TITLE: Optimal Road Capacity Building

-Road Planning by Marginal Cost Pricing-

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ABSTRACT:

The purpose of this study is to propose a new road planning and financing scheme based on short-term social marginal cost pricing that facilitates the establishment of optimal road standards in the long term. We conducted a simulation analysis based on the proposed planning scheme and observed that the simulation calculated the optimal road capacity in the future, and thus proved that the new planning scheme is feasible.
1. Introduction

Under the conventional road planning scheme in Japan, arterial road network standard or density has been determined in an “engineered” way, with the aim of adequately dealing with the future traffic volume. 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). On the other hand, for the urban arterial road network, necessary network density and the number of lanes have been determined based on the land use and traffic generation density (City Bureau of the former Japanese Ministry of Transport, 1992). These “engineered” methods might be most appropriate during the high-growth period, when no one doubts the continuous growth of transportation demand.

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 benefit principle (beneficiaries-pay principle), the price must be set considering the road supply cost. Based on this principle, the price of road use would be high on a costly section of roads, and the higher price leads to lower transportation demand. It is necessary to develop a method for estimation the price of road use, based on the estimated
cost of road construction, maintenance, and renewal, so that it is possible to maintain an optimal road supply standard through a new planning and financing scheme (a mile-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 growing number of practical 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 run. Our paper is also based on the assumption of road capacity as “variable.”

Since, according to the road pricing theory, 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 (Information and Communication Technology) and
ITS (Intelligent Transport System), such as DSRC (Dedicated Short Range Communication), GPS (Global Positioning System), 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 scheme is now required to be restructured, so that it reflects the environmental changes in road pricing.

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 standards in the long term. If the road is congested or the capacity does not meet the transportation demand, short-term social marginal cost pricing (congestion pricing) brings more revenue than is necessary to maintain and renew the existing road. Then, we can increase the capacity using the funds in the long term, 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. Issues of Earmarked Tax Revenue for Road and Toll Road System in Japan

Road administrators in Japan have been developing road networks by adapting two remarkable systems in the postwar period; “Earmarked Tax Revenue for Road” and “Toll Road System.” Both systems are based on the beneficiaries-pay principle since they collect the necessary amount for road development from road users.

These systems can be seen as “pseudo” markets of road demand and road supply and in this market, both demanders (road users) and suppliers (road administrators) are expected behave rationally and realize the optimal resource allocation. When the demand exceeds the supply, fuel tax and toll increase thereby increasing supply. On the other hand, when the demand is less than supply, the supply decreases (Nemoto(1999), Nemoto and Misui(2002)).

These economic implications, however, does not necessarily imply that these current systems (earmarked tax revenue for road and the toll road system) are economically efficient. For example, the empirical study by Misui (2005 a, b) pointed out that there exists a divergence of benefits and burdens under the current systems. The divergence means that the road users are taxed regardless of the necessary amount for road supply and thus yields excess supply or excess demand. This results in distortion of resource allocation and decrease in social welfare.
For example, the principal revenue for the earmarked fund for road is the fuel tax revenue (revenues from gasoline tax, diesel delivery tax, etc.). Fuel tax is imposed on the volume of gasoline consumed. In this tax scheme, every road user is charged the same level of tax regardless of which road they use. Therefore, the tax burden has no relationship with road construction/maintenance cost, number of users, congestion, air pollution, or with duration period of roads and future number of users.

As mentioned above, under the current road planning scheme, the government first established the road network density plan (or planned capacity) based on indicators such as population density, land use, and traffic generation density and then has been developing the planned network within the earmarked tax revenue for road. This engineered approach might be the most effective during the high-growth period, when there was no or little uncertainty with regard to future traffic growth.

The same can be said for the toll road system, which adopts the system of pooling the toll revenue. Tolls are charged on users on the basis of the miles driven and the toll is the same on every section of the national expressway network, regardless of the road development or driving environment. The initial network plan of Japanese expressways has been set at 11,520km based on the engineered standard. However, because of the recent unprofitability, the construction plan has been limited to 9,342km. In this sense, the current toll road system, in some ways or contingently, seems to take the condition of demand
into consideration.

2.2 Cost Classification and Cost Burden

The "Cost Incidence Table" (Table 1) shows the types of road costs and the share of its burden. This has been created borrowing the concept of "Benefit Incidence Table." It shows the classification of road cost from two perspectives: cause of generation and cost burden. Among the stakeholders, the road administrator and road users form a “pseudo” market of road service. In this context, cost types regarding road administrator and road users are “internal” costs and cost types involving other stakeholders can be defined as “external” costs.

Among the costs passed on to road users (benefits of road administrators), vehicle related tax (fuel tax, etc.) have been spent mainly to cover the internal cost of road administrators and partly to internalize the external cost (anti-noise measures, etc.) (This is represented as $D + I < B + C + F + G + H$ in Table 1.). According to the pricing theory proposed in section 2.2, however, it is more desirable if all the costs passed on to road users (benefits of road administrators) are used to cover the internal cost and to internalize the external cost (This is represented as $D + I = B + C + F + G + H$ in 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 (2005b) studies the same issue in Japan. With regarding to external costs, there exist more studies such as Greene, Jones, and Delucchi (1997), which surveys and refines the previous studies.

(Insert Table 1)

2.3 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. The former focuses on economical optimum (that is, maximization of social welfare), a typical example of which is congestion pricing. The weakness of this pricing principle, however, is that the revenue from marginal pricing is relatively low and is not enough to cover the necessary maintenance and renewal cost, since most sections of highways (except urban networks) are not congested and the toll has to be set at relatively low level. Compensation from the general budget would not be always available because of the budget constraint. Thus far, in Japan, rates for fuel tax and toll of expressway are nationally uniform and the revenues are used to develop the national arterial highway
networks. This financing system can be understood as a type of average cost pricing whereby road users are charged the full cost. Using the average cost pricing scheme as a base, the government has recently has started to introduce marginal cost pricing schemes, for instance, congestion charge or environmental road pricing in order to address the urban problems such as congestion and air pollution.

Both pricing theories are, however, lacking in the perspective that road capacity as “variable.” 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 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 long-term average cost curve of road is horizontal, “the optimal road level is realized when the price is set at short-term marginal cost.” We applied this concept to propose 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 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 must “give up” on maintaining the capacity and reduce the road capacity to the
revenue shortage level.

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 determined according to the transportation demand. We need to explain some road related costs. In this paper, we assume that the road costs consist of the infrastructure cost for the road and the total time cost of road users. (This concept will be fully explained in section 3.1). Short-term Social Average Cost (SSAC) is calculated as the road costs divided by traffic demand. 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 (see Figure 1). 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 lower, 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 (Figure 2).

(Insert Figure 1)

(Insert Figure 2)

Over repeated pricing and investments, long-term optimal road capacity for the road is realized 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, in both cases (Figure 4).

(Insert Figure 4)

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

We run a simulation in this section, of optimal road capacity building based on the financing scheme described in the section 2. The purpose of this simulation is, assuming that there exists some amount of road stock, to calculate the toll based on SMCP and also the toll revenue, then to calculate the optimal level of road capacity given that the revenue is to be allocated for the maintenance and renewal of the tolled section of the road.

The framework of simulation is presented in the Figure 5 below. First, we set the initial amount of the road capacity as given. The road capacity along with the traffic volume (transportation demand) determines the travel speed on the section and eventually determines the toll revenue. This process can be defined as “Revenue Side,” as shown on the left side of Figure 3. On the other hand, road capacity also determines the necessary amount of expenditure to maintain, and renew the tolled section. This is the “Costs Side” as shown on the right side of the figure. At the end of each period, we calculate either the excess amount (toll revenue minus the expenditure for maintenance and renewal), which can be spent to increase road capacity (lane widening), or the deficit amount, which will lead to a decrease in the road capacity.

As a result, we calculate the increased or decreased amount of the road capacity at the end of period,
which is the initial capacity for the next period. We assume that it is possible to reduce the capacity of arterial roads for some period of time, since road stock has a life or is durable for a certain number of years. Reducing capacity in our model can be understood as the conversion of some links from the arterial network into local roads.

(Insert Figure 5)

The excess amount of toll revenue minus expenditure will decrease with the passage of time, because the toll decreases and costs increase as the capacity increases. The excess amount will be zero where the toll revenue equals the costs for maintenance and renewal. The road capacity at this point is defined as “optimal,” and we will examine how the road capacity changes through the simulation periods.

We assumed that the number of lanes, which means the road capacity, is variable. Although this assumption might be permissible given that the tolled section is only one route in this simulation, it would be more validated when we consider the road network as being composed of some routes. Although this assumption has been adopted in this study, the road network should be examined in the future. The following sections explain the outline of revenue and costs calculations.
1) Revenue Calculation in the Simulation Model

We first need to estimate the cost function of roads and also the transportation demand function to calculate the toll based on the SMCP theory. We used the observed data on traffic volume and corresponding travel speed and the existing studies to estimate the cost function of a road and transportation demand function, respectively.

Regarding the cost function of a road, Small, Winston, and Evans (1989) assumed that the road cost could be explained by the below function. This equation consists of the infrastructure cost of road (the first term on the right side) and the total time cost of road users (the second term on the right side).

\[ RC(Q, K) = aCC(K) + Qht(Q, K) \]  

(1)

Where:

\( RC(Q, K) \): cost function of the road

\( Q \): hourly traffic volume

\( K \): road capacity

\( CC(Q) \): construction cost for road capacity \( Q \)

\( aCC(Q) \): yearly road cost (including maintenance and renewal)
h: unit value of time

t(Q,K): travel time as a function of traffic volume and capacity

We first estimated the QV function, which calculates travel speed as a function of traffic volume so as to estimate the cost function of the road.

We obtained data on hourly traffic volume and travel speed on the Kosei highway (limited access, 2-lane highway) and estimated the parameters (Figure 6). The estimated QV function is shown as below.

\[
V(Q) = 60 \times (1/(V_f (1 + \alpha(Q/K)^\beta)))
\]  

(2)

Where:

V(Q): travel speed as a function of traffic volume

V_f: free flow speed

Q: hourly traffic volume

K: hourly traffic capacity

\( \alpha, \beta \): parameters

The estimated variables and parameters for the Kosei highway are \( V_f = 65, \ K = 800, \ \alpha = 0.15, \ \beta = 4. \)

Based on the QV function estimated as above, we now estimate the cost function of road as below.
RC(Q, L) = RDC(L) + Q h (D / V(Q))  \quad (3)

Where:

RC(Q, L): total cost function of road (yen/km/hour)

Q: hourly traffic volume

RDC(L): cost function of road development (construction, land acquisition and maintenance)

L: number of lanes

h: unit value of time

D: Length of tolled road

V(Q): travel speed as a function of traffic volume

Variables are set as RDC(L) = 66,000 * L, h = 3,772, and D = 10. Second, we estimated the (inverse) demand function, based on past studies, such as Small and Yan (2001). We assumed that the demand function has a linear shape as shown below.

\[ P(TD) = a - b \cdot TD \quad (4) \]

Where:

P: generalized cost for road users

TD: transportation demand
a, b: parameters (estimated using a = 5,000 and b = -3.75)

Although we have assumed that the demand curve would remain unchanged in the future, this assumption should be reconsidered in future studies, since the demand curve could change according to the infrastructure development level.

(Insert Figure 6)

We can now calculate toll with the SMCP theory, using the cost function and demand function estimated as above. For example, toll is set at 688 yen/10km in the first period, which is the difference of SSMC and SMPC, where SSMC intersects the demand curve. Out of the tolled 688 yen, 156 yen (difference between SSAC and SPMC) is the amount to be spent on maintenance, and 532 yen (difference between SSMC and SSAC) is spent on investment so as to increase road capacity.

(2) Calculation of costs in the simulation model

The cost of road is defined as cost for maintenance, land, and renewal in this model. The unit cost of maintenance is set as 4.1 million yen/km/year as presented in the Road Bureau and Urban and Rural

Second, the unit land cost is set at 8.5 million yen/km, as a result of the average of actual 11 general road works adapted in FY 2005 (average land purchase cost = 140 million yen/km) times typical ground rent (6%). Therefore, the land cost for each period is calculated as initial road capacity times unit land cost.

Third, the renewal cost is calculated on the assumption that the durability of road stock is 46 years (Cabinet office, (2002)) and therefore the capacity would be lost by one-forty sixth in every period, if without renewal. Hence, the necessary renewal cost for each period is calculated as the initial monetary value of road capacity times 1/46.

These three cost items are necessary for each period to keep the road capacity intact. The investment cost for increasing the road capacity is set at 287.5 million yen/km/lane. In other words 2,875 million yen is necessary to add a lane to this 10km section.

3.2 Simulation Results

Simulation results are summarized in figures 7 to 9.
In the first period, the toll is 688 yen (SSMC (1,441 yen) minus SMPC (753 yen)) and the traffic volume (number of tolled vehicles) is 949 vehicles/hour. From the second period onward, the SSMC, SMPC, and toll are all decreasing gradually, while the traffic volume is increasing gradually. Toll revenue is about 1 billion yen in the first period, but it rapidly decreases as the toll decreases (Figure 8).

When we consider the cost components, the maintenance and renewal costs are increasing gradually, while the investment cost is decreasing. As the investment cost decreases, additional lanes also decreases (0.1 lanes are added in the first period but fewer in the following periods). As a result of this simulation, the initial road capacity (1 lane for each direction (2-lane highway)) will grow by investments to 2 lanes for each direction in the 20th period. This is the optimal and convergent capacity of this road (Figure 9).
Since the purpose of this simulation was to theoretically derive the optimal road capacity, we adopted a “single-year” assumption; that is, “the yearly revenues are to be spent (invested) within the same year.” In practice, however, road administrators should decide the timing of investments, based on the yearly revenues from such pricing, in order to realize the theoretically derived optimal road capacity.

4. Conclusion

In this study, we proposed a new road planning scheme to build optimal road capacity through social marginal cost pricing (SMCP), by applying the concept introduced by Mohring (1976). 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 in the short term, the latter insists that the toll is optimal 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 mile-based social marginal cost pricing.

Furthermore, we ran a simulation based on the proposed model in order to see how the optimal toll and
road capacity would be realized throughout the periods. By applying the data obtained from the actual road works in Japan to the cost function of road construction/maintenance and cost function of time. The simulation results have given political indications for optimal point and periods of time for road investment on such tolled roads.

We recognize, however, that this model involves further issues to be solved. First, we need some more simulation analyses by applying other conditions, since the optimal road stock does not always converge with a certain level as shown in the simulation in this study. Second, we need additional and detailed examples of road cost, price elasticity of transportation demand, etc. so as to refine the exogenous variables. Finally, although we only examined the case of the demand curve as fixed, we also need to examine the appropriate financing and planning scheme for the cases where the transportation demand will change in the future.

References


beyond generations- , Tokyo (in Japanese).


Table 1. Cost Incidence Table (Cost Classification and Cost Burden)

<table>
<thead>
<tr>
<th>Cause of Generation</th>
<th>Cost Burden</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Internal Cost</td>
</tr>
<tr>
<td></td>
<td>Road Users</td>
</tr>
<tr>
<td>Vehicle Cost</td>
<td>−A</td>
</tr>
<tr>
<td>Construction and Maintenance Cost (lights, etc.)</td>
<td>−B</td>
</tr>
<tr>
<td>Environmental Destruction</td>
<td>−C</td>
</tr>
<tr>
<td>Vehicle Ownership Tax, etc.</td>
<td>−D</td>
</tr>
<tr>
<td>Travel Time Cost, Vehicle Operating, and Ownership Cost</td>
<td>−E</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Maintenance Cost</td>
<td>−F</td>
</tr>
<tr>
<td>(pavement, etc.)</td>
<td></td>
</tr>
<tr>
<td>Congestion, Air</td>
<td>−G</td>
</tr>
<tr>
<td>Pollution, and Noise</td>
<td></td>
</tr>
<tr>
<td>Fuel Tax, Mileage</td>
<td>−I</td>
</tr>
<tr>
<td>Tax, etc.</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>−(A+D+E+G+I)</td>
</tr>
</tbody>
</table>
Figure 1: Road costs before investment
Figure 2: Toll for road before investment
Figure 3: Road costs at optimal capacity
Figure 4: Toll for road at optimal capacity
Road capacity at the beginning of period (Lane number, road length)
*In this simulation: 1 lane(period 1st), 10km

Revenue
- Q-V formula
- Demand function
- Road infrastructure cost function
- Amount of pricing
- The number of vehicles

Costs
- Maintenance cost (4.1 million yen per lane-kilometer)
- Land cost (8.5 million yen per lane-kilometer)
- Road capacity depreciation (1/46 per year)
- Renewal cost (= Road capacity depreciation)

Difference between Revenue and Costs
- Revenue of pricing
- Costs for keeping the same road capacity

If revenue > costs: increasing road capacity
If revenue < costs: decreasing road capacity

Road capacity at the end of period (Lane number, road length)

Figure 5: Framework of the optimal capacity building simulation
Figure 6: QV function of Kosei Highway
Figure 7: Toll and traffic volume for each period
Figure 8: Use of the toll revenue for each period

Figure 9: Total number of lanes and added lanes in each period
Double-spaced list of figure captions

Table 1. Cost Incidence Table (Cost Classification and Cost Burden)

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Figure 4: Toll for road at optimal capacity

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