ROAD PLANNING THROUGH LONG-RUN MARGINAL SOCIAL COST CHARGING

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ABSTRACT

In the past decade, there have been many studies concerning the application of short-run marginal social cost (SMC) charging on road use. However, SMC charging has hardly been applied to actual cases and the surrounding situation of LMC charging is almost similar to SMC charging.

In this paper, we discuss several issues relevant to SMC charging and propose a new road-planning scheme based on long-run marginal social cost (LMC) charging with a simulation analysis. As the results of the simulation analysis, we revealed the following.

- The SMC charging achieves the long-run optimal road capacity efficiently but then the charging requires the abrupt changes of the amount.
- The LMC charging with bond (like current toll scheme) is a good choice respect to the equity between generations, but it cannot achieve the long-run optimal level of cost benefit ratio.
- The LMC charging is the useful second best alternative to achieve the long-run optimal road capacity moderately with a small loss of cost benefit ratio.

Keywords: Long-run marginal social cost (LMC), Short-run marginal social cost (SMC), Mile-based charging, Road capacity optimization

1. INTRODUCTION

This paper proposes long-run marginal social cost (LMC) charging as a method of road governance and, by means of simulation analysis, aims to compare LMC charging and short-run marginal social cost (SMC) charging.

In the past decade, there have been many studies concerning application of SMC charging for road use; some governments, such as those of the European Union, U.K., and U.S.A., have published white papers and propositions on the topic. Unfortunately, most studies are limited to theoretical study and the application of road charging systems based on SMC is seldom seen in the world. However, several previous studies have clarified the theoretical basis for our study. Especially, Mohring (1976) pointed out that we can achieve the long-run optimal road capacity through the repeated application of SMC charging and new investments using the revenue under constant returns.

The question arises as to why, despite the awareness that this is the optimal solution, it is not usually carried out. In recent years, the U.S.A. and Europe have certainly implemented measures to provide for mile-based charges based on the need to levy charges on vehicle from outside the relevant regions and for the decline in tax revenues influenced by improvement in the fuel economy (NSTIFC [2009], the UK House of Commons [2009]). These mile-based charges become an important factor in the realization of the above optimal solution. In contrast, however, last year, the Japanese opposition party, which included free use of expressways and gasoline tax reduction in its manifesto, was victorious in the general election and became the ruling party.

We suppose that the reason for the stasis mentioned above is the gap between economic theory and road governance. Road improvement requires huge expenses, but from the viewpoint of political acceptance, it is not easy to impose high charges because the roads are crowded. Primarily, traffic congestion is the result of road capacity lower than that necessary to accommodate traffic volume actually on the road; the major reason for traffic congestion is not the behavior of the current road user but the lack of past investment in roads.

Under these circumstances, it is not easy to implement SMC charging. We believe that an LMC charging scheme can solve this problem and make sustainable road investment a reality based on sharing a long-term burden.

In the next section, based on the discussion mentioned above, we consider the optimal method of road capacity building through SMC charging. Section 3 looks at issues relevant to SMC charging and proposes the concept of LMC charging. In section 4, we undertake simulation analysis to explore the advantages of LMC charging over SMC charging, based on the discussion in Section 3.

2. OPTIMAL ROAD CAPACITY BUILDING THROUGH THE SHORT-RUN MARGINAL SOCIAL COST CHARGING

As CE Delft (2002) has shown that "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 (CE Delft [2002] and Nemoto, Misui, and Kajiwara [2009], etc.). 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 the road capacity is given and fixed and have focused on whether it is more appropriate to adopt SMC pricing or short-run average cost (SAC) pricing. The former focuses on the economical optimum (that is, maximization of social welfare), of which congestion pricing is a typical example. The weakness of this pricing principle, however, is that the revenue from marginal pricing is relatively low and is not sufficient to cover the necessary maintenance and renewal costs, since most sections of highways (except urban networks) are not congested and the charge has to be set to be relatively low. Financing in the general budget would not be always available because of budget constraints. Thus far, in Japan, rates for fuel tax and expressway toll are nationally uniform, and the revenues are used to develop the national arterial highway network. This funding system can be understood as a type of average cost pricing, whereby road users are charged the full cost of road use. Using the average cost pricing scheme as a base, the government has recently started to introduce marginal cost pricing schemes, for instance, congestion charges or environmental road pricing, in order to address urban problems such as congestion and air pollution.

However, both pricing theories lack in the perspective that considers road capacity as a variable. In order to manage the road network efficiently, it is more desirable to increase the road capacity if demand exceeds supply, and 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, or 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 LAC curve of 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 pricing. Under the new planning scheme, when a road is congested, the road administrator levies a congestion charge to bring in the excess revenue and invest it in increasing the road capacity. On non-congested sections, on the other hand, since the charge set by marginal cost pricing 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. We need to discuss some road-related costs here. 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 marginal private cost (SPC), which is equal to short-run average private cost, is a time cost at a certain traffic volume (see Figure 1).

Cost

Demand curve

SMC

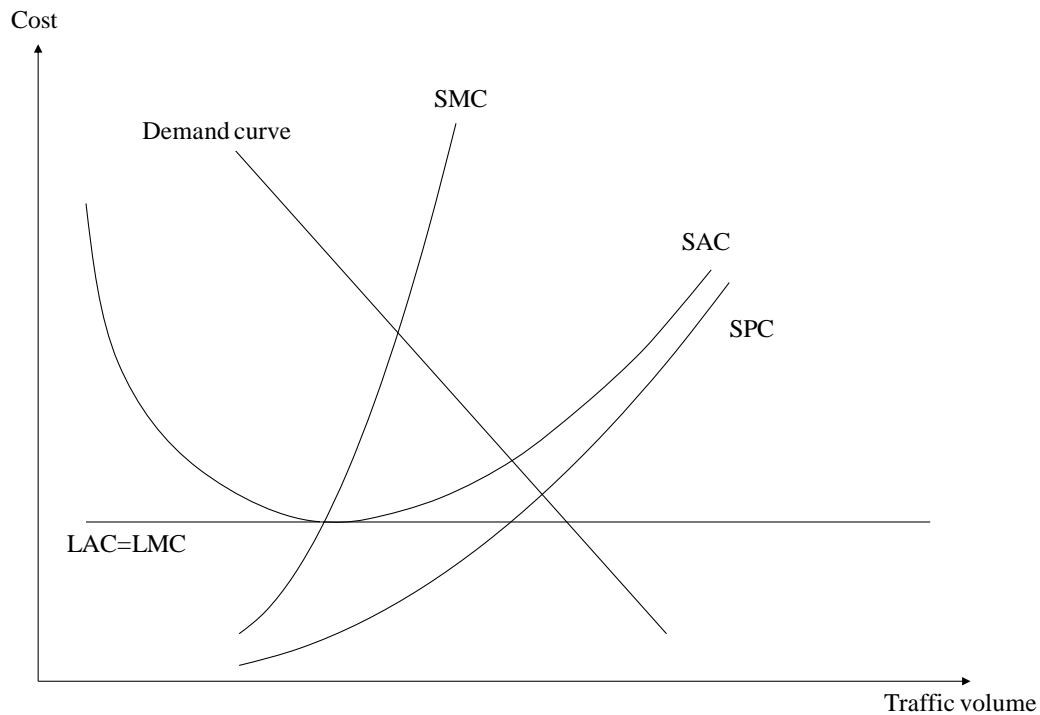SAC

SPC

LAC=LMC

Traffic volume

Figure 1—Road costs before investment

Under the proposed scheme based on 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 period. When the road capacity is lower, SMC is higher than SAC. In that case, charged revenue exceeds maintenance and renewal costs. 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 increases, as a result of the investment in the previous period (Figure 2).

With repeated pricing and investments, long-run optimal road capacity is realized where the SMC curve intersects the SAC curve and also 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 the charge equals the necessary amount for road maintenance, in both cases (Figure 3).
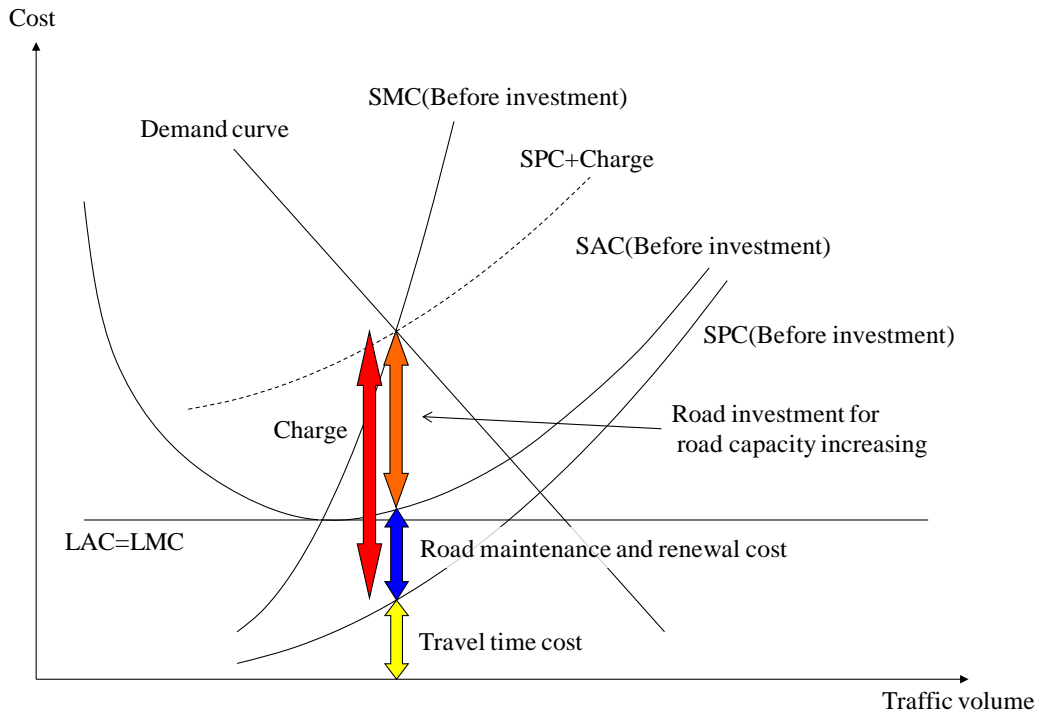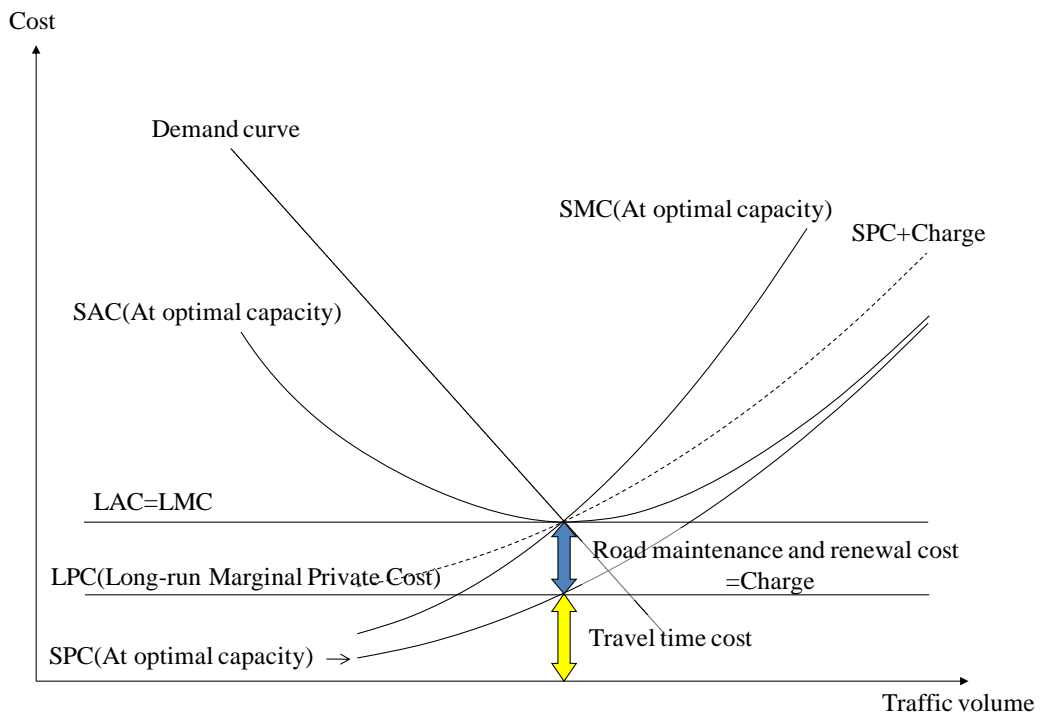
Figure 2 – Charge for road before investment

Figure 3 – Road costs and charges for road at optimal capacity

3. ISSUES RELEVANT TO SMC CHARGING AND ADVERNTAGE OF ROAD PLANNING THROUGH LMC CHARGING

Optimal road capacity building through SMC charging, which is described in Section 2, is not quite practical. There are several reasons for this.

First, the implementation of SMC charging requires the charging scheme to consider external costs. Current taxes and tolls (fuel taxes, acquisition tax, ownership tax, a fixed toll per year [a so-called vignette], etc.) are scarcely able to support SMC charging. Therefore, we need large changes of road user charge system. Indeed, recently, mile-based charging has attracted attention as not only the optimal pricing scheme from the viewpoint of resource allocation but also the most sustainable scheme for funding road maintenance and renewal. As NSTIFC (2009) and the UK House of Commons (2009) discussed, mile-based charging is becoming realistic now. However, the amount of charging may become very high level depending on the situation of congestion. We also need to change every time the amount of charging according to the change of the level of SMC. The feasibility of the SMC charging is low, and we believe that the feasible amount of SMC charging is quite averaged amount.

The second reason, as Nash (2008) has mentioned, is the risk of giving road administrators an incentive to limit road capacity and raise charges. That is to say, the road expansion of congested road bring the improvement of driving environment to road users, but the revenue of road administrators will reduce through cut-down of marginal social cost.

As can be easily imagined, however, if SMC chargings are implemented for crowded roads with capacity less than the optimal road capacity, road users face very high charges. On the other hand, if SMC chargings are implemented for roads with capacity close to the optimum, road users can enjoy a comfortable driving environment and pay charges at a moderate rate. Thus, the inevitable consequence is that road users faced with insufficient road capacity are asked to pay high charges in an early stage and road users who are facing sufficient road capacity enjoy comfortable drive paying low charge. Road users faced with insufficient road capacity are not responsible for the poor road capacity, and the equity gap is significantly unfair.

As NSTIFC (2009) discussed, the funding scheme for road investment should incorporate equity considerations (generational equity, equity across income groups and geographic equity, etc.). Furthermore, Whitty and Svadlenak (2009) remarked that it is necessary to evaluate public acceptance and understanding of the opportunities for rate structuring and to consider the effect of rate setting on equity among the motorist classes, especially rural drivers and poorer drivers.

Kotlikoff (1992) proposed "Generational Accounting" as an indicator of fiscal policy to replace the fiscal deficit. The proposition of "Generational Accounting" suggests that it is essential to consider the relationship between benefits and burdens among generations, and the road charging scheme is no exception to this requirement. Based on this perspective, the adoption of an SMC charging scheme is not easy.

Therefore, this paper focuses on LMC charging in terms of equally distributing burdens between generations. Verhoef, Koh, and Shepherd (2008) has also focused on the relationship between road capacity and long-run cost, but equity of the amount charged is not considered. In Figure 4, the optimal charge based on SMC charging is determined as the difference between SMC^{now} and SPC^{now}, where the SMC^{now} curve intersects the demand curve. In contrast, the optimal charge based on LMC charging is determined as the difference between LMC and LMPC, where the LMC curve intersects the demand curve.

Cost

Demand Curve

$SMC^{optimal}$

$SAC^{now}(SPC + infra\ cost)$

$SAC^{optimal}$

$SPC^{optimal}$

$Charge^{SMC}$

LAC=LMC

$Charge^{LMC}$

LPC

SMC^{now}

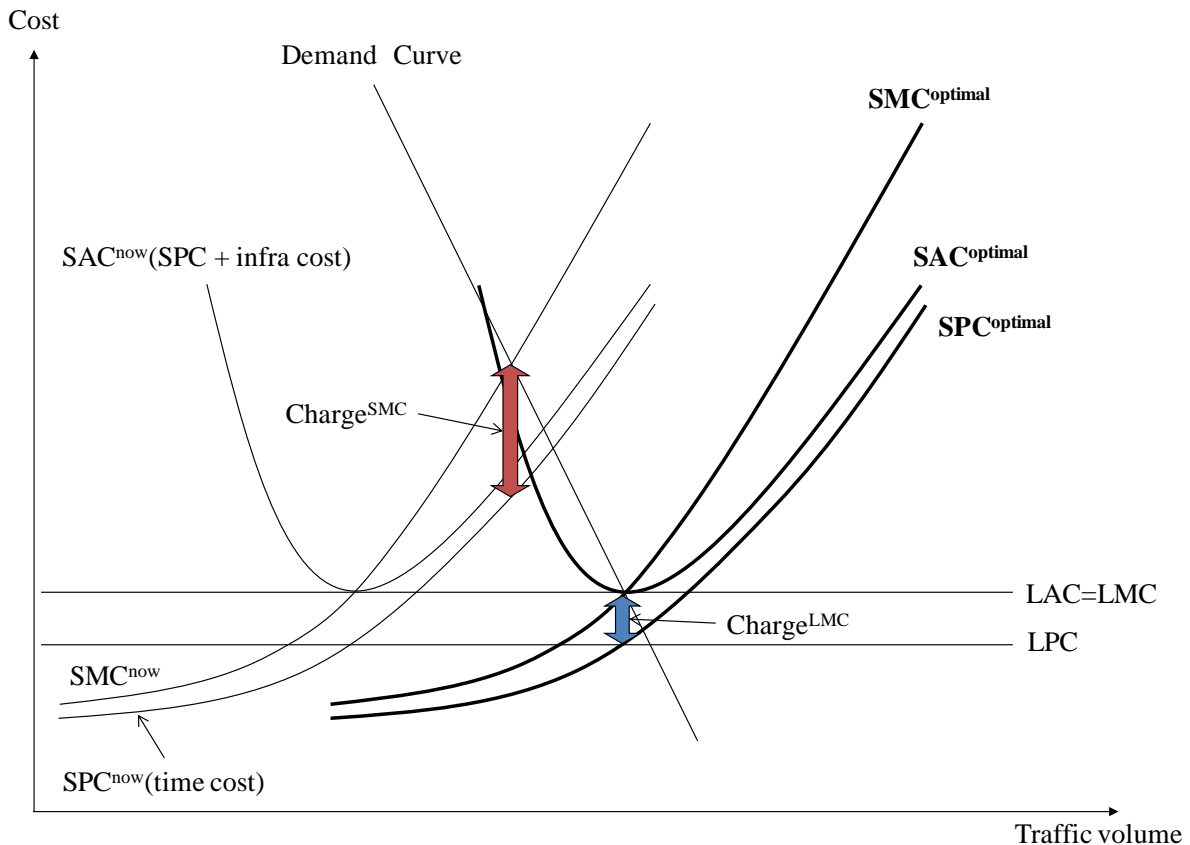$SPC^{now}(time\ cost)$

Traffic volume

Figure 4 – SMC charging and LMC charging

Of course, current road users face short-run road cost functions based on the current road network. Figure 4 shows that, if the economies of scale are neutral, the difference between SMC and SPC at the lowest point of SAC is always equal to charge^{LMC}. On the other hand, if there is congestion, the facing traffic volume is larger than the traffic volume at the lowest point of SAC, so the difference between SMC and SPC is smaller than charge^{LMC}. Therefore, we can expand road capacity using LMC charging. However, the amount charged under LMC will dip from the optimal amount charged under SMC charging. As a result, the dead weight loss generated by the excess demand is not completely eliminated (see Figure 5). In addition, depending on the slope of the demand curve, the revenue from LMC charging is generally less than the revenue from SMC charging, and the period of funding to achieve long-run optimal road capacity is longer than the period for SMC charging. Consequently, more road users encounter the remaining dead weight loss.

This LMC scheme, however, will achieve the equal distribution of the burden between different generations. It is necessary to choose the charging scheme on the grounds of the above costs and benefits. These effects and influences are considered through a simulation analysis in Section 4.
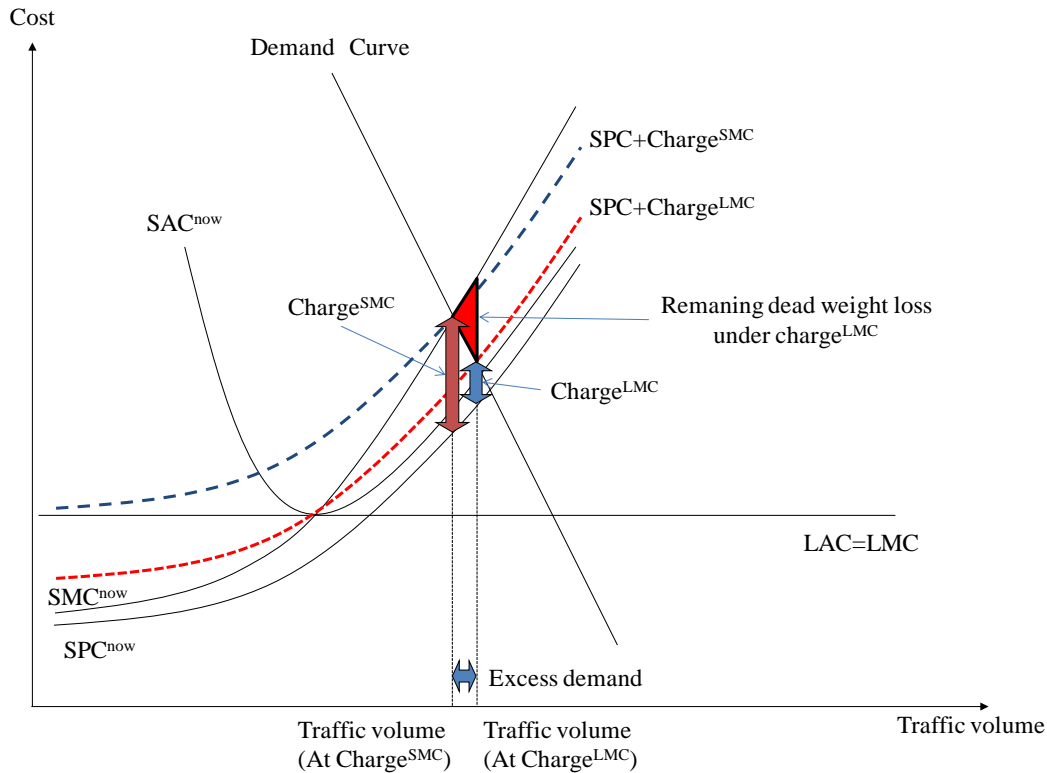
Figure 5 – Excess demand and dead weight loss of LMC charging

4. SIMULATION ANALYSIS

4.1 Setting of simulation analysis

4.1.1 Network

In this simulation analysis, we assume a ladder network, which consists of four routes in an east-west direction (expressway, main arterial highway, arterial highway, and sub arterial highway) and some access roads in a north-south direction. This network has nodes on 4 routes in an east-west direction every 5 km, and access roads connect each node. The length of each east-west route is 50 km. The length of each access road is totally 6 km, and that between the expressway and the main arterial highway is 3 km. 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. Additionally, in this simulation, we suppose constant returns to scale based on previous researches (Kanemoto [2007], etc.).

Table 1 – Characteristics of 4 routes constituting the network

	Free flow speed (km/hour)	Road capacity per lane (vehicles/hour)	Renewal cost (yen/km)	Land cost (yen/km)	Maintenance cost (yen/km)
Expressway (east-west)	100	2,000	1,200M yen /40years	3% of 400M yen	27M yen
Main arterial highway (east-west)	70	1,500	600M yen /40years	3% of 200M yen	13.5M yen
Arterial highway (east-west)	50	1,200	600M yen /40years	3% of 200M yen	5.3M yen
Sub arterial highway (east-west)	30	1,000	600M yen /40years	3% of 200M yen	0.41M yen
Access road (north-south)	30	- (99,999)	-	-	-

Expressway

Main arterial highway

Arterial highway

Sub arterial highway
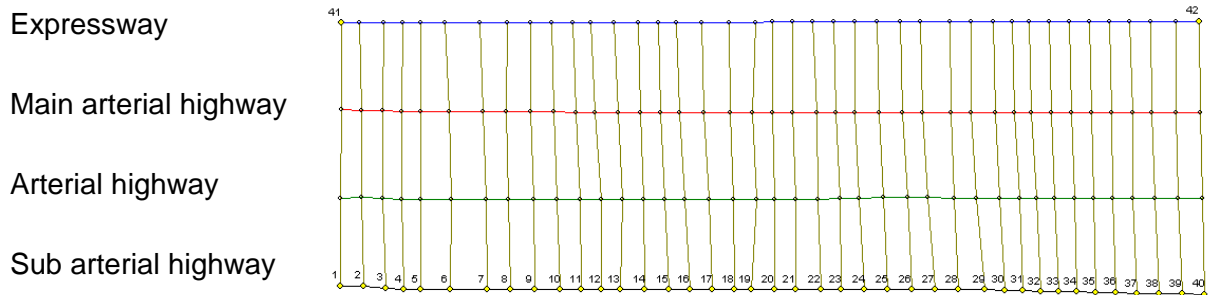
Figure 6 – Network structure

4.1.2 OD trip

Each OD trip generates 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 through reference to the road traffic census survey in Japan.

Table 2– Distribution of OD trip length

Trip length	Low demand case	Base case	High demand case	Component ratio
5km	400	600	800	40.0%
10km	250	375	500	25.0%
20km	200	300	400	20.0%
30km	100	150	200	10.0%
70km	50	75	100	5.0%
Cross traffic volume	3,000 vehicle/hour	4,500 vehicle/hour	6,000 vehicle/hour	-

In addition, this simulation analysis assumes three cases of road demand (base case: 4,500 vehicle/hour, low demand case: 3,000 vehicle/hour and high demand case: 6,000 vehicle/hour).

4.1.3 Link performance function

It is necessary to specify the user cost function (link performance function) to analyze the simulation model in this section. 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 based on 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 equivalent to assuming that the demand curve is vertical. Therefore, we cannot analyze the effect of the remaining dead weight loss under LMC charging, presented in Section 3. Consideration of this problem is left for future research. In addition, we should note that the amount charged with the assumption that the demand curve is vertical is larger as compared to what it would be if we assumed a normal downward-sloping demand curve.

Moreover, this simulation analysis considers that the road administrator invests in each route in a range of one-lane highway to three-lane highways. This means that we can consider totally 81 network sizes (road capacity is between 5,700 vehicles/hour—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. 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 based on Nemoto and Misui (2008).

4.2 Results of simulation analysis

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

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

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 shown in Table 3. Table 3 shows that traffic is allocated in a manner nearly proportional to the road capacity of each route.

Table 3—Results of traffic assignment and charged amount for each route

	Road capacity (vehicles/hour)	Traffic volume (vehicles/hour)	Traffic speed (km/hour)	Amount charged (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

The (weighted base traffic volume) average SMC amount 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. Based on the discussion in Section 2, we can allocate the difference between revenue and cost (32.7 billion yen) to expand road capacity.
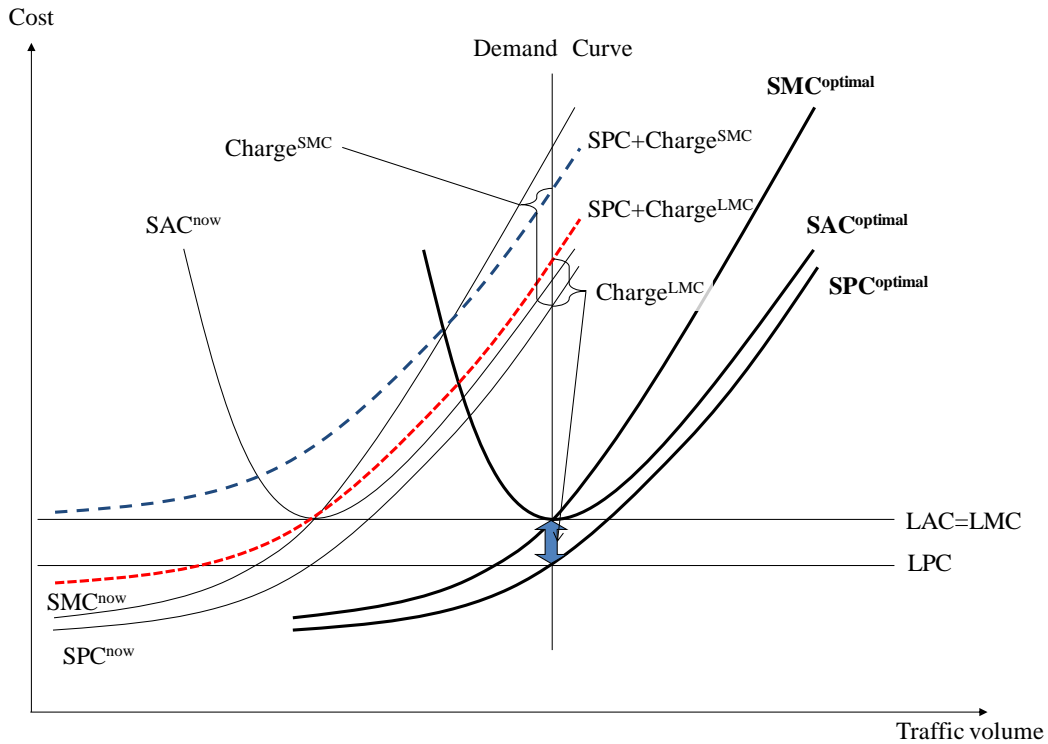
Figure 7—SMC charging and LMC charging in fixed demand

With the same cross traffic volume, Figure 8 shows the change in traffic assignment when the scale of the network increases (traffic figures for the multilane route are relatively large, of course). In addition, as the network grows, the speed of each route is closer to the free-flow speed, because congestion is gradually eliminated (see Figure 9). Moreover, as shown in Figure 10, in response to the elimination of congestion, the amount charged for each route goes down gradually, including minor increases or decreases, depending on the results of traffic assignment between routes. The decreasing average SMC amount reflects this trend.
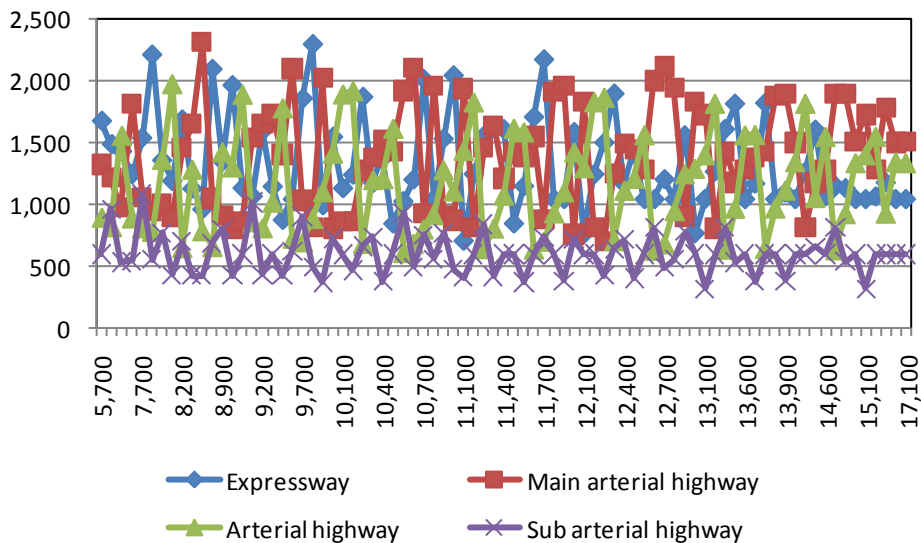
Figure 8—Results of traffic assignment for each route (traffic volume [vehicles/hour], 4,500 vehicles/hour)
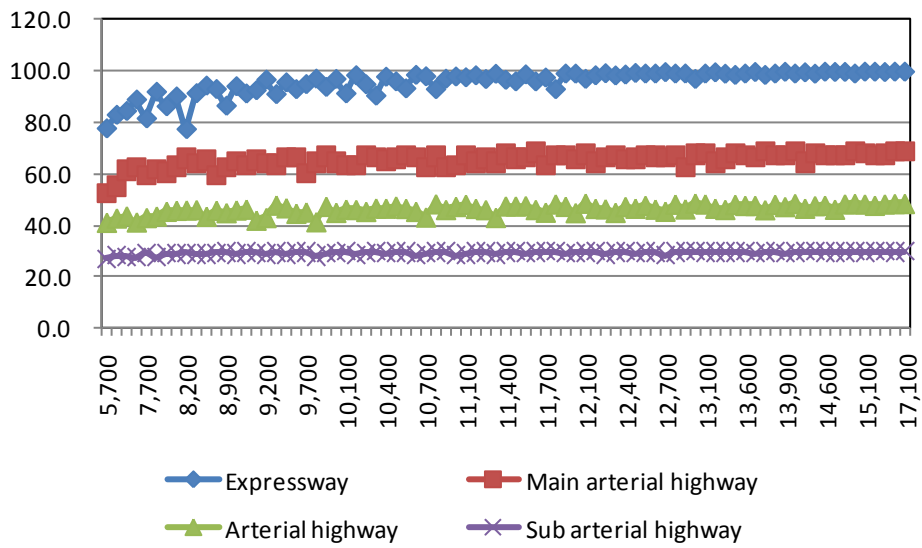
Figure 9—Results of traffic assignment for each route (traffic speed [km/hour], 4,500 vehicles/hour)
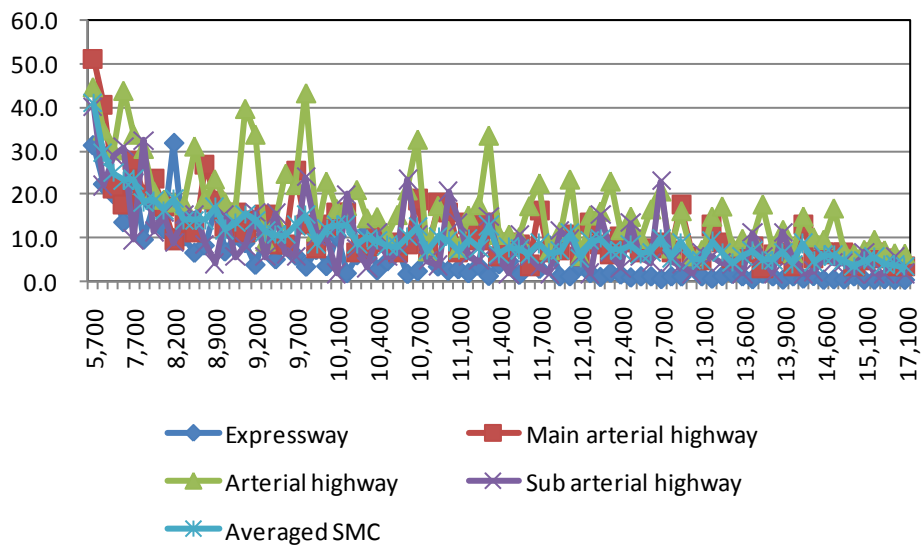

Figure 10—Results of traffic assignment for each route (charge [yen/km], 4,500 vehicles/hour)

In contrast, under the same cross traffic volume, Figure 11 shows the result of traffic assignment based on SAC charging.
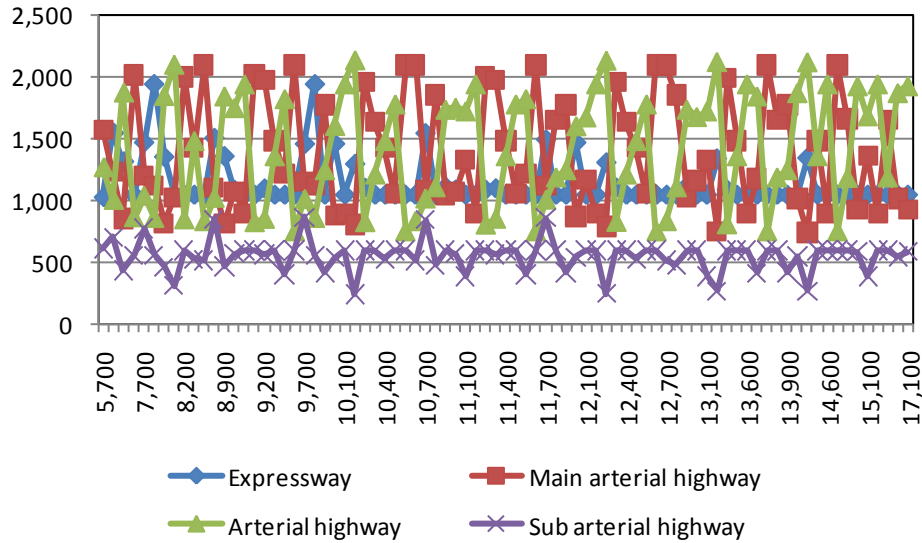
Figure 11—Results of traffic assignment for each route based on SAC charging (traffic volume [vehicles/hour], 4,500 vehicles/hour)

As we increase the size of the network, the SAC charge amount also increases gradually, reflecting road costs (road renewal cost, land cost, and maintenance cost), as opposed to the average SMC amount in Figure 10. Figure 12 shows the trajectory of the SAC charge amount and the average SMC charging amount shown in Figure 10.
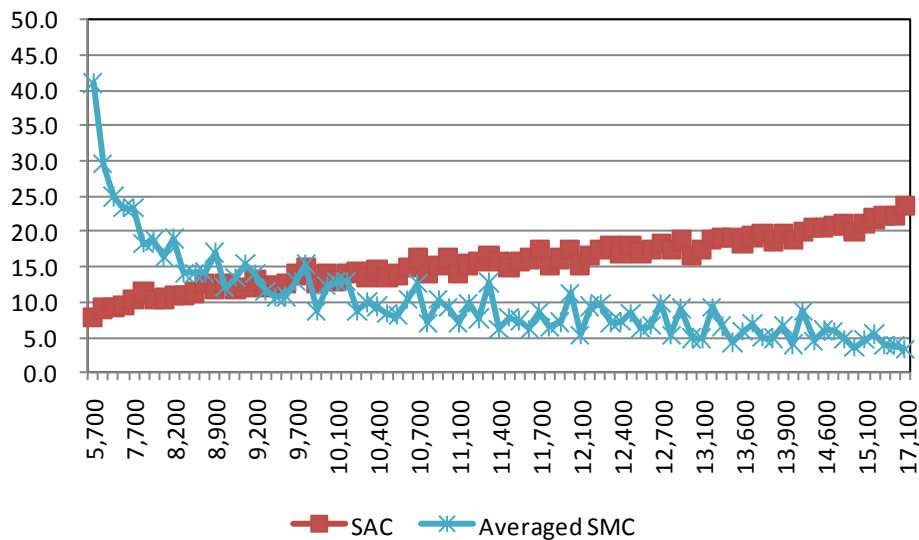

Figure 12—Results of SMC and SAC charging (charge [yen/km], 4,500 vehicles/hour)

As you can see from Figure 7, SMC is equal to SAC at the optimal road capacity. This implies that the road capacity is optimal, since the SMC charging amount is equal to the SAC charge amount. If the cross traffic volume is 4,500 vehicles/hour, the optimal road capacity is 10,100 vehicles/hour (expressway: one lane, main arterial highway: one lane, arterial highway: three lanes, sub arterial highway: three lanes), and LAC (=LMC) is 13.1 yen/km.

Similarly, Figures 13 and 14 show the SMC and SAC charge amounts when the cross traffic volume is 3,000 vehicles/hour (two-thirds of base case).
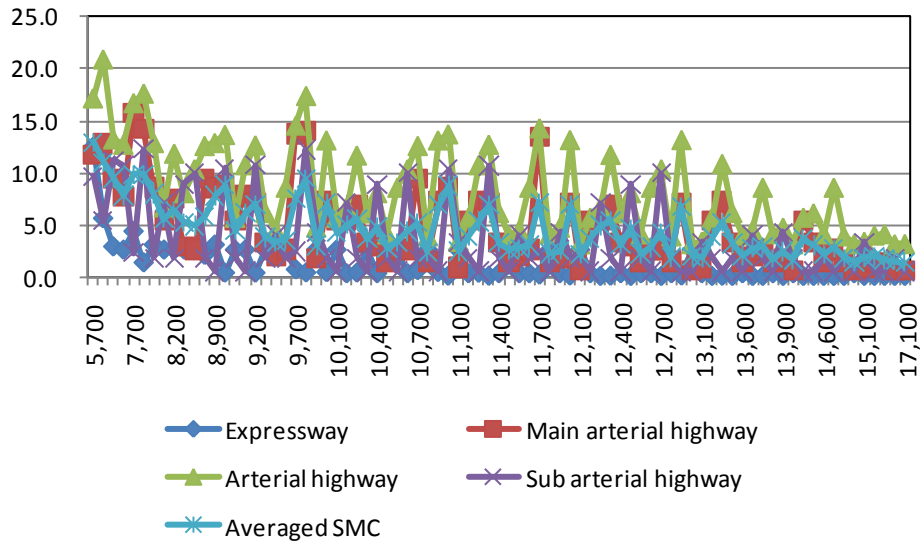

Figure 13— Results of traffic assignment for each route (charge [yen/km], 3,000 vehicles/hour)
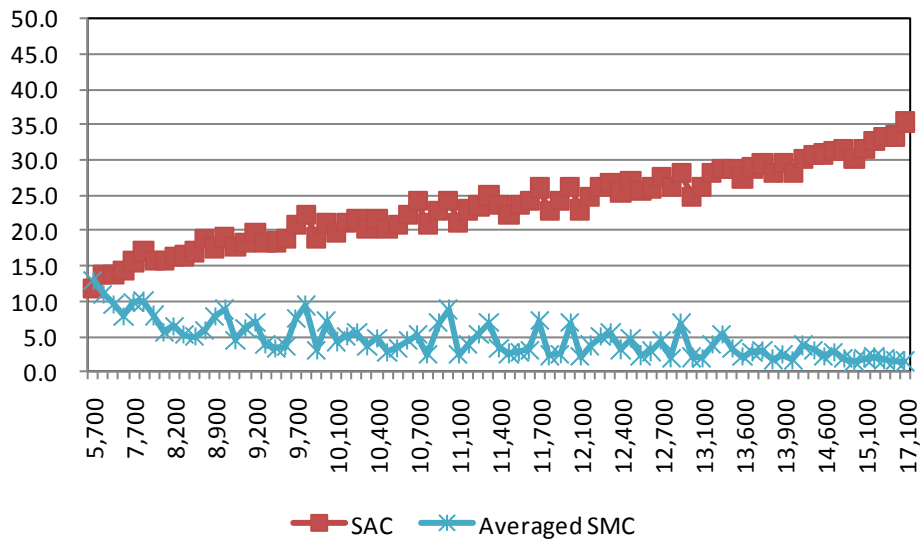

Figure 14— Results of SMC and SAC charging (charge [yen/km], 3,000 vehicles/hour)

In addition, with 6000 vehicles/hour (1.5 times the base case), Figure 15 shows the amount of SMC charging, while Figure 16 shows the amount of SAC charge.
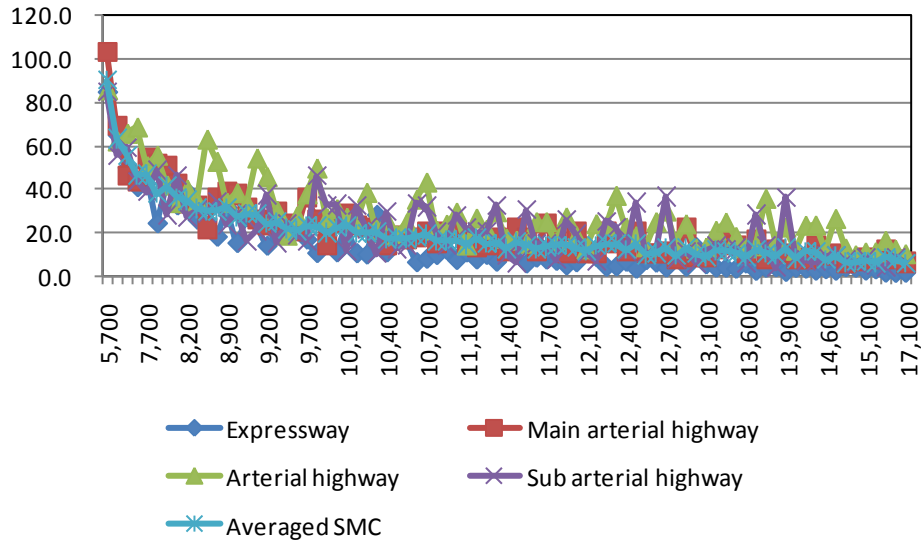
Figure 15— Results of traffic assignment for each route (charge [yen/km], 6,000 vehicles/hour)
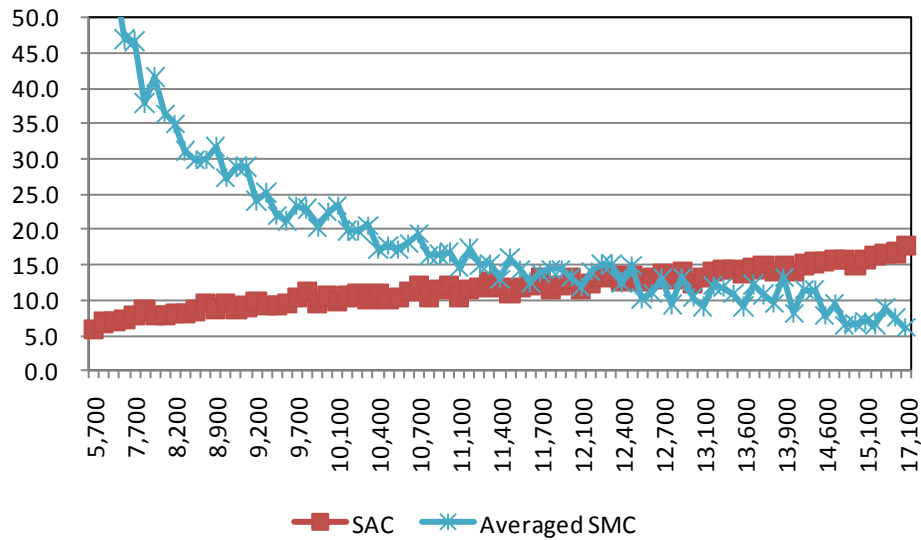

Figure 16— Results of SMC and SAC charging (charge [yen/km], 6,000 vehicles/hour)

The averaged SMC amount shown in Table 14 and Table 16 has a downward trajectory while the SAC amount shown in Table 14 and Table 16 has an upward trajectory. In addition, we can confirm that LAC is constant, which implies constant returns of scale because the level of each intersection is similar to the intersection in the 4,500 vehicles/hour case.

However, optimal road capacity in each case is, of course, different from the optimal road capacity in the 4,500 vehicles/hour case. The optimal road capacity of the 3,000 vehicles/hour case is 5,700 vehicles/hour (expressway: 1 lane, main arterial highway: 1 lane, arterial highway: 1 lane, sub arterial highway: 1 lane) and the optimal road capacity of the 6,000 vehicles/hour case is 11,900 vehicles/hour (expressway: 3 lanes, main arterial highway: 1 lane, arterial highway: 2 lanes, sub arterial highway: 2 lanes).

4.3 Comparison between SMC charging and LMC charging

4.3.1 Optimal road capacity building through SMC charging

We now consider a scheme for optimal road capacity building through SMC charging using the results from the above simulation analysis. We assume that current cross traffic volume is 4,500 vehicles/hour and that the road capacity of the current network is 5,700 vehicles/hour (expressway: 1 lane, main arterial highway: 1 lane, arterial highway: 1 lane, sub arterial highway: 1 lane). As indicated in the previous section, the net income of road administrator is 32.7 billion yen, which is the difference between revenue (40.4 billion yen) and road costs (7.7 billion yen), and the road administrator will allocate 32.7 billion yen to expand road capacity.

Now, the optimal road capacity is 10,100 vehicles/hour (expressway: 1 lane, main arterial highway: 1 lane, arterial highway: 3 lanes, sub arterial highway: 3 lanes) and investment of 120 billion yen is needed to achieve the optimal road capacity (2 lanes × 0.6 billion yen × 2 × 50km). For simplicity in our discussion, the expansion of the road capacity will realize in 3.67 years' time (120/32.7) if the road administrator expands the road capacity after funding it completely.

4.3.2 Optimal road capacity building through LMC charging

On the other hand, the scheme for optimal road capacity building through LMC charging equals that for SMC charging based on the optimal road capacity. Here, for convenience, we set that the amount of LMC charging for each route is equal to the amount of SMC charging for each route in the optimal road capacity. Therefore, as a result of traffic assignment between 4 routes, the (weighted base traffic volume) averaged amount of LMC is a little different from LAC (13.1 yen/km). Under the circumstances, the LMC charge amounts for current four routes are 10.4 yen/km (expressway), 15.7 yen/km (main arterial highway), 16.6 yen/km (arterial highway), and 1.8 yen/km (sub arterial highway) based on the SMC charging amounts at the optimal road capacity. The revenue is the sum of these amounts multiplied by each traffic volume.

In this case, the estimated revenue is 12.1 billion yen per year, so 4.4 billion yen (12.1 – 7.7) will be allocated to expand the road capacity. As discussed above, it is necessary to invest 120 billion yen to achieve the optimal capacity. Therefore, the period required to realize the optimal road capacity is 27.3 years (120/4.4). In comparison with what was implied by previous results, LMC charging requires 23.6 years more than SMC charging.

We attempted the same analysis for a high demand case. In this case, the investment required is 180 billion yen ([2 lanes × 1.2 billion yen + 2 lanes × 0.6 billion yen] × 50km).

From Table 4, it is evident that with a cross traffic volume of 6,000, LMC charging requires about 12 years more. In addition, the comparison with the above results shows that the period required to achieve the optimal capacity decreases as cross traffic volume increases and both schemes needs a smaller period than the life of the road (approximately 40 years) to achieve optimal capacity.

Table 4—Charge for each route and period required for optimal capacity (6,000 vehicles/hour)

		SMC	LMC
Charge amount at current road capacity	Expressway	84.5 yen/km	6.0 yen/km
	Main arterial highway	103.5 yen/km	20.7 yen/km
	Arterial highway	86.0 yen/km	18.5 yen/km
	Sub arterial highway	84.8 yen/km	19.3 yen/km
	Averaged amount	90.2 yen/km	15.8 yen/km
Difference between revenue and cost		110.7 billion yen/year	13.0 billion yen/year
Period required		1.63 years	13.9 years

Moreover, the above analysis reveals that SMC charging can result in adequate funding within a short time, but the SMC charging amount is very high compared to the LMC charge amount. For example, when cross traffic volume is 6,000 vehicles/hour (Table 4), the SMC charging amount (90.2 yen/km) is about six times the LMC charge amount (15.8 yen/km) and equals about 15 times the amount required to maintain the current network size (SAC, 5.9 yen/km). That is to say, SMC charging is a scheme that imposes a great burden on road users using the current road network, while optimizing resource allocation to achieve and decrease social acceptability for the funding scheme.

4.4 Consideration with respect to generational equity

In this section, we attempt to consider the issue of social acceptability noted in the previous section, comparing both schemes quantitatively, based on the results of simulation analysis.

Here, we compare LMC and SMC based on the concept of "Generational accounting," which is proposed by Kotlikoff (1992). Assumptions of the comparison are as follows.
- People use cars over 40 years, from the age of 20 to the age of 59.
- The starting year for the charge is T-year.
- The generation (people) unit is one year.
- For example, people who are born in T-year start to use their cars in T+20-year and stop using their cars in T+59-year.
- On the other hand, people of forty generations, from the people born in T-59-year, to the people born in T-20-year, use roads and pay their share of the burden in T-year.
- Because the cross traffic volume is fixed, we assume that the number of people in each generation is constant and they pay 2.5% of cost generated in the year.
- The cost of each generation is a sum of the amount paid during their lifetime; the benefits are the inverse of the time cost during their lifetime.
- SAC charging based on the current network size has been applied before the new charging scheme has started in T-year.

Figure 17 shows the level of road users' payment per year in the case of SAC charging (current scheme), the case of SMC charging and the case of LMC charging. Similarly, Figure 18 shows the level of road users' time cost per year in the case of SAC charging (current scheme), the case of SMC charging and the case of LMC charging. In these figure, we can grasp that the level of payment through SMC charging is extremely high to LMC charging while SMC charging enable reduction of time costs in early years to us.
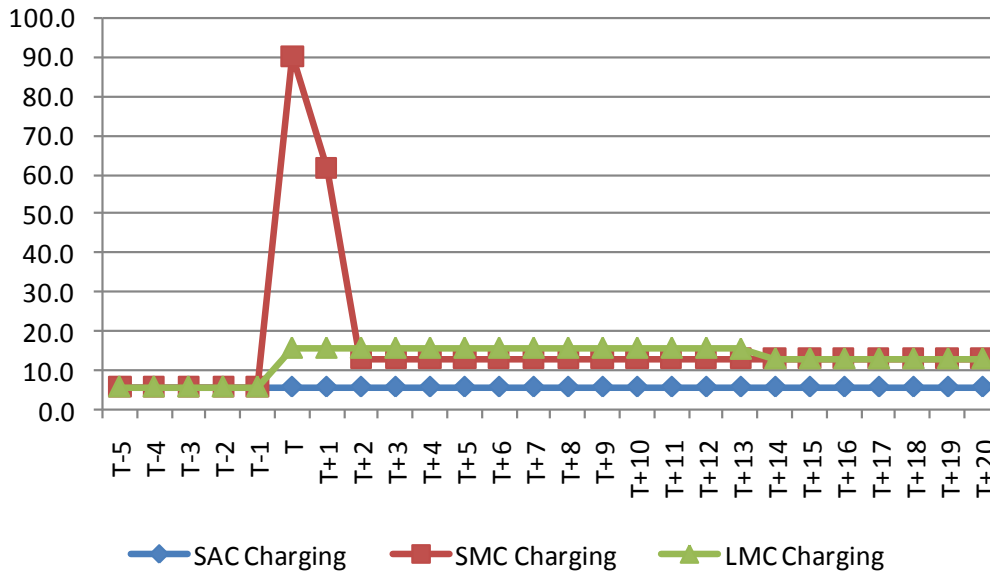
Figure 17—Payments per year (charge [yen/km], 6,000 vehicles/hour)

Note: The payment before T-5-year are equal with that of T-5-year and the payment after T+19-year are equal with that of T+19-year.
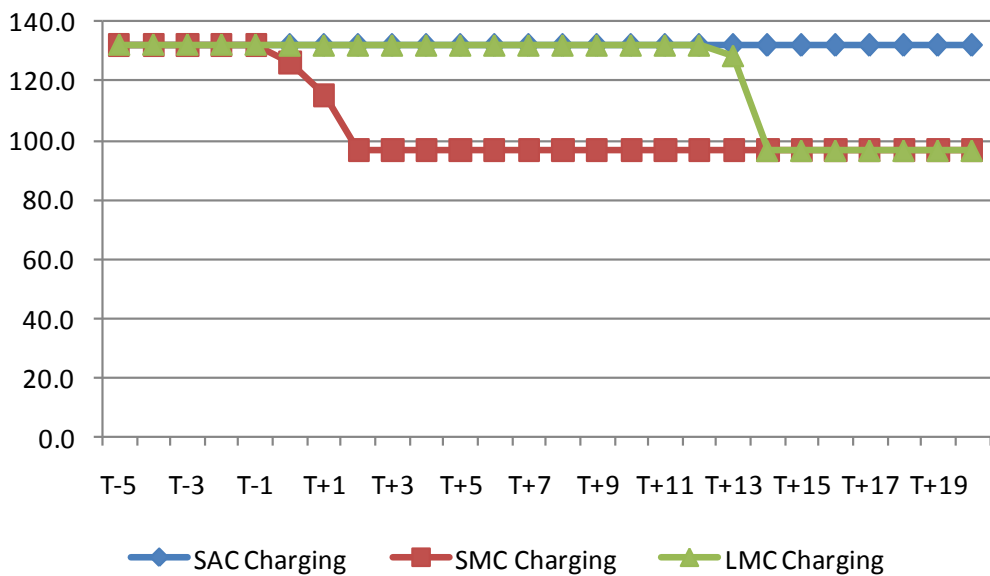

Figure 18—Time costs per year (time cost [yen/km], 6,000 vehicles/hour)

Note: The time cost before T-5-year are equal with that of T-5-year and the time cost after T+19-year are equal with that of T+19-year.

To transform the above results per year into the results per generation, we need to sum the payments and time costs which every generation is facing. For example, people who are born in T-year (the generation of T-year) start to use their cars in T+20-year and stop using their cars in T+59-year. Similarly, people who are born in T-20-year (the generation of T-20-year) start to use their cars in T-year and stop using their cars in T+39-year. Therefore, time cost of the generation of T-year is summation from the time cost in T+20-year to the time

cost in T+59-year and payment of the generation of T-20-year is summation between the payment in T-year to the payment in T+39-year (Figure 19).
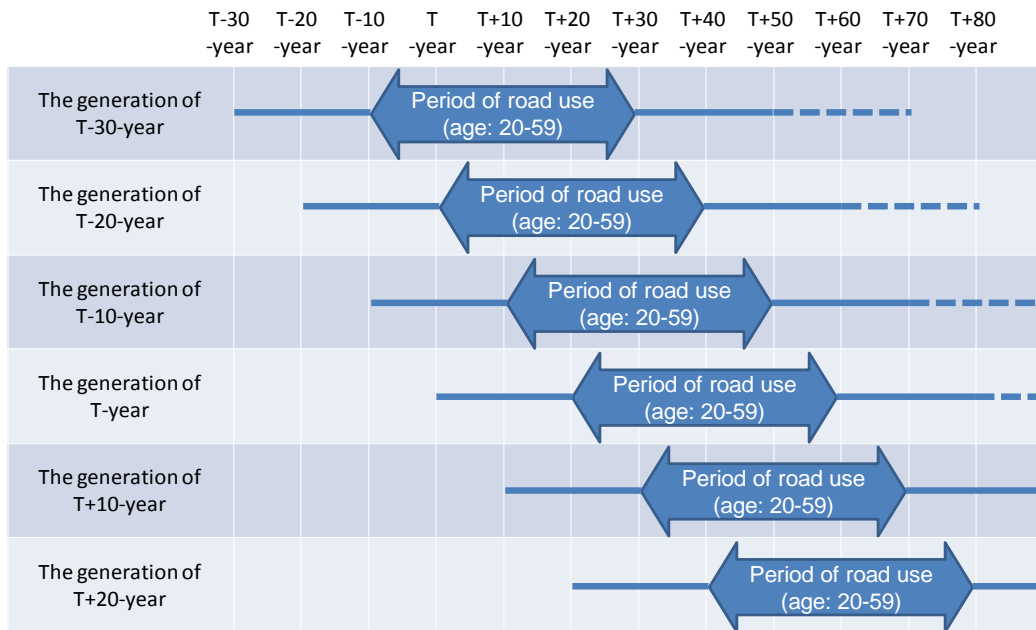

Figure 19—Transformation from results per year into results per generation

We can raise revenue to invest the long-run optimal road capacity in about two years through SMC charging or in about 14 years through LMC charging, so the payment and time cost in SMC charging or those in LMC charging are equal after T+14-year. Therefore, SMC charging and LMC charging are indifference for the generation of T-6-year who start to use their cars in T+14-year (Figure 20 and 21). In addition, for simplicity in our discussion, we do not discount the cost and benefit in this analysis.
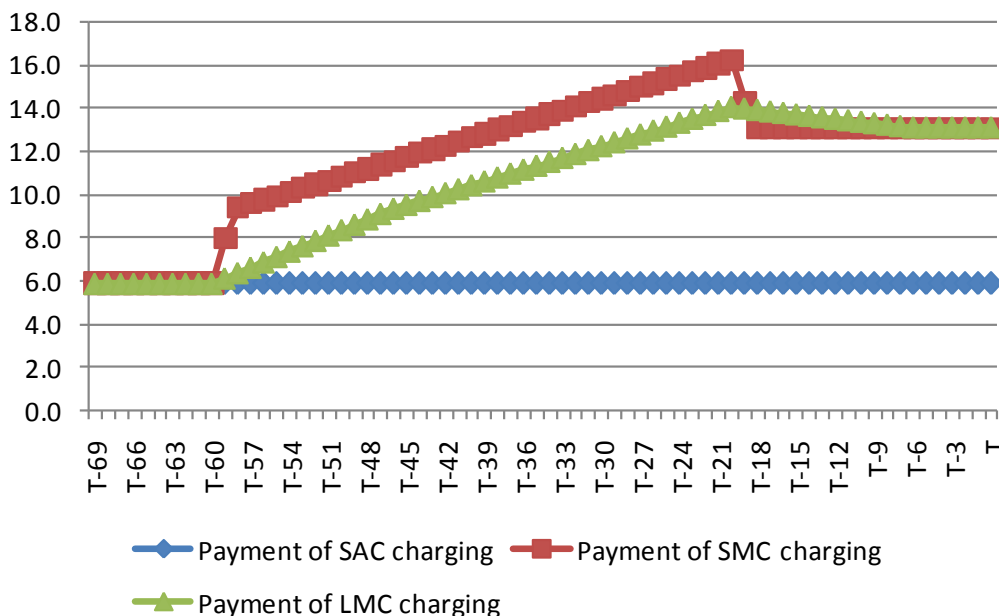

Figure 20—Payments per generation (charge [yen/km], 6,000 vehicles/hour)

Note: The payment of the generations before T-69-year are equal with that of the generation
of T-69-year and the payment of the generations after T+1-year are equal with that of
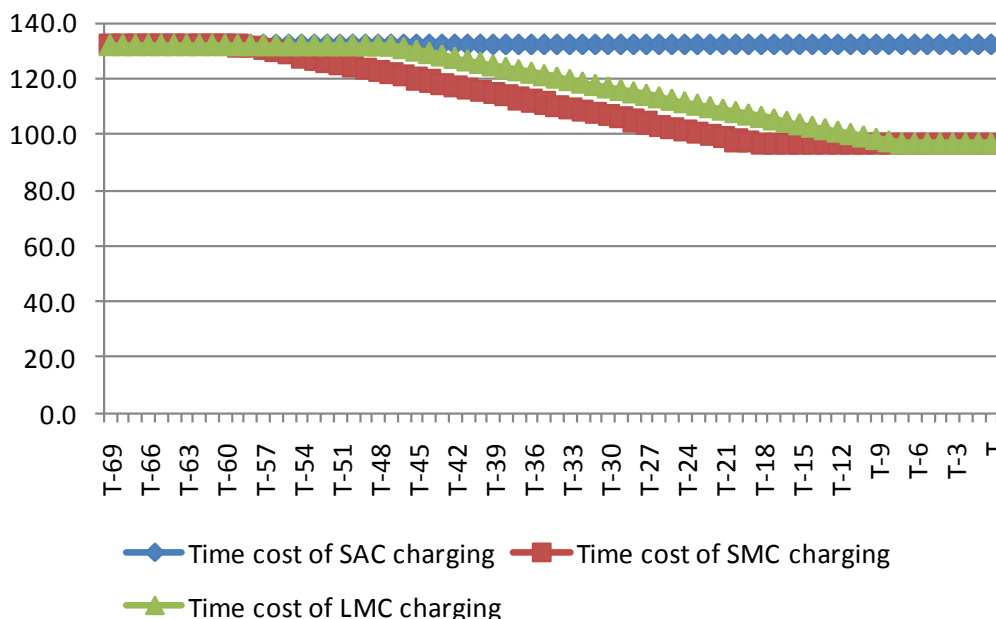the generation of T-year.

Figure 21—Time costs per generation (time cost [yen/km], 6,000 vehicles/hour)

Note: The time cost of the generations before T-69-year are equal with that of the generation
of T-69-year and the time cost of the generations after T+1-year are equal with that of
the generation of T-year.

Figure 20 and 21 show the costs and benefits starting LMC charging and SMC charging from. That is to say, the difference of payments between LMC charging and SAC charging mean the cost of LMC charging and the difference of time costs between SMC charging and SAC charging mean the benefit of SMC charging.

However, because LMC and SMC are different at the starting year of investment (the finishing year of funding), the simple comparison involves a misunderstanding. Therefore, we also compare the optional case to invest the long-run optimal road capacity at the starting year of LMC charging (the LMC-bond case). In the LMC-bond case, however, it is impossible to raise revenue of the initial cost of long-run optimal road capacity, so we assume to fund through a bond by government. Therefore, the amount of charging in the LMC-bond case is added the long-term government bond rate (4%) of the initial cost to the amount of LMC.

The cost benefit ratios (CBR) of three cases are derived from dividing the benefits by the costs (Figure 21). Figure 21 shows the CBR of the LMC-bond case lies higher than the CBRs of the LMC case and SMC case in former generations (from T-59-year generation to T-34-year generation). The LMC charging with bond is almost equal to the current toll road scheme and this result suggests that the current toll road scheme investing the road ahead is high in equity between generations. In latter generations (after T-33-year generation), however, the CBRs of the LMC case and SMC case lie the CBR of the LMC-bond case and the CBR of the SMC case lies higher than the CBR of LMC charging in all generation

quantitatively. This result suggests that, if we can accurately forecast the long-run optimal road capacity and consider based on the long-term perspective, it is useful to levy the SMC charging to road user and the LMC charging is second best solution to avoid abrupt changes of the amount.
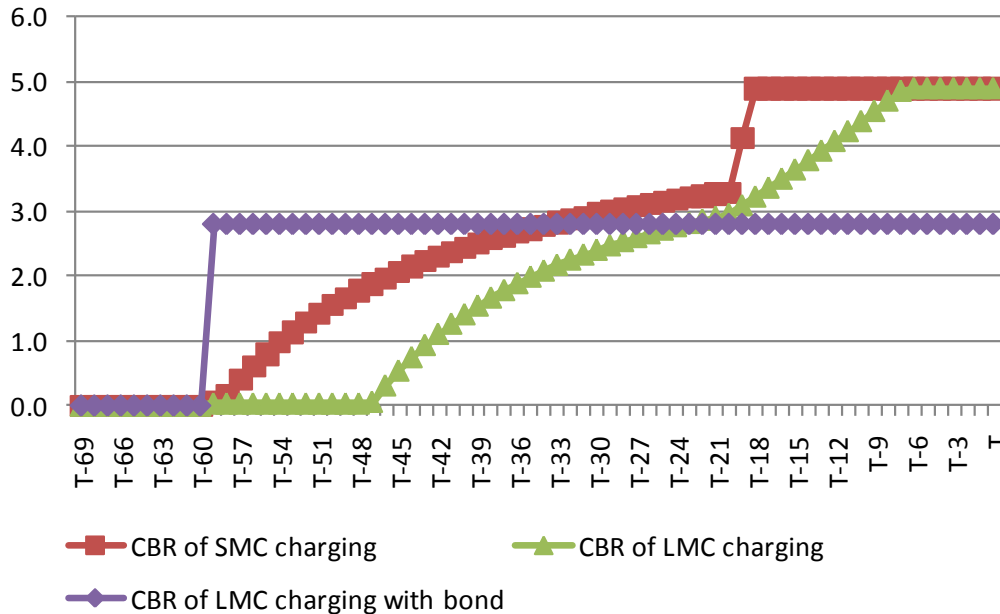

Figure 22—Cost benefit ratios of road users per generation (CBR [benefit/cost])

Note: The cost benefit ration of the generations before T-69-year are equal with that of the generation of T-69-year and those of the generations after T+1-year are equal with that of the generation of T-year.

5. CONCLUSION

Previous researches have revealed that SMC charging is desirable from the viewpoint of resource allocation, and long-run optimal road capacity can be achieved through repeatedly applying SMC charging to road use. However, actual adoption of SMC charging has been slow.

This paper focused on social acceptability for a change in road charge system in terms of governance of the road and compared SMC and LMC charging. Through simulation analysis, we showed quantitatively that the SMC charging achieves the long-run optimal road capacity efficiently but then the charging requires the abrupt changes of the amount. In addition, we revealed that the LMC charging with bond is a good choice respect to the equity between generations, but the charging cannot achieve the long-run optimal level of the cost benefit ratio. Based on the above discussion, we can consider that the LMC charging is the second best alternative to achieve the long-run optimal road capacity moderately with a small loss of cost benefit ratio.

Relevant issues for future study are the elaboration of our simulation analysis (e.g., the assumption of economy of scale, fixed cross traffic volume, etc.) and the exploration of road governance issues (e.g., the problem of coexistence of multiple road administrators).

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