constant regardless of the road capacity.

Figure 20 summarizes the benefit (time cost saving), the cost (incremental road cost) and the difference of both (benefit-cost) of the road project optimizing the road capacity at a certain level of road capacity. This figure shows, the benefit (time cost saving) optimizing the road capacity is extremely large when the existing road capacity is small but decreases rapidly as the road capacity increases. On the other hand, the cost (incremental road cost) optimizing the road capacity decreases constantly by the road capacity increases. As a result, the curve of the difference of both (net present value) is U-shaped curve and the bottom of the curve is at 9,100 vehicles/hour of the road capacity.

The highest cost benefit ratio (benefit/cost) does not necessarily indicate the optimal road project. We should not confuse 'a road planning having just one time decision/investment' with 'a road planning having a series of decisions/investments'. In the latter planning the first decision/investment justified by high cost/benefit ratio and any subsequent decision/investment may have smaller cost/benefit ratio. The important issue is how to reach the optimal road capacity by a series of decision/investments.

3) Long-term relationship between the urban structure and the road network

The road infrastructure has a long duration period. So the urban structure and transportation demand may be changed in the period. There is a forecast that the population decreases by about 25% in 50 years in Japan. The transportation demand is expected to change greatly under such an environment. It is necessary to plan the road network flexibly without assuming a current urban structure unchanged.

There is another important causal relation where the road network affects the urban structure. In the simulation we optimized the road network assuming an urban structure. If we change the urban structure by easing the assumptions, we could further reduce the total travel time keeping the same population in the area, which is examined in the future research.

IV. *Conclusion*

In this study, we enhanced the simulation analysis conducted in Misui and Nemoto (2010, 2011), and evaluated the SMC charging through the examination of the relationship between the road capacity of the network and the traffic environment road users faced. First we considered the SMC charging theoretically, and we executed the simulation analysis of the SMC charging assuming the road network consisted of four routes and access routes.

In the simulation, we could demonstrate a planning to decide the optimal road capacity. Under our assumptions, the optimal road capacity is 9,100 vehicles/hour.

The additional road investment cost optimizing road capacity become small when the existing road capacity is large. The charging revenue, however, decreases relatively by an increase of the road capacity. As a result, the charging period covering the additional investment cost becomes longer. The road cost to renew and maintain the existing road capacity increases by an increase of the road capacity.

Based on the above-mentioned discussion, we point out the following three policy issues: (1) modification of SMC charges considering public acceptance, (2) feasibility of the optimal road capacity under cost-benefit criterion, and (3) long-term relationship between the urban structure and the road network.

In the future researches we plan (1) to ease the assumption of road network in the simulation analysis (lane number, link composition and origin-destination trip distribution and so on), (2) to examine a simulation analysis comparing high charge and speedy optimization with low charge and moderate optimization (including an alternative financing scheme using debt), and (3) to develop a simulation model to consider the effects of road network on the urban structure.

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