Joint Provision of Transportation Infrastructure

Se-il Mun

Graduate School of Economics, Kyoto University,

Yoshida Hon-machi, Sakyo-ku, Kyoto 606-8501, Japan

mun@econ.kyoto-u.ac.jp

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Abstract

This paper considers the following scheme for the joint provision of transportation infrastructure: two regions jointly establish an operator for the infrastructure who is then responsible for collecting the user charges. The two regions make financial contributions to cover the costs of the infrastructure investment, and the revenue from user charges is distributed according to the share of contribution. The governments of the two regions choose the contribution that maximizes their regional welfare. Assuming that the infrastructure use is non-rival, we show that financing the infrastructure with revenue from user charges is better than financing it with tax revenue. We extend the analysis by incorporating congestion in infrastructure use. We show that independent decisions on contributions by two governments attain the first-best optimum when the operator sets the user charge such that the toll revenue just covers the cost of the investment. We further examine the conditions under which two governments participate in joint provision at Nash equilibrium.

Keywords: transportation infrastructure, joint provision, congestion, self-financing
JEL Classification: H54, H77, L91, R41, R48

1 Introduction

This paper concerns the transportation infrastructure that is provided locally but may serve users from multiple jurisdictions. There are a number of such cases in the real world: bridges and tunnels crossing borders between cities, regions or countries; ports and airports serving users from the areas without those facilities, etc. This paper considers the following scheme for the joint provision of transportation infrastructure: two regions jointly establish an operator for the infrastructure who is responsible for collecting the user charges. The two regions make financial contributions to cover the costs of the infrastructure investment, and the revenue from user charges is distributed according to the share of contribution. Similar practices are found in the real world. For example, the United States and Canada jointly established the Niagara Falls Bridge Commission to finance, construct, and operate the Rainbow Bridge. The Port Authority of New York and New Jersey is a joint venture between two states to build, operate, and maintain transportation infrastructure throughout the region[1]. Other than transportation, there are many voluntary arrangements of cooperation by local governments for public services (e.g., water supply, education, police, and waste), and joint ventures for regional development (e.g., site development for industrial parks)[2]. Our scheme is applicable to various types of infrastructure that involves user charges.

We examine the performance of joint provision using a simple two-region model in which the transportation demand depends on the capacity and the user charges (e.g., road tolls) of the infrastructure. The government of each region chooses the amount of contribution that maximizes its regional welfare. The sum of the contributions by two regions is spent on investment, thereby determining the capacity of the infrastructure. We consider two cases: first, the infrastructure use is non-rival; second, the infrastructure is congestible. In the non-rival case, a standard result is that the optimal user charge is zero. However, setting a positive level of user charge improves welfare since it encourages contributions from the two governments. We further show that joint provision leads to under- or over-investment in capacity if the revenue is smaller (or greater) than the cost of investment. In the case of congestible infrastructure, joint provision attains the first-best optimum when the operator sets the user charge such that the toll revenue just covers the cost of investment. This is an extension of the well-known self-financing theorem by Mohring-Harwitz (1962). Unlike the original setting in which a single government chooses the capacity based on a benefit-cost criterion, we obtain the result when the capacity is determined by non-cooperative contributions from multiple governments. In this sense, our study is closely related to Brueckner (2015) and De Borger and Proost (2016)[3].

The structure of the problem addressed in this paper is similar to that in the literature on voluntary provision of public goods (Bergstrom, Blume, and Varian (1986)); Cornes and

[1] The port authority receives no financial contribution from governments. This scheme can be considered the case of break-even pricing discussed in this paper, in which there is no net spending for the governments.

[2] See, e.g.,Feiock, Steinacker and Park (2009), Hawkins (2010).

[3] A detailed discussion on the link with Brueckner (2015) and De Borger and Proost (2016) is given in Section 4.

Sandler (1996); Andreoni (1998); and Batina and Ihori (2005)). Unlike public goods, transportation infrastructures collect user charges, such as road tolls. If users are not charged for the use of infrastructure, our formula for determining the capacity of the infrastructure is equivalent to the formula for voluntary provision of public goods, leading to under-provision. There have been several proposals to induce efficient voluntary provision of public goods (e.g., Falkinger (1996), Morgan (2000), and Zubrickas (2014)). The present paper introduces charging users and using the revenue to reward the contribution of each region[4]. We show that user charging gives an incentive to increase the amount of voluntary contribution and results in greater welfare in the case of non-rivalry. Furthermore, if the infrastructure is congestible, joint provision can attain the optimal level of capacity through voluntary contributions.

There is a large body of literature on the pricing and capacity choice of transportation infrastructure in the system of multiple governments (e.g., the review by De Borger and Proost (2012)). Bond (2006) shows that independent decision-making by governments leads to under-investment of infrastructure, and examines the effects of trade liberalization on the incentive to invest. Mun and Nakagawa (2010) consider cross-border transportation infrastructure that consists of two links, each of which is constructed and operated by the government of its territory. They evaluate the effects of alternative pricing and investment policies for the infrastructure on the economic welfare of the two regions. Recently, Xiao, Fu and Zhang (2016), and Verhoef (2017) discuss similar problems to ours in that small number of agents contribute to capacity investment[5]. Xiao et al consider the situation that competing airlines contribute to capacity investments and share airport revenues. Although the model in Xiao et al incorporates demand uncertainty, the contribution share is treated as an exogenously given parameter. Verhoef (2017) is more closely related to ours in that the amount of contributions is endogenous and the self-financing of optimal capacity result is obtained. His result is strong in that self-financing holds in broader situations in which capacity cost does not exhibit constant returns. Note that government subsidy is required to attain efficiency and self-financing in Verhoef's model. By contrast, the scheme proposed in this paper does not require intervention from a higher level of government, which is particularly useful in the case of international infrastructure for which higher level government does not exist, as in the example of Niagara Falls Bridge. No earlier study deals with the decision whether to participate in the joint provision of transportation infrastructure.

The rest of this paper is organized as follows. Section 2 presents the model setting and describes the problem to be considered. In Sections 3 and 4, we examine the outcome of joint provision for non-rival and congestible cases, respectively. Section 5 investigates whether two governments would choose to participate in joint provision. Section 6 concludes the paper.

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[4] In the absence of congestion, the service provided by the infrastructure is considered excludable but non-rival. Excludable public goods can be provided by private firms. For example, Oakland (1974) and Brito and Oakland (1980) consider this problem in cases of perfectly competitive and also monopolistic markets. They suggest that the market provision of excludable public goods does not attain an efficient allocation, and under-provision is likely.

[5] Agents are, firms with market power in Xiao, Fu and Zhang (2016), and Verhoef (2017), and regional governments in our paper.

2 Basic Setting

2.1 The model

Consider an economy with two regions, indexed by i ($i = 1, 2$). In each region, there is demand for transportation, using infrastructure. The demand depends on the infrastructure charge and user cost. Transportation demand originating in region i is described by function, $D_i(p)$, where p is the full price of transportation per trip[6]. p is the sum of the infrastructure charge, f (such as road toll), and the user cost, $C(x, k)$ that depends on the traffic volume, x, and capacity of the infrastructure, k. Traffic volume is the sum of trips originating from the two regions, i.e., $x = x_1 + x_2$. We assume that both the demand function and user cost function are differentiable, and have the following properties: $D_i' \equiv dD_i/dp < 0, C_x \equiv \partial C/\partial x \geq 0$, $C_k \equiv \partial C/\partial k < 0, C_{xx} \equiv \partial^2 C/\partial x^2 \geq 0, C_{kk} \equiv \partial^2 C/\partial k^2 > 0$. Time is the major part of user cost in transportation. The case of $C_x > 0$ implies that the infrastructure is congestible. On the other hand, $C_x = 0$ implies the case of non-rival infrastructure. $C_k < 0$ means that larger capacity reduces the user cost for transportation. A typical example of the capacity expansion effect is time saving by mitigating congestion. We define capacity in a broader sense, such that k may represent the quality of service. Even without congestion, i.e., non-rival case, capacity expansion reduces the user cost; for example, better quality of pavement, less steep road design could increase the speed of transportation or reduce the damage to cargo.

The number of trips from region $i, (i = 1, 2)$ is determined such that

$$x_i = D_i(f + C(x, k)). \tag{1}$$

Differentiation of (1) yields the followings:

$$\frac{\partial x_i}{\partial f} = \frac{D_i'}{[1 - (D_1' + D_2')\, C_x]} < 0 \tag{2}$$

$$\frac{\partial x_i}{\partial k} = \frac{D_i' C_k}{[1 - (D_1' + D_2')\, C_x]} > 0 \tag{3}$$

Our formulation allows for various applications: the infrastructure located on the border between two regions (e.g., bridges, tunnels); or infrastructure located in one of two regions (e.g., port, airport). In the former type, the infrastructure serves cross-border transportation between the two regions, and in the latter type, the infrastructure serves transportation demand originating from the two regions to the rest of the world.

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[6] Measuring by the number of trips is naturally applicable to passenger transportation, such as in tourism and shopping. In the case of freight transportation, the quantity (e.g., weight of goods) is the usual unit of measurement; however, hereafter, we use trips as the unit of measurement.

2.2 Social optimum

The social optimum is defined as a vector (f, k) that maximizes the social welfare function, as follows:

$$W(f,k) = \int_{f+C(x,k)}^{\infty} D_1(p)\,dp + \int_{f+C(x,k)}^{\infty} D_2(p)\,dp + \Pi \tag{4}$$

where Π is the profit of the infrastructure project, $\Pi = fx - p^k k$, and p^k is the unit cost of infrastructure capacity. The linearity of the capacity cost means that there is no scale economy in capacity investment. In addition, this formulation implies that the marginal cost of infrastructure operation with respect to traffic is set to zero.

The conditions for social welfare maximization (first-best) are as follows:

$$f = xC_x \tag{5}$$

$$-xC_k = p^k \tag{6}$$

These two conditions are standard formulas for pricing and investment of transportation infrastructure. (5) is the optimal pricing rule: the infrastructure charge should be chosen such that each user incurs the social marginal cost. Note that $f = 0$ is optimal if the infrastructure is non-rival. The left-hand side of (6) is the transport cost savings from increasing the capacity, $-C_k$, multiplied by the number of users, x. Thus, it represents the social marginal benefit. The right-hand side is the marginal cost of increasing the capacity. (6) is equivalent to the benefit-cost rule for the transportation project, according to which the social marginal benefit from capacity expansion should equal to the marginal cost of investment. Furthermore, (6) has the same formal structure as Samuelson's condition for optimal public goods provision.

2.3 Joint provision of transportation infrastructure

Under joint provision, two regions jointly establish an operator of the infrastructure, which constructs the facility and collects the user charge. The costs of infrastructure investment are covered by financial contributions from the two regions. And the revenue from the infrastructure charge is shared according to the contribution made. For the joint provision to be realized, the two governments should agree on the scheme described above. It is the governments' decision whether to participate in the joint provision.

We consider the following two-stage game: 1) each of two governments chooses whether to participate in the joint provision of the infrastructure; 2) user charge and capacity are determined by the decisions of three agents – two regional governments and the operator.

In the first stage, the government compares the outcome of the joint provision with that of the alternative form. We choose single provision as an alternative form. Single provision is conventional in that the regional government provides its own infrastructure and bears all costs alone (Brueckner (2015), De Borger and Proost (2016)). Participation to the joint provision implies there is agreement on the tasks that the operator should perform, among which pricing policy is essential. The pricing policy is a rule that the operator should follow in setting the level of infrastructure charge (e.g., profit maximization, marginal cost pricing, or break-even rule).

In the second stage, each of the two governments chooses the amount of financial contribution, and the operator sets the level of user charge. The sum of contributions from the two governments determines the capacity of the infrastructure. The operator sets the level of user charge following the pricing policy that is specified by the agreement among the governments at the first stage. In this sense, the operator is a kind of "Special Purpose Vehicle" that is supposed to perform the task given by the governments. We assume that there is no price discrimination: user charge is the same regardless of users' location. This assumption is justifiable because there are legal restrictions, as described by Czerny, Hoeffler and Mun (2014) in the context of port pricing. The operator takes the financial contributions by two governments as given. On the other hand, each of two governments takes into account the response of the operator in its choice of contribution.

The two-stage game is solved backward. Sections 3 and 4 investigate the second-stage outcomes under joint provision for non-rival and congestible cases, respectively. The first-stage problem is analyzed in Section 5.

3 Joint Provision of Non-rival Infrastructure

3.1 User charge and decisions of regional governments

In the case of non-rival infrastructure, the user cost does not depend on the traffic level. Thus, we denote the user cost function for non-rival infrastructure by $C(0,k)$.

In this subsection, we first look at how user charging affects the contribution decisions of regional governments by treating the user charge as a parameter[7]. Each regional government chooses the level of financial contribution to maximize the regional welfare. The regional welfare in region i is defined as the sum of users' welfare and the dividend of the revenue minus the expenditure for financial contribution, as follows:

$$W_i = \int_{f+C(0,k)}^{\infty} D_i\,(p)\,dp + \frac{k_i}{k} fx - p^k k_i \tag{7}$$

where k_i is the amount of financial contribution from region i [8]. $k_1 + k_2 = k$ should hold.

The government of each region takes the infrastructure charge as given, and chooses the amount of financial contribution k_i so as to maximize regional welfare defined by (7). The

[7] As described in the previous section, regional governments should take into account the effect of their investment decisions on the operator's pricing behavior. So we later treat the user charge as a function of capacity.

[8] We also use the following expression for regional welfare,

$$W_i = \int_{f+c(0,k)}^{\infty} D_i\,(p)\,dp + \frac{k_i}{k}\Pi$$

The second term on the right hand side, $\frac{k_i}{k}\Pi$ is the dividend of profit.

optimality condition for the government of region i is

$$-x_i C_k + \frac{k_j}{k^2} f x + \frac{k_i}{k} f \frac{\partial x}{\partial k} = p^k, \qquad j \neq i \tag{8}$$

where $\frac{\partial x}{\partial k} \equiv \frac{\partial x_1}{\partial k} + \frac{\partial x_2}{\partial k} > 0$. The first term on the left-hand side of (8) is the marginal benefit of users in the home region, and the second and third terms are the effects on the dividend through changes in the share of contribution and in capacity, respectively. For the special case, $f = 0$, (8) is reduced to

$$-x_i C_k = p^k \tag{9}$$

Comparing (9) with (6), we see that the regional government ignores the benefit of the users in the other region, which leads to too small capacity. This discrepancy is essentially the same as that between voluntary provision and optimal provision of public good (Cornes and Sandler (1996), Batina and Ihori (2005)).

As shown earlier, $f = 0$ is the optimal pricing policy in the non-rival case. This implies that the first-best optimum is never achieved under the decisions of the regional government.

Let us examine the effects of varying the level of infrastructure charge on the contributions and the level of economic welfare. Summing up the investment rule (8) for two regions yields

$$-x C_k + \frac{1}{k} f x + f \frac{\partial x}{\partial k} = 2p^k \tag{10}$$

Let the solution of (10) for k be $K^J(f)$. Totally differentiating (10) with respect to k and f , evaluated at $f = 0$, we obtain the following:

$$\left.\frac{dk}{df}\right|_{f=0} = \frac{dK^J(0)}{df} = \frac{\frac{1}{k} x}{x C_{kk} + \frac{\partial x}{\partial k} C_k} \tag{11}$$

The denominator of the RHS of (11) is positive from the second-order condition for (8). Thus we have $\frac{dK^J(0)}{df} > 0$: k is increased by increasing f from zero. Differentiating the social welfare function (4) with respect to f while k is determined by $k = K^J(f)$, we have the following:

$$\frac{dW(0, K^J(0))}{df} = p^k \frac{dK^J(0)}{df} > 0$$

The above analysis is summarized as follows.

Proposition 1 *Increasing the infrastructure charge from zero improves social welfare by encouraging capacity investment of the infrastructure.*

If the infrastructure charge is zero, the regional government should use tax revenue to finance the contribution to the infrastructure project. Also note that the optimal infrastructure charge is zero in the non-rival case, so increasing the infratructure charge from zero means a deviation from optimal pricing. The above proposition implies that shifting the revenue source from taxes to user charges, in other words, a deviation from optimal pricing, improves welfare.

For the subsequent analysis, we investigate the socially optimal capacity choice when the infrastructure charge, f, is fixed. The condition to maximize social welfare, (4), with respect to k, incorporating $C_x = 0$, is

$$-xC_k + f\frac{\partial x}{\partial k} = p^k \tag{12}$$

Let the solution of (12) be $K^O(f)$. Differentiating the social welfare function (4) with respect to f at $k = K^O(f)$, we have the following:

$$\frac{dW(f, K^O(f))}{df} = f\frac{\partial x}{\partial f} < 0 \tag{13}$$

where $\frac{\partial x}{\partial f} \equiv \frac{\partial x_1}{\partial f} + \frac{\partial x_2}{\partial f} < 0$. The above inequality (13) is consistent with the result that the social welfare is maximized at $f = 0$ while the capacity is determined by (12).

We examine the efficiency of capacity choice under joint provision for various levels of user charges. This could address the question: what does an efficient infrastructure charge look like under joint provision based on voluntary contributions by the regional governments? In the following, we assume that the operation of the infrastructure is profitable[9].

Proposition 2 *Assume that the operation of the infrastructure is profitable.*

(i)Capacity determined by contributions from two regional governments is socially optimal if the user charge is equal to $\widehat{f}$ *, at which the profit of the infrastructure operation is break even;*

(ii) The capacity under joint provision is smaller (resp. larger) than the optimal if the user charge is smaller (resp. larger) than $\widehat{f}$ *.*

(iii) There exists an infrastructure charge f^**, at which social welfare is maximized under joint provision;*

(iv) f^* *is smaller than* $\widehat{f}$*.*

Proof. (i) From the assumption that the operation of the infrastructure is profitable, there exists a user charge, $\overline{f}$, at which $\Pi > 0$. Let $\widehat{f}$, be the break-even user charge, at which $\Pi = 0$. From the intermediate value theorem, $\widehat{f}$ should exist in $[0, \overline{f}]$, since $\Pi < 0$ at $f = 0$, and $\Pi > 0$ at $\overline{f}$. (10) is rewritten as follows:

$$-xC_k + \frac{1}{k}\Pi + f\frac{\partial x}{\partial k} = p^k \tag{14}$$

The above equation is reduced to (12) at $f = \widehat{f}$ where $\Pi = 0$. Thus $K^J(\widehat{f}) = K^O(\widehat{f})$; thereby $W(\widehat{f}, K^J(\widehat{f})) = W(\widehat{f}, K^O(\widehat{f}))$.

[9] In other words, there exists a range of user charges, in which the profit is positive.

(ii) From the result of (i), Π is negative in $[0,\, \widehat{f})$, and positive in $(\widehat{f},\, \overline{f}\,]$. It follows that $\Pi \lesseqqgtr 0 \iff f \lesseqqgtr \widehat{f}$. If $\Pi > 0$, the LHS of (14) is larger than the LHS of (12) thereby $K^J(f) < K^O(f)$ and vice versa.

(iii)(iv) We know $\frac{dW(0,K^J(0))}{df} > 0$ from Proposition 1, and $\frac{dW(\widehat{f},K^J(\widehat{f}))}{df} = \frac{dW(\widehat{f},K^O(\widehat{f}))}{df} < 0$ from (13). Thus there must be $f^*, 0 < f^* < \widehat{f}$, where $\frac{dW(f^*,K^J(f^*))}{df} = 0$. ■

We explain the results of Propositions 1 and 2 using Figure 1. $W(f, K^O(f))$ and $W(f, K^J(f))$ in the figure are loci of social welfare when capacity is determined optimally and by joint provision, respectively. As Proposition 1 states, social welfare under joint provision is increased by increasing f from zero. From (13), the optimal value function $W(f, K^O(f))$ decreases with f, so the first-best optimum is attained at $f = 0$. These two curves touch at $f = \widehat{f}$ where the revenue just covers the cost of investment ((i) of Proposition 2). In addition, we observe that there exists a point f^* where social welfare under joint provision is maximized ((iii) of Proposition 2). This point can be regarded as the second-best[10].

From (ii) and (iv) of Proposition 2, the revenue from the infrastructure charge at f^* is not sufficient to cover the cost of investment. This result, together with (i), implies that break-even pricing is the most efficient among the schemes in which capacity investment is financed solely by the revenue from the infrastructure charges. In addition, (ii) of Proposition 2 implies that over-investment of capacity could arise if the infrastructure charge is larger than $\widehat{f}$. This result never arises in earlier studies, such as Mun and Nakagawa (2010), who examine a number of alternative pricing schemes for cross-border transportation infrastructure consisting of two links, but they all result in under-investment.

3.2 Equilibrium with break-even pricing

Equilibrium user charge and capacity are determined by the strategic interaction among three players, i.e., two regional governments and the operator. The two governments choose the contribution level, as described in the previous subsection. The operator sets the level of infrastructure charge according to the pricing policy. We assume that the two governments agree to adopt break-even pricing. We focus on this case because the break-even pricing rule is widely adopted in practice in provision of public utilities, including transportation. Another good reason is that break-even pricing attains an efficient outcome, as shown in

[10] f^* maximizes $W(f, K^J(f))$. The optimality condition, $\frac{dW(f,K^J(f))}{df} = 0$, is written as

$$f\frac{\partial x}{\partial f} + \left[-xC_k + f\frac{\partial x}{\partial k} - p^k\right]\frac{dK^J}{df} = 0$$

The first term is negative, and is the direct effect of the user charge that reduces the transportation demand. The second term is positive, and is an indirect effect through encouraging capacity investment. The second-best is characterized by the trade off of these negative and positive effects on global welfare.

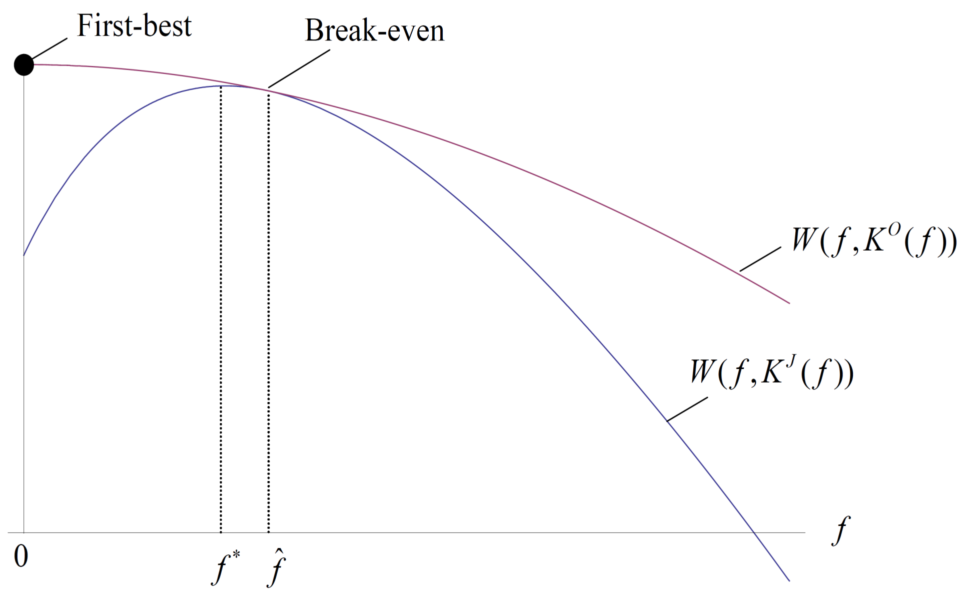

Figure 1 Infrastructure charge and global welfare

Proposition 2[11]. To enforce the break-even pricing, the governments may use an auction to select the operator that offers the lowest user charge, conditional on the amount of contributions. In this case, competitive bidding would eliminate positive profit, thereby lead to the break-even user charge.

The operator sets the level of infrastructure charge such that the revenue equals the cost of investment, taking the contributions from two governments as a given. Let us denote by $F(k)$ the response function of the operator, which is obtained by solving the following equation for f

$$fx - p^k k = 0$$

The governments consider the user charge as a function of its contribution. So the objective function of a regional government is redefined by replacing f in (7) with $F(k)$, as follows

$$W_i = \int_{F(k)+C(0,k)}^{\infty} D_i(p)\, dp + \frac{k_i}{k} F(k)x - p^k k_i$$

The government of region i chooses k_i to maximize W_i . k_i is a solution of the following

[11]Proposition 2 shows that the break-even pricing is the third-best: there is the second-best infrastructure charge, f^*. However the profit of the infrastructure project is negative under the second-best pricing. Another advantage of break-even pricing is that implementation is much easier. On the other hand, finding the second-best charge would be difficult in practice.

equation.

$$-x_i\left(F_k+C_k\right)+\frac{k_j}{k^2}F(k)x+\frac{k_i}{k}\left(xF_k+F(k)\frac{\partial x}{\partial k}\right)=p^k, \quad j\neq i \tag{15}$$

where F_k is the derivative of $F(k)$. Summing up the above expression for two regions and incorporating the break-even condition yields[12]

$$-xC_k+F(k)\frac{\partial x}{\partial k}=p^k \tag{16}$$

The above expression is equivalent to (12) with $f=F(k)$. Thus we have the following proposition.

Proposition 3 *Capacity of non-rival infrastructure is efficient under joint provision with break-even pricing.*

Proposition 3 states that only the rule to determine capacity is efficient. So the outcome is not the first-best since the pricing rule is different from the optimal rule for non-rival infrastructure, i.e., $f=0$. Other than the break-even policy, we can also consider various pricing policies by specifying the behavioral rule that determines the form of $F(k)$.

4 Congestible Infrastructure

We assume constant returns to scale in congestion technology. In this case, the user cost function is homogeneous of degree zero in volume and capacity, and thereby $C_x x+C_k k=0$ holds from Euler's theorem.

The conditions for social welfare maximization (first-best) are (5) (6) as shown in Section 2.

Under the scheme of joint provision by the two governments, each government chooses the amount of contribution to maximize regional welfare.

$$W_i=\int_{F(k)+C(x,k)}^{\infty}D_i\left(p\right)dp+\frac{k_i}{k}F(k)x-p^k k_i \tag{17}$$

The optimality condition for the government of region i is:

$$-x_i\left(F_k+C_x\frac{\partial x}{\partial k}+C_k\right)+\frac{k_j}{k^2}F(k)x+\frac{k_i}{k}\left(F(k)\frac{\partial x}{\partial k}+xF_k\right)=p^k, \quad j\neq i \tag{18}$$

Summing up the investment rule (18) for the two regions and rearranging it, we have the following:

$$-xC_k+\left(F(k)-xC_x\right)\frac{\partial x}{\partial k}+\frac{F(k)x}{k}=2p^k \tag{19}$$

[12]Note that the terms with F_k are canceled out. This implies that functional form of $F(k)$ does not affect the rule to determine capacity.

Substituting the conditions of break-even pricing and the constant returns in congestion technology into the above equation, we obtain the following[13]:

$$\left(1 - \frac{\partial x}{\partial k}\frac{k}{x}\right)\left(C_k x + p^k\right) = 0 \tag{20}$$

The above equality holds when the condition for optimal capacity, (6) holds. And zero profit together with optimal capacity leads to (5), the optimal pricing rule. Thus, we have the following proposition.

Proposition 4 *With break-even pricing, joint provision of congestible infrastructure attains the first-best charge and capacity.*

The above proposition shows that the self-financing theorem of Mohring-Harwitz (1962) can be extended to the case in which capacity is determined in a decentralized way. Brueckner (2015) and De Borger and Proost (2016) also show that the self-financing result is obtained by decentralized decision making of local governments. Brueckner considers a bridge between jurisdictions in a monocentric metropolitan area. He assumes that the capacity of a bridge is determined solely by the government of jurisdiction on the outer side[14]. In this setting, Brueckner shows that decentralized capacity choice with a budget-balancing user charge attains an efficient allocation. De Borger and Proost obtain similar result for a situation in which two governments provide two facilities, each in its own territory. In both papers, the decisions on pricing and capacity choice are made by a single government. By contrast, we consider a different situation in which a single facility is jointly provided by two governments. In this case, the two governments share the cost of the capacity investment. To see this point, refer to the decision rule of an individual government, (18), which is quite different from the optimal rule. The sum of the decisions by the two governments, (19), turns out to be consistent with the optimal one. This is different from Brueckner (2015) and De Borger and Proost (2016), in which the decision rule of a single government becomes the optimal.

5 Participation in Joint Provision

This section examines the incentives for the two governments to join the infrastructure project. There are several alternative ways to provide the infrastructure. One common alternative to joint provision is for only one of the two regions to build and operate the

[13] Recall that $C_x x = -C_k k$ holds from the constant returns to scale in congestion technology. And $F(k) = \frac{p^k k}{x}$ from the break-even condition. Substituting these expressions into (19) we obtain the following

$$-C_k x + \left(\frac{p^k k}{x} + C_k k\right)\frac{\partial x}{\partial k} - p^k = 0$$

Rearranging terms in the above expression yields (20).

[14] This assumption is reasonable in the context of a monocentric metropolitan area since a bridge is used only by residents in outer locations.

transportation infrastructure. Hereafter, we call this case “single provision.” Brueckner (2015) considers exactly this situation: a bridge between jurisdictions of a mid-city and central areas is built by the government of the mid-city.

This section examines whether joint provision is realized by the decisions of two governments seeking to maximize regional welfare. Each government chooses whether to participate in joint provision by comparing regional welfare for alternative choices[15]. There are four possible combinations of choices by the two regional governments: case YY (joint provision) in which both regions participate in joint provision; case NN in which no region commits to the infrastructure; case YN (single provision by region 1) in which region 1 builds the infrastructure individually; and case NY (single provision by region 2) in which region 2 builds the infrastructure individually. Let us denote the regional welfare of region i for the four cases by $W_i^{YY}, W_i^{NN}, W_i^{YN}, W_i^{NY}$, respectively.

The conditions under which joint provision is Nash equilibrium are as follows

$$W_1^{YY} > W_1^{NY} \text{ and } W_2^{YY} > W_2^{YN}$$

Throughout this section, we assume that the break-even pricing is adopted under the joint provision, case YY.

5.1 Non-rival case

When the infrastructure use is non-rival, W_i^{YY} is obtained by substituting into (7) the capacity obtained in Section 3. In cases YN or NY, the infrastructure charge and capacity are determined by the decision of the government that implements the infrastructure project. Without loss of generality, we consider the case YN in which region 1 provides the infrastructure. The problem to be solved by the government of region 1 is[16]

$$\max_{f,k} \int_{f+C(0,k)}^{\infty} D_1(p)\,dp + fx - p^k k \tag{21}$$

The optimality conditions with respect to the user charge and capacity of the infrastructure are

$$x_2 + f\frac{\partial x}{\partial f} = 0 \tag{22}$$

$$-x_1 C_k + f\frac{\partial x}{\partial k} = p^k \tag{23}$$

[15]The problem discussed in this section is similar to the voluntary participation of public goods provision (Saijo and Yamato (1999) ; Furusawa and Konishi (2011)). The difference is that the infrastructure use is excludable.

[16]In the case of single provision, the regional government can totally control the operation of the infrastructure. Thus, we assume that the government determines the user charge and the capacity of the infrastructure. On the other hand, in the case of joint provision, no single government can choose the level of infrastructure charge by itself.

respectively.

(22) is rewritten as $f = -x_2 / \frac{\partial x}{\partial f}$. In words, the user charge is positive, and higher than the efficient level (i.e., zero). $-x_2 / \frac{\partial x}{\partial f}$ is the mark-up to exploit users from other region, i.e., the region 2. Substituting (22) to (23), and using the relation, $\frac{\partial x}{\partial k} = C_k \frac{\partial x}{\partial f}$ from (2) and (3), we have $-xC_k = p^k$. In words, the investment rule is consistent with the benefit-cost rule. We denote the solution of the above equation by (f^{YN}, k^{YN}). Substituting (f^{YN}, k^{YN}) into the objective function in (21) we have W_1^{YN}. In addition, we obtain $W_2^{YN} = \int_{f^{YN}+C(0,k^{YN})}^{\infty} D_2(p)\, dp$. Under case NY(single provision by region 2), W_1^{NY} and W_2^{NY} are obtained likewise.

In the non-rival case, either joint provision or single provision can be realized in equilibrium. To see this, we provide the following example:

Example 1 *Suppose that break-even pricing is adopted in the case of joint provision. We specify the forms of the demand function and user cost function as follows:*

$$D_i(p) = A_i \exp\left[-\alpha p\right] \tag{24}$$

$$C(0,k) = -\beta \ln k, \tag{25}$$

where A_i, α, and β are parameters[17]. *Under the above specifications, joint provision is Nash equilibrium if the following inequality holds (see Appendix A for details of the derivation),*

$$\frac{\alpha\beta}{1-\alpha\beta} + \alpha\beta \ln(1-\alpha\beta) < s \tag{26}$$

where $s \equiv \min\{\frac{A_1}{A_1+A_2}, \frac{A_2}{A_1+A_2}\}$, which is the share of demand from the smaller region.

The condition for joint provision, (26), depends on s and $\alpha\beta$. Note that $\alpha\beta$ is equal to the demand elasticity with respect to capacity, k. Figure 2 illustrates the condition on the $s-$ $\alpha\beta$ plane. We observe that joint provision is more likely when the demand sizes of the two regions are symmetric and the transportation demand is less sensitive to the capacity of the infrastructure. In the special case in which the two regions are symmetric, $s = 0.5$, the inequality (26) is approximately equivalent to $\alpha\beta < 0.4227$. Joint provision is unlikely when two regions are asymmetric. In the very asymmetric case, $s = 0.1$, joint provision is realized if $\alpha\beta < 0.0994$. According to the calibration by Mun and Nakagawa (2010), $\alpha\beta = 0.0499$. In other words, joint provision is realized even in this very asymmetric case[18].

From the above discussion, we have the following proposition.

Proposition 5 *If the infrastructure is non-rival, either joint provision or single provision may be realized in equilibrium.*

[17] A_i represents the demand size of region i.

[18] The details of the calibration are provided in the working paper version, which is downloadable from http://www.econ.kyoto-u.ac.jp/~mun/papers/Pricing_and_investment091006.pdf

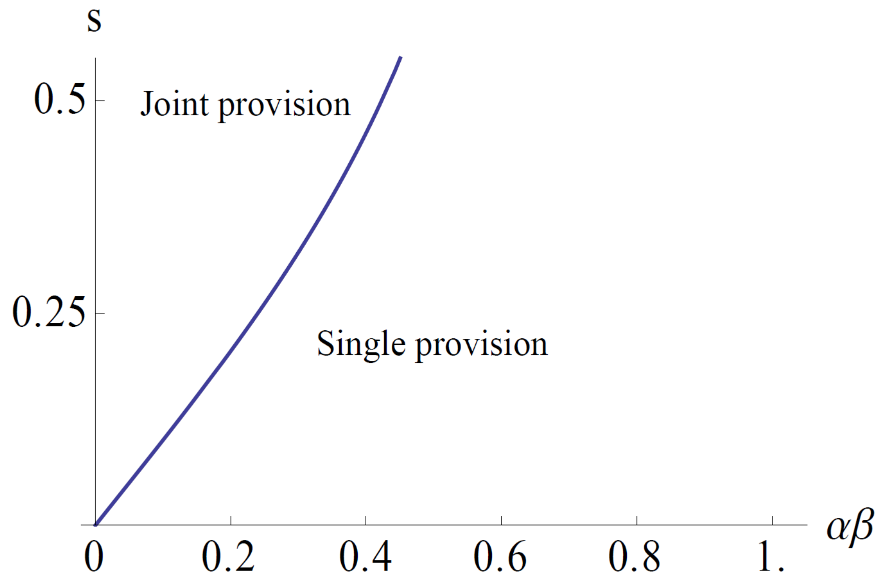

Figure 2 Parameter region of joint provision

5.2 Congestible Case

As in the previous subsection, we compare the outcomes of cases YY and YN. The former is obtained in the Section 4. For case YN (single provision by region 1), the regional government solves the following problem:

$$\max_{f,k} \int_{f+C(x,k)}^{\infty} D_1(p)\,dp + fx - p^k k \tag{27}$$

The optimality conditions with respect to the user charge and capacity of the infrastructure are

$$f = C_x x - \frac{x_2}{\frac{\partial x}{\partial f}} \tag{28}$$

$$-xC_k = p^k \tag{29}$$

respectively. The first term on the RHS of (28) is the congestion externality, and the second term is the mark-up, so the user charge in the case of single provision is higher than the optimal level[19]. The investment rule (29) is the same as in the social optimum, (6). However, owing to the excessively high user charge, the capacity under single provision is smaller than that in the social optimum.

[19] As shown by Proposition 4, joint provision with break-even pricing is the first-best, in which the infrastructure charge equals the congestion externality.

We then have the following result.

Proposition 6 *With break-even pricing, joint provision is a Nash equilibrium.*

Proof. See Appendix B. ■

Consider the choice of region 1 between cases YY and NY. In both cases, region 1 does not obtain any profit, so the welfare of region 1 equals the users' benefit, which depends solely on the full price of transportation, $f + C(x, k)$ [20]. Under case NY, users in region 1 incur a higher full price than they do under case YY, since the user charge is higher and the capacity is smaller. Thus, region 1 is better off by choosing joint provision.

Proposition 6 is based on the hypothesis that, under single provision, the regional government should choose the infrastructure charge that maximizes local welfare. Such rational choice results in positive profit to the region. However, as discussed in Subsection 3.2, break-even pricing is widely adopted in practice, since it is simple to implement and easily obtains public acceptance. Earlier studies, such as Brueckner (2015), and De Borger and Proost (2016), also suppose break-even pricing under single provision, even though it is not the optimal pricing policy for the region. Thus, it is worthwhile to examine single provision with break-even pricing and we obtain the following result.

Proposition 7 *If break-even pricing is adopted in both joint provision and single provision of congestible infrastructure, the two cases yield the same outcome, and they attain the first-best optimum.*

Proof. See Appendix C. ■

The optimality of capacity choice under single provision with break-even pricing is shown by Brueckner (2015) and De Borger and Proost (2016) as discussed earlier. We confirm that this result holds in the context of our model. Combining this result together with Proposition 4 yields Proposition 7. Given the equivalence of single provision and joint provision, it may follow that the regions would not undertake joint provision. Joint provision would incur transaction cost in the process of reaching agreement on the design of the facility, pricing policy, organization of the operator, and other such concerns[21]. Note that the equivalence of the two cases is true only if break-even pricing is adopted. The question is whether the government actually chooses break-even pricing that is not optimal to maximize regional welfare, as shown by Proposition 6. For the single provision with break-even pricing to be realized, there must be the other social or political factors that offset the loss of profit opportunity.

[20] In the case YY, profit is equal to zero since break-even pricing is adopted. In the case NY, region 1 is not involved in the infrastructure provision, so it has no profit.

[21] Feiock, Steinacker and Park (2009) and Hawkins (2010) investigate the effect of transaction cost on the decision to establish the joint venture with other local governments.

6 Conclusion

This paper investigates the performance of a scheme for joint provision of a transportation infrastructure facility that benefits users from multiple jurisdictions. We find that decentralized contributions by two regions might lead to an efficient level of transportation infrastructure. The dividend of revenue from infrastructure charge plays an essential role in inducing the governments to provide efficient levels of contributions. In particular, joint provision with break-even pricing attains the first-best optimum in the case of congestible infrastructure. This is an extension of the self-financing theorem of Mohring and Harwitz to a situation in which capacity is determined by non-cooperative decisions of multiple governments. We further examine whether the governments would participate in joint provision by analyzing the choice between joint provision and single provision. In a non-rival case, either joint provision or single provision can be realized in equilibrium. On the other hand, joint provision with break-even pricing is always Nash equilibrium when the infrastructure is congestible.

There are several topics for future research. First, in the non-rival case, joint provision does not attain the first-best outcome although it improves efficiency. This is because joint provision requires positive user charge, which implies a deviation from the first-best policy, i.e., the policy of free-of-charge use of non-rival infrastructure. In addition, note that the first-best result in the congestible case crucially depends on the assumption of constant returns to scale in congestion technology. We should consider additional instruments or alternative designs of schemes for transportation infrastructure to attain the first-best optimum in broader classes of transportation costs[22]. Second, we observe that private involvement in infrastructure provision, such as a public-private partnership, is increasingly common worldwide. In our setting, a private firm can be the operator of the infrastructure. There are several issues in this regard, such as the design of an auction to select the operator and the forms of regulatiing the behavior of the private operator.

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[22] Verhoef (2017) provides useful insights on this issue.

Appendix A: Derivation of (26)

For the specified functions (24) and (25), the equation to determine the capacity, (16), becomes

$$-\beta x + \alpha\beta F(k)x = p^k k$$

Soving the above equation together with the break-even condition, $F(k)x - p^k k = 0$, we have the solution (f^{YY}, k^{YY}), as follows,

$$\begin{aligned} f^{YY} &= \frac{\beta}{1-\alpha\beta} \\ k^{YY} &= \left(\frac{\exp[-\frac{\alpha\beta}{1-\alpha\beta}](A_1+A_2)\beta}{p^k(1-\alpha\beta)} \right)^{\frac{1}{1-\alpha\beta}} \end{aligned}$$

The formula to calculate regional welfare (7) becomes $\frac{x_i}{\alpha} + \frac{k_i}{k}\Pi$. Using the above solution yields

$$W_i^{YY} = \frac{A_1}{\alpha} \left(\frac{(A_1+A_2)\beta}{p^k(1-\alpha\beta)} \right)^{\frac{\alpha\beta}{1-\alpha\beta}} \exp\left[-\frac{\alpha\beta}{(1-\alpha\beta)^2} \right]$$

Under single provision, the user charge and capacity of the infrastructure are determined by (22) and (23). In case NY in which region 2 provides the infrastructure, the solution is

$$\begin{aligned} f^{NY} &= \frac{A_1}{\alpha(A_1+A_2)} \\ k^{NY} &= \left(\frac{(A_1+A_2)\beta}{p^k} \right)^{\frac{1}{1-\alpha\beta}} \exp\left[-\frac{A_1}{(A_1+A_2)(1-\alpha\beta)} \right] \\ W_1^{NY} &= \frac{A_1}{\alpha} \left(\frac{(A_1+A_2)\beta}{p^k} \right)^{\frac{\alpha\beta}{1-\alpha\beta}} \exp\left[-\frac{A_1}{(A_1+A_2)(1-\alpha\beta)} \right] \end{aligned}$$

The expressions for case YN are obtained likewise.

Substituting these results into the conditions for joint provision to be Nash equilibrium, $W_1^{YY} > W_1^{NY}$ and $W_2^{YY} > W_2^{YN}$, we have

$$\begin{aligned} \frac{\alpha\beta}{1-\alpha\beta} + \alpha\beta\ln(1-\alpha\beta) &< \frac{A_1}{(A_1+A_2)} \\ \frac{\alpha\beta}{1-\alpha\beta} + \alpha\beta\ln(1-\alpha\beta) &< \frac{A_2}{(A_1+A_2)} \end{aligned}$$

It is observed that the inequality for the smaller region is critical. Thus the condition is reduced to

$$\frac{\alpha\beta}{1-\alpha\beta} + \alpha\beta\ln(1-\alpha\beta) < s$$

where $s \equiv \min\{\frac{A_1}{A_1+A_2}, \frac{A_2}{A_1+A_2}\}$, which is the share of demand from the smaller region. Thus (26) is the condition for Nash equilibrium.

Appendix B: Proof of Proposition 6

The conditions for joint provision to be Nash equilibrium are $W_1^{YY} > W_1^{NY}$ and $W_2^{YY} > W_2^{YN}$.

We examine $W_1^{YY} > W_1^{NY}$ first. The regional welfare of region 1 in the two cases are

$$\begin{aligned} W_1^{YY} &= \int_{f^{YY}+C(x,k^{YY})}^{\infty} D_1(p)\,dp \\ W_1^{NY} &= \int_{f^{NY}+C(x,k^{NY})}^{\infty} D_1(p)\,dp \end{aligned}$$

Note that the profit from the infrastructure project disappears in case YY, since break-even pricing is adopted. Therefore, $W_1^{YY} > W_1^{NY}$ is equivalent to $f^{YY} + C(x, k^{YY}) < f^{NY} + C(x, k^{NY})$. As shown in Section 4, under joint provision with break-even pricing, the infrastructure charge equals the congestion externality, i.e., $f^{YY} = C_x x$. On the other hand, the infrastructure charge under single provision (case NY) is $f^{NY} = C_x x - \frac{x_1}{\frac{\partial x}{\partial f}}$ from (28). Thus, for given k, $f^{YY} < f^{NY}$.

The investment rule in both cases is (6). Totally differentiating (6) yields.

$$\left[-C_{kk}x - C_k\frac{\partial x}{\partial k} - C_{kx}x \cdot \frac{\partial x}{\partial k}\right] dk + \left[-C_{kx}x \cdot \frac{\partial x}{\partial f} - C_k\frac{\partial x}{\partial f}\right] df = 0$$

The first bracket is negative from the second-order condition for optimality. And the second bracket is negative since $C_{kx} < 0$.[23] Thus $\frac{dk}{df} < 0$ should hold on the locus of (6) . Synthesizing these results, we obtain $f^{YY} < f^{NY}$ and $k^{YY} > k^{NY}$. Thus $f^{YY} + C(x, k^{YY}) < f^{NY} + C(x, k^{NY})$. In words, in case NY, users in region 1 incur a higher full price than in case YY since the user charge is higher and the capacity is smaller. Thus, region 1 is better off by choosing the joint provision. $W_2^{YY} > W_2^{YN}$ is shown in a similar manner.

Appendix C: Proof of Proposition 7

Under single provision, the government that provides the infrastructure chooses the user charge and capacity, subject to the break-even condition. The problem to be solved is

$$\max_{f,k} \int_{f+C(x,k)}^{\infty} D_1(p)\,dp + fx - p^k k$$

$$\text{s.t.} \quad fx - p^k k = 0$$

The optimality conditions with respect to f and k are respectively

$$\begin{aligned} -x_1\left(1 + C_x\frac{\partial x}{\partial f}\right) + (1+\lambda)\left[x + f\frac{\partial x}{\partial f}\right] &= 0 \\ -x_1(C_k + C_x\frac{\partial x}{\partial k}) + (1+\lambda)\left[f\frac{\partial x}{\partial k} - p^k\right] &= 0 \end{aligned}$$

[23] This inequality is true under the assumption that $C(x, k)$ is homogeneous of degree zero.

where λ is the Lagrange multiplier of the break-even constraint. Combining the two optimality conditions to eliminate the Lagrange multiplier yields the following

$$\left(1 - \frac{\partial x}{\partial k}\frac{k}{x}\right)\left(C_k x + p^k\right) = 0$$

The above equality holds when the condition for optimal capacity, (6) holds. This optimal capacity together with the break-even condition leads to (5), the optimal pricing rule.

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