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Second-best Investment Policy for Urban and Rural Highways

Yukihiro Kidokoro*

Center for Spatial Information Science, University of Tokyo

Faculty of Economics, University of Tokyo, 7-3-1, Hongo, Bunkyo, Tokyo, 113-0033, Japan

Tel&Fax: +81-3-5841-5641, E-mail: kidokoro@csis.u-tokyo.ac.jp

Abstract: In this paper, we analyze the second-best investment policy for urban and rural highways, when only uniform highway fees are feasible. We demonstrate that the second-best distortion is smaller and the first-best investment criterion, which implies that the timesaving benefits equal the additional highway investment costs, is more valid when urban and rural highways are closer to being complements. If the second-best distortion is small because of a complementary relationship between urban and rural highways, it is likely that revenues are less than the construction cost regarding urban highways but revenues exceed the construction cost regarding rural highways. That is, the financing of urban highways using excess revenues from rural highways could be justified. Theoretical results are derived and illustrated by simulations based on Japanese highway data.

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1 Introduction

Building rural highways is unpopular among urban residents, especially when the 'revenue-pooling system', which is typical in Japan, is adopted. Under the revenue-pooling system, revenues from all highways are pooled for the construction of new highways. This means that revenues from urban highways are invested in rural highways if rural highways are less developed than urban highways. Is a policy that favors the construction of rural highways economically justified? Until now, such a policy has been justified as a second-best policy. In practice, user fees for urban and rural highways rarely differ. For instance, in Japan, highway tolls per kilometer hardly vary and there is only one fuel tax for the whole country. In the U.S. freeway system, highway tolls are zero on all highways except toll roads, and the fuel tax is uniform across the state. Thus, second-best outcomes are typical under uniform fees. Since congestion is insignificant in rural areas, uniform user fees probably exceed congestion externalities in many rural areas. Reducing the distortion due to higher user fees for rural highways requires overinvestment in rural highways. This is the implication of the second-best investment policy, as has been shown by Henderson (1985).

To what extent is a second-best policy valid in relation to investments in urban and rural highways? This paper attempts to answer this question. Focusing on the fact that urban and rural highways are complements rather than substitutes, we point out that the second-best distortion, due to uniform fees, is probably small. Consequently, one could rely on the first-best analysis being a reasonable approximation.

The main results of the paper are as follows. In the second-best situation, in which only uniform fees are feasible, the optimal user fees for highways are a weighted sum of the congestion externalities in urban and rural highways. Consider a situation in which congestion is severer in urban highways than in rural highways. In such a situation, second-best user fees are lower than the congestion externality in urban areas and higher than the congestion externality in rural highways. Given second-best user fees, the optimal investment policy is to overinvest in rural highways and underinvest in urban highways to reduce the second-best distortion. However, urban and rural highways are complements because they are connected and jointly used in many cases. Hence, the second-best distortion is probably small. We demonstrate that the second-best distortion is smaller and the first-best analysis is more valid as the extent to which urban and rural highways are complements becomes greater. This result has an important implication for financing the construction costs of urban and rural highways. If the second-best distortion is large, it is possible that, for urban highways, revenues exceed costs of construction, whereas, for rural highways, construction costs might exceed revenues. Hence, building rural highways using excess revenues from urban highways could be justified. However, if the second-best distortion is small, building urban highways using excess revenues from rural highways could be justified.

Next, we briefly relate our study to the existing literature. First, Wheaton (1978), Wilson (1983), and D'Ouville and McDonald (1990) analyzed second-best capacity for a single highway. Henderson (1985), Arnott and Yan (2000), and Kraus (2003) focused on the existence of another highway or railway, but their analysis is conducted within the context of the 'two-mode problem', in which the two transport routes are substitutes. This paper differs from the existing literature by considering the second-best optimal highway capacity for urban and rural highways and by allowing the highways to be complements. Second, the analysis of financing highway investment originated with

Mohring and Harwitz (1962) and Strotz (1965), who showed that the revenues from the first-best congestion tax exactly cover the construction costs of highways if the production technology of highway services exhibit constant returns to scale. Arnott et al. (1993) and Arnott and Kraus (1995) extended the analysis by investigating bottleneck congestion, and Bichsel (2001) extended the analysis by considering two groups of road users, such as commuters and shoppers, using the same road at different time periods. However, since these analyses consider single roads, they shed no light on the problem of financing two different types of highway. In this paper, we explicitly focus on the problem of financing urban and rural highways.

The structure of this paper is as follows. In Section 2, we set up the model. In Section 3, we derive the first-best results for reference. In Section 4, we derive results for the second-best case, in which only uniform user fees are feasible. In Section 5, using data on Japanese highways, we perform simulations to test our theoretical predictions. Section 6 concludes our analysis.

2 Model

Consider an urban highway (A) and a rural highway (B), which are connected. The representative consumer demands the composite consumer good, z, the price of which is normalized at unity, urban highway travel, x^A, and rural highway travel, x^B. We assume that the utility function of the representative consumer has the following quasi-linear form:

$$U = z + u(x^A, x^B) . \qquad (1)$$

The above quasi-linear utility function implies that we neglect income effects.

The budget constraint of the representative consumer is:

$$y = z + p^A x^A + p^B x^B, \tag{2}$$

where y is the consumer's income and p^A and p^B are the generalized prices, which include time costs, of urban and rural highway travel, respectively.

Solving the utility-maximization problem of the representative consumer, we obtain:

$$p^A = u_{x^A}(x^A, x^B), \tag{3}$$

$$p^B = u_{x^B}(x^A, x^B). \tag{4}$$

Hereafter, subscripts denote partial derivatives. Given (3) and (4), the demand functions for x^A and x^B are:

$$x^A = x^A(p^A, p^B), \tag{5}$$

$$x^B = x^B(p^A, p^B), \tag{6}$$

where

$$\frac{dx^A}{dp^B} = \frac{dx^B}{dp^A} = \frac{-u_{x^A x^B}}{u_{x^A x^A} u_{x^B x^B} - (u_{x^A x^B})^2}. \tag{7}$$

Since the utility function, (1), is concave, we obtain:

$$u_{x^A x^A} u_{x^B x^B} - (u_{x^A x^B})^2 > 0, \tag{8}$$

which implies that x^A and x^B are substitutes if $u_{x^A x^B} < 0$ and are complements if $u_{x^A x^B} > 0$.

In this paper, we assume that both urban and rural highways are potentially congestion prone. The degree of congestion on an urban highway depends on the highway's travel demand, x^A, and its (nominal) highway capacity, K^A. Similarly, the degree of congestion on a rural highway depends on its travel demand, x^B, and (nominal) highway capacity, K^B. The following generalized prices of urban and rural highway travel are assumed:

$$p^A = \tau^A + \overline{c^A} + c^A(x^A, K^A), \tag{9}$$

$$p^B = \tau^B + \overline{c^B} + c^B(x^B, K^B). \tag{10}$$

In this context, τ^A and τ^B are user fees for travel on urban and rural highways, respectively, and $\overline{c^A}$ and $\overline{c^B}$ are the monetary costs of urban and rural highway travel. Since the levels of $\overline{c^A}$ and $\overline{c^B}$ are irrelevant to our analysis, we set $\overline{c^A}$ and $\overline{c^B}$ at zero. The functions $c^A(x^A, K^A)$ and $c^B(x^B, K^B)$ represent monetized time costs for urban and rural highway travel, respectively; c^A and c^B are nondecreasing in x^A and x^B and decreasing in K^A and K^B, respectively; i.e., $c^A_{x^A} \geq 0$, $c^B_{x^B} \geq 0$, $c^A_{K^A} < 0$, and $c^B_{K^B} < 0$. We assume that $c^A(x^A, K^A)$ and $c^B(x^B, K^B)$ are homogeneous of degree zero. Using (9) and (10), we rewrite the demand functions for x^A and x^B, (5) and (6), as follows:

$$x^A = x^A(\tau^A, \tau^B, K^A, K^B), \tag{11}$$

$$x^B = x^B(\tau^A, \tau^B, K^A, K^B). \tag{12}$$

The profits relating to urban and rural highway travel, respectively, are:

$$\pi^A = p^A x^A - c^A(x^A, K^A)x^A - c^{AK}K^A = \tau^A x^A - c^{AK}K^A, \tag{13}$$

$$\pi^B = p^B x^B - c^B(x^B, K^B)x^B - c^{BK}K^B = \tau^B x^B - c^{BK}K^B, \tag{14}$$

where c^{AK} and c^{BK} are unit capacity costs for urban and rural highways, respectively. Given (1), (2), (13), and (14), total social welfare, SW, is:

$$\begin{aligned} SW &\equiv U + \pi^A + \pi^B \\ &= y - p^A x^A - p^B x^B + u(x^A, x^B) + \tau^A x^A - c^K K^A + \tau^B x^B - c^K K^B, \\ &= y - c^A x^A - c^B x^B + u(x^A, x^B) - c^{AK}K^A - c^{BK}K^B. \end{aligned} \tag{15}$$

3 First Best

For reference, we obtain the first-best results. Maximizing total social welfare, (15), with respect to τ^A, τ^B, K^A, and K^B yields:

$$\tau^A = c^A_{x^A} x^A, \tag{16}$$

$$\tau^B = c^B_{x^B} x^B, \tag{17}$$

$$-c^A_{K^A} x^A = c^{AK}, \tag{18}$$

$$-c^B_{K^B} x^B = c^{BK}. \tag{19}$$

The derivation of (16) to (19) is in the Appendix. Equations (16) and (17) represent the optimal conditions for highway user fees, which are that highway user fees equal congestion externalities in urban and rural highways. In (18) and (19), $-c^A_{K^A} x^A$ and $-c^B_{K^B} x^B$ represent the (monetized) timesaving benefits generated by investments in highway capacity, or the marginal benefits of highway capacity. Equations (18) and (19) imply that the marginal benefits of highway capacity equal their marginal costs in urban and rural highways.

Since $c^A(x^A, K^A)$ and $c^B(x^B, K^B)$ are assumed to be homogeneous of degree zero, the total social costs of urban highway travel, $c^A(x^A, K^A)x^A + c^{AK}K^A$, and rural highway travel, $c^B(x^B, K^B)x^B + c^{BK}K^B$, are both homogeneous of degree one. Consequently, the so-called 'self-financing property' of highways, originally derived by Mohring and Harwitz (1962) and Strotz (1965), applies. That is:

$$\tau^A x^A = c^{AK} K^A, \tag{20}$$

$$\tau^B x^B = c^{BK} K^B. \tag{21}$$

(The derivation of (20) and (21) are in the Appendix.) Equations (20) and (21) imply that the revenues from first-best user fees cover construction costs in urban and rural highways.

4 Second Best

In section 3, we considered the first-best case, in which user fees in urban and rural can differ. However, the first-best outcome is unlikely to arise in practice. Hence, we extend our analysis to consider the second-best case, in which only uniform user fees are feasible.

Consider uniform user fees, τ :

$$\tau \equiv \tau^A = \tau^B . \tag{22}$$

Given (11), (12), and (22), the demand functions for x^A and x^B in the second-best case are:

$$x^A = x^A(\tau, K^A, K^B) , \tag{23}$$

$$x^B = x^B(\tau, K^A, K^B) . \tag{24}$$

The solutions in the second-best case are obtained by maximizing total social welfare, (15), with respect to τ , K^A, and K^B.

4.1 Second-best user fees

We begin by examining second-best user fees. The uniform user fees are:

$$\tau = \frac{\theta^A x^A (c^A_{x^A} x^A) + \theta^B x^B (c^B_{x^B} x^B)}{\theta^A x^A + \theta^B x^B} , \tag{25}$$

where the elasticity of travel demand with respect to user fees is given by $\theta^i \equiv -\frac{\partial x^i}{\partial \tau}\frac{\tau}{x^i}$ ($i = A, B$). Throughout the paper, we assume that $\theta^i > 0$. The derivation of (25) is in the Appendix. Equation (25) shows that, in the second-best case, the optimal user fees are a weighted average of the congestion externalities in urban and rural highways.[1] The weights are related to travel demand and the elasticities of travel demand with respect to user fees in urban and rural highways. The larger the travel demand or the larger the elasticity for urban highways, the larger is the weight for urban highways. Consequently, for urban highways, the second-best optimal user fees approach the first-best user fees.

First, suppose that travel demand is high on an urban highway but low on a rural highway. In this case, it is better in terms of total social welfare to reduce the second-best distortion on the highway with higher travel demand; i.e., the urban highway. To reduce the distortion on the urban highway, greater weight must be given to the first-best user fees on the urban highway.

Second, suppose that the elasticity of travel demand with respect to user fees is large for the urban highway but small for the rural highway. In this case, it is desirable in terms of total social welfare to reduce the second-best distortion on the highway for which demand is more elastic; i.e., the urban highway. This is because, when demand is more elastic, there is a greater change in travel demand, which yields a larger distortion. Thus, greater weight must be assigned to first-best user fees on an urban highway for which demand is more elastic.

[1] Verhoef et al. (1995) point out that the second-best user fees are a weighted average of congestion externalities. In (25), we rearrange their result by using the elasticity of travel demand with respect to user fees.

4.2 Second-best investment criteria

We consider the second-best investment criteria in this subsection. Without loss of generality, we focus on the case in which $c^A_{x^A} x^A \geq c^B_{x^B} x^B$; i.e., congestion is severer on an urban highway than on a rural highway. Second-best highway capacity satisfies:

$$-c^A_{K^A} x^A = c^{AK} + \frac{(\tau - c^B_{x^B} x^B) c^A_{K^A}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}} > c^{AK}, \tag{26}$$

$$-c^B_{K^B} x^B = c^{BK} - \frac{(\tau - c^B_{x^B} x^B) c^B_{K^B}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}} < c^{BK}. \tag{27}$$

The derivation of (26) and (27) is in the Appendix. We denote the second-best distortion in urban and rural highways by $SBDWL^A \equiv \frac{(\tau - c^B_{x^B} x^B) c^A_{K^A}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}}$ and $SBDWL^B \equiv \frac{(\tau - c^B_{x^B} x^B) c^B_{K^B}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}}$, respectively. Equations (26) and (27) show that optimal highway capacity in the second-best case differs from that in the first-best case by the amount $SBDWL^A$ for an urban highway and by $SBDWL^B$ for a rural highway.

When $c^A_{x^A} x^A \geq c^B_{x^B} x^B$, (25) implies that $\tau \geq c^B_{x^B} x^B$. Given that $\tau \geq c^B_{x^B} x^B$, $c^A_{K^A} < 0$, and $c^B_{K^B} < 0$, the numerators of $SBDWL^A$ and $SBDWL^B$ are negative. Their denominators are negative if $\theta^i > 0$, as shown in the Appendix. Since both the numerators and denominators are negative, $SBDWL^A$ and $SBDWL^B$ are positive. For an urban highway, the difference, $SBDWL^A$, makes the marginal benefit of highway capacity exceed its marginal cost. For a rural highway, the difference, $SBDWL^B$, makes the marginal benefit of highway capacity fall below its marginal cost. This implies that, relative to the first-best case, there is underinvestment in urban highways and overinvestment in rural highways in the second-best case.

The important issue is whether $SBDWL^A$ and $SBDWL^B$ are large or small. Suppose that x^A and x^B are substitutes and, consequently, that $u_{x^A x^B} < 0$ from (7). In this case, $u_{x^B x^B} - c^B_{x^B} < 0$ and $-u_{x^A x^B} > 0$ offset each other and, consequently, the absolute values of the denominators of $SBDWL^A$ and $SBDWL^B$, $\left| u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B} \right|$, are likely to be small, *ceteris paribus*. Thus, $SBDWL^A$ and $SBDWL^B$ are large. By contrast, if x^A and x^B are complements, the absolute values of the denominators of $SBDWL^A$ and $SBDWL^B$, $\left| u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B} \right|$, are likely to be large, *ceteris paribus*, given that $u_{x^B x^B} - c^B_{x^B} < 0$ and $-u_{x^A x^B} < 0$. In this case, $SBDWL^A$ and $SBDWL^B$ are small and, consequently, highway capacity in the second-best case approaches highway capacity in the first-best case.

Since urban and rural highway travel are jointly consumed in many cases, urban and rural travel demand are complements to some extent. Thus, the distortion due to second-best uniform user fees is probably small. This suggests that the first-best investment criterion, which is based on a comparison of marginal benefits and costs of highway capacity, is practically useful in the second-best case.

4.3 The modified self-financing property in the second-best case

In this subsection, we focus on how the self-financing property in the first-best case, (20) and (21) is modified. In the second-best case, with $c^A_{x^A} x^A \geq c^B_{x^B} x^B$, we obtain:

$$\tau x^A < (c^{AK} + SBDWL^A)K^A\ , \tag{28}$$

$$\tau x^B > (c^{BK} - SBDWL^B)K^B\ . \tag{29}$$

The derivation of (28) and (29) is in the Appendix. Recall that $SBDWL^A$ and $SBDWL^B$ are positive. If $SBDWL^A$ and $SBDWL^B$ are large, it is possible that $\tau x^A > c^{AK}K^A$ and $\tau x^B < c^{BK}K^B$; i.e., for urban highways, revenues from user fees exceed construction costs, whereas, for rural highways, costs exceed revenues. Since profits are positive for urban highways and negative for rural highways, subsidizing the latter by using excess profits from the former could be justified. That is, there is an economic justification for the revenue-pooling system, under which urban highway users bear the cost of building rural highways. However, if urban and rural highways are complements, at least to some extent, $SBDWL^A$ and $SBDWL^B$ are likely to be sufficiently small to imply $\tau x^A < c^{AK}K^A$ and $\tau x^B > c^{BK}K^B$. If so, the results are reversed. Since the urban highway makes a loss and the rural highway is profitable, subsidizing urban highways by imposing financial burdens on rural highway users could be justified on the grounds of economic efficiency.

5 Numerical simulations

In this section, we test the theoretical predictions using numerical simulations based on Japanese highway data. The urban highway (A) that we chose is the Tomei highway connecting Tokyo and Nagoya, which is one of the most congested highways in Japan. The rural highway (B) chosen is the Joban highway, which stretches from Tokyo to the Tohoku area (in the northern part of mainland Japan).

For convenience, a representative consumer is assumed to consume 100 kilometers (km) of highway services, x^A and x^B. When there is no congestion, the consumer can drive at 100 km per hour on either highway. The time costs for both highways are assumed to be the same and are given by:

$$c(x,K) = w\left(1+\alpha\left(\frac{x}{K}\right)^{\beta}\right), \tag{30}$$

where w is the value of time. We set $\alpha = 0.48$ and $\beta = 2.82$, as proposed by the Japan Society of Civil Engineers (2003) for Japanese highways. According to the Japan Institute for Labor Policy and Training (2003), the average hourly wage was 2240 (yen) in 2003. Following Small (1992), we set the value of time as half the hourly wage; i.e., $w = 1120$ (yen). Following the Japan Society of Traffic Engineers (1999), we set the congestion rate, $\frac{x}{K}$ in (30), at 0.9 for A and 0.47 for B. The actual highway toll for a 100 km highway drive is 2610 (yen) for both A and B. Thus, the actual generalized prices of A and B, respectively, are:

$$p^A = 2610 + 1120\left(1+0.48\left(0.9\right)^{2.82}\right) = 4130, \tag{31}$$

$$p^B = 2610 + 1120\left(1+0.48\left(0.47\right)^{2.82}\right) = 3800. \tag{32}$$

We assume the following quadratic utility function:

$$U = z - k^1(x^A)^2 - k^2(x^B)^2 + k^3x^Ax^B + k^4x^A + k^5x^B, \tag{33}$$

where k^1, k^2, k^3, k^4, and k^5 are parameters. Given (33), the linear inverse demand functions are:

$$p^A = \text{-}2k^1 x^A + k^3 x^B + k^4 , \tag{34}$$

$$p^B = \text{-}2k^2 x^B + k^3 x^A + k^5 . \tag{35}$$

Given (7), the sign of k^3 determines whether x^A and x^B are substitutes or complements. We use $k^3 = -100, -50, 0, 50, 100$, with larger k^3 values implying greater complementarity between x^A and x^B. The price elasticity of travel demand is assumed to be 0.4 when $k^3 = 0$. (We change the price elasticity of travel demand to 0.2 and 0.6 in subsection 5.3.) Actual 12-hour travel demand is 45700 (vehicles) for A and 24700 (vehicles) for B. Thus, given $-\frac{\partial x^A}{\partial p^A}\frac{p^A}{x^A} = -\frac{\partial x^B}{\partial p^B}\frac{p^B}{x^B} = 0.4$, $x^A = 45700$, $x^B = 24700$, (31), and (32), we obtain $k^1 = 113$, $k^2 = 192$, $k^4 = 14500$, and $k^5 = 13300$.

We compute the unit capacity costs of A and B, c^{AK} and c^{BK}, from total construction costs divided by total highway capacity. Since we have no reliable data on the historical construction costs of the highways already built, we use current cost estimates of comparable highways that are currently being built. Specifically, we use the projected construction cost of the second Tomei highway as a substitute for the cost of the current Tomei highway (A). For the Joban highway (B), we use the construction cost of the section of the Joban highway currently being built. From information provided by the Ministry of Land, Infrastructure, and Transport (2003a), we estimate the construction cost of the Tomei highway (A) to be 18800 (million yen/km) and that of the Joban highway (B) to be 3520 (million yen/km). The capacity of the highways per lane is assumed to be 2200 (vehicles per hour), on the basis of information from the Japan Road Association (1984). Assuming four lanes each for A and B implies a total highway daily capacity of 2200 × 4 × 24 = 211000 (vehicles). Since we assume that a representative consumer consumes 100 km of highway services, the unit capacity costs of A and B are:

$$c^{AK} = \frac{100 \times 18800}{211000} = 8.91 \text{ (million yen per vehicle)}, \tag{36}$$

$$c^{BK} = \frac{100 \times 3520}{211000} = 1.67 \text{ (million yen per vehicle)}. \tag{37}$$

The project period and the interest rate are assumed to be 40 (years) and 4%, based on information from the Ministry of Land, Infrastructure, and Transport (2003b). We assume that all values apply for 40 years.

5.1 Main results

The simulation results obtained using these parameters are presented in Table 1, with distortions in K and SW being defined as percentage deviations from first-best values.

In the first-best case (FB), the highway toll for A is 1300 (yen), while that for B is 378 (yen). Thus, the optimal highway toll for A is 344% of that for B. In the second-best case (SB1), the highway toll is 928–1010 (yen), which is 71.3–77.6% of the first-best highway toll for A and 245–267% of that for B.

The investment criteria derived in (26) and (27) imply underinvestment in the urban highway (A) and overinvestment in the rural highway (B) in the second-best case. Note that these criteria do not imply that the actual amounts of investment in the second-best case are larger or smaller than those in the first-best case. For all values of k^3, the levels of K^A and K^B in SB1 are higher and lower, respectively, than those in FB. However, in practice, one could disregard the second-best distortion in capacity when urban and rural highways are complements, as suggested by the theoretical result in subsection 4.2. The results in Table 1 show that the second-best distortions in K^A and K^B are smaller the more complementary are A and B. Specifically, in SB1, K^A is 3.73% larger and K^B is 8.52% smaller than in FB when $k^3 = -100$. However, when $k^3 = 100$, the corresponding differences are 1.14% larger and 1.69% smaller. Thus, if the second-best highway toll is charged when an urban and a rural highway are complements rather than substitutes, in practice, one could rely on the first-best optimal capacity to be a reasonable approximation because the second-best distortion in capacity is small enough to be ignored.

Regarding financing properties, in SB1, for all values of k^3, revenues are below capacity costs in A, whereas revenues exceed capacity costs in B. This result suggests that, in SB1, $SBDWL^A$ and $SBDWL^B$ in (28) and (29) are so small that financing an urban highway using extra revenues from a rural highway is justified.

In practice, second-best highway tolls are rarely applied. Hence, we consider two additional cases. In SB2, highway tolls are zero in both A and B, as in the U.S. freeway system. In SB3, the current Japanese highway toll of 2610 (yen per 100 km) is charged. In SB2, in which highway tolls are zero, travel demand for both A and B are higher, and optimal capacity is also higher so that the highways can cope with higher travel demand. Consequently, the levels of distortion in K^A and K^B shift upwards to be 5.67–6.06%

higher than those in SB1 and 5.77–6.54% higher than those in SB1, respectively. By contrast, in SB3, highway tolls are higher than the first-best tolls. Relative to SB1, higher tolls reduce travel demand in both A and B and subsequently reduce their capacities. Consequently, the levels of distortion in K^A and K^B shift downwards to be 9.87–10.6% lower than those in SB1 and 10.7–10.8% lower than those in SB1, respectively. That is, as shown in Figure 1, the line that represents the distortions in K^A and K^B in SB2 is above that representing those in SB1 (in the direction of the solid arrows), whereas the line representing the distortions in SB3 is below that representing those in SB1 (in the direction of the broken arrows). By contrast, in SB3, highway tolls are higher than the first-best tolls. Relative to FB, higher tolls reduce travel demand in both A and B and subsequently reduce their capacities. Consequently, the distortions in K^A and K^B increase to be 9.87–10.6% lower than in FB and 10.7–10.8% lower than in FB, respectively. That is, as shown in Figure 1, relative to SB1, the distortions in K^A and K^B in SB2 shift upwards (in the direction of the solid arrows), whereas those in SB3 shift downwards (in the direction of the broken arrows). Because of the effects of these distortions in highway tolls, we cannot say that the distortions in K^A and K^B are smaller as A and B become the more complementary when second-best optimal tolls are not charged.

Finally in this subsection, for all values of k^3, the ranking of total social welfare is such that $\text{FB}>\text{SB1}>\text{SB2}>\text{SB3}$. Provided that the optimal highway tolls in FB are 1300 (yen) for A and 378 (yen) for B, total social welfare is higher in SB2 than in SB3 because the highway tolls of 2610 (yen) in SB3 are more distortionary than are the zero tolls in SB2.

5.2 Varying B's travel demand

Hereafter, we refer to the case analyzed in subsection 5.1 as the base case. In the base case, the parameters are set under the condition that the actual travel demand of B is 100 × (24700/54700), which is 54.1% of that of A. In this subsection, we check the effects of differences in travel demand between A and B on the results, by setting $k^2 = 130$, $k^2 = 519$, or $k^2 = 1040$, which implies that B's actual travel demand is 80%, 20%, or 10% of A's. The results are presented in Tables 2a, 2b, and 2c. Essentially, the results in the base case apply whether the difference in travel demand between A and B is large or small.

Further explanation is warranted on two points.

First, if B's travel demand is high, it is important to deal with the distortion in B in SB1. As Figure 2 shows, while the distortion in K^B is smaller, that in K^A is larger, compared with the base case. By contrast, if B's travel demand is lower, while dealing with the distortion in B is less important, it is important to take into account the distortion in A in SB1. This is why the distortion in K^A is smaller while that in K^B is larger, compared with the base case, in Tables 2b and 2c.

Second, if B's travel demand is higher, the difference in the distortion in total social welfare between SB2 and SB3 is greater. Specifically, if B's travel demand is 10% of A's travel demand, the distortion in total social welfare hardly differs between SB2 and SB3: –1.05% to –1.18% in SB2 and –1.41 to –1.52% in SB3. However, if B's travel demand is 80% of A's travel demand, the distortion in total social welfare depends significantly on whether SB2 or SB3 is chosen: –0.602% to –0.928% in SB2 and –2.28% to –2.51% in SB3. The reason for these relationships is as follows. When B's travel demand is high, it is important to consider B's condition; congestion is less severe and, consequently, the optimal highway toll on B is low. A high toll generates significant distortion, whereas little distortion is generated by a zero toll. That is, the distortion from SB2 is smaller, the distortion in SB3 is larger and, hence, the difference in total social welfare between SB2 and SB3 is greater the higher B's travel demand.

5.3 Varying the price elasticity of travel demand

In the base case, we set the price elasticity of travel demand at 0.4 when $k^3 = 0$. Hence, we check the effects on the results of different values of the price elasticity, namely 0.2 and 0.6. When the price elasticity of travel demand is 0.2, $k^1 = 226$, $k^2 = 384$, $k^4 = 24800$, and $k^5 = 22800$. When the price elasticity of travel demand is 0.6, $k^1 = 75.3$, $k^2 = 128$, $k^4 = 11000$, and $k^5 = 10100$. As Tables 3a and 3b show, the qualitative results are similar when the price elasticity changes. However, a higher price elasticity leads to a larger change in the distortion in K. This is because travel demand and highway capacity are likely to change to a greater extent when the price elasticity is larger. Thus, whether urban and rural highways are substitutes or complements is more important the larger the price elasticity of travel demand. Figure 3 displays the results for SB1, which confirm that the change in the distortion in K is larger the greater the price elasticity. (Since the figures for SB2 and SB3 show the same trends, they are omitted due to limitations on space.) A higher price elasticity also leads to a greater distortion in total social welfare. Thus, in SB1, SB2, and SB3, the distortion in SW is greater the larger the price elasticity of travel demand.

5.4 Varying B's construction cost

Finally, in this section, we check the effects of differences in construction costs between A and B on the results. In the base case, B's construction costs are 100 × (1.67/8.91) =

18.7% of A's. In this section, we consider B's construction costs being 80%, 50%, and 10% of A's. The results are presented in Tables 4a, 4b, and 4c. Although the results in the base case apply whether differences in construction costs between A and B are large or small, two trends are worth explaining.

First, we check the results for SB1, which are illustrated in Figure 4. The larger the difference in construction costs between A and B, the larger the difference in congestion rates. This is because investment in B's capacity increases while investment in A's capacity decreases because of the difference in construction costs. The difference in congestion increases the second-best distortion caused by uniform highway tolls and, consequently, makes the distortions in K larger in SB1. By contrast, the smaller the difference in construction costs between A and B, the smaller the difference in congestion rates. Hence, the second-best distortion caused by uniform highway tolls is smaller. Thus, the distortions in K are reduced in SB1. In addition, the larger the second-best distortion, the greater the distortion in total social welfare. Thus, the distortion in SW is larger the greater the difference in construction costs between A and B.

Second, in relation to SB2 and SB3, the larger the difference in construction costs between A and B, the greater the difference in the distortion in total social welfare between SB2 and SB3. The explanation is similar to that used to explain the effects of B's travel demand in subsection 5.2. Specifically, the greater the difference in construction costs between A and B, the less severe is congestion in B. Consequently, the lower the optimal highway toll in B. This is because investment in B's capacity is higher. In this case, a high toll generates a large distortion, whereas little distortion is induced by a zero toll. That is, the greater the difference in construction costs between

A and B, the larger the distortion in SB2 and the smaller the distortion in SB3 and, hence, the greater the difference in total social welfare between SB2 and SB3.

6 Conclusion

In this paper, we analyzed the second-best investment policy for an urban and a rural highway when only uniform highway fees are feasible. The main points are summarized as follows. First, if urban and rural highways are complements rather than substitutes, the second-best distortion in highway capacity is lower. In such a case, the first-best investment criterion, which implies that the timesaving benefits equal the additional highway capacity costs, is approximately valid. Second, if the second-best distortion in highway capacity is small, for urban highways, revenues from highway fees are less than highway construction costs, whereas, for rural highways, revenues from highway fees exceed highway construction costs. This result suggests that using excess revenues from rural highways to finance the construction of urban highways is justified. These two predictions are supported by simulations based on Japanese highway data.

The results in this paper are applicable when we examine actual highway investment policies. For example, in Japan, there has been much debate on investment in rural highways that have traffic demands that are lower than those of urban highways. Note that, in all SB3 results, second-best distortions in capacity are negative; that is, second-best optimal capacity is below first-best optimal capacity. This suggests that the first-best optimal capacity provides an upper limit for investments in rural highways in Japan. That is, second-best arguments are unlikely to justify overinvestment in rural highways on which traffic demand is low and, hence, expected timesaving benefits are small.

In concluding the paper, we comment on one issue. The analysis in this paper focused on economic efficiency under the assumption that all consumers are homogeneous and have the same utility function. Thus, we ignored equity issues. However, in practice, highway investments are at least partly determined on the basis of equity because of political pressures. Taking account of equity issues in a model that incorporates heterogeneous consumers would complicate the analysis, but warrants further research.

Tables and Figures

Table 1. Base case

	k^3	FB A	FB B	SB1 A	SB1 B	SB2 (τ=0) A	SB2 (τ=0) B	SB3 (τ=2610) A	SB3 (τ=2610) B
p (yen)	-100	2880	1630	2610	2250	1630	1250	4160	3840
	-50	2880	1630	2570	2220	1620	1260	4160	3840
	0	2880	1630	2550	2200	1620	1260	4150	3840
	50	2880	1630	2530	2190	1620	1260	4150	3850
	100	2880	1630	2510	2180	1610	1260	4150	3850
τ (yen)	-100	1300	378	1010		0		2610	
	-50	1300	378	977		0		2610	
	0	1300	378	955		0		2610	
	50	1300	378	940		0		2610	
	100	1300	378	928		0		2610	
x (1000 vehicles)	-100	42.9	19.2	45.1	17.0	48.7	18.7	39.4	14.4
	-50	46.0	24.4	47.8	22.6	51.5	24.7	41.5	19.2
	0	51.4	30.4	52.9	28.9	57.0	31.4	45.8	24.6
	50	59.8	38.2	61.1	36.9	65.8	39.9	52.8	31.5
	100	73.3	49.5	74.4	48.3	80.1	52.2	64.1	41.3
K (1000 vehicles)	-100	45.3	31.4	47.0	28.8	49.7	30.8	42.5	25.4
	-50	48.6	39.9	49.9	37.8	52.8	40.2	45.0	33.5
	0	54.3	49.7	55.4	47.9	58.6	50.9	49.8	42.6
	50	63.2	62.5	64.2	60.9	67.8	64.6	57.6	54.2
	100	77.4	80.9	78.2	79.6	82.6	84.2	70.1	70.8
Congestion Rate (%)	-100	94.7	61.1	96.0	59.2	97.9	60.7	92.6	56.7
	-50	94.7	61.1	95.7	59.9	97.6	61.3	92.2	57.4
	0	94.7	61.1	95.5	60.3	97.3	61.6	91.9	57.8
	50	94.7	61.1	95.3	60.6	97.1	61.8	91.7	58.1
	100	94.7	61.1	95.1	60.8	97.0	62.0	91.5	58.3
Distortion in K (%)	-100	/	/	3.73	-8.52	9.78	-1.98	-6.14	-19.2
	-50	/	/	2.83	-5.41	8.72	0.796	-7.31	-16.1
	0	/	/	2.13	-3.64	7.93	2.36	-8.20	-14.4
	50	/	/	1.58	-2.50	7.30	3.37	-8.89	-13.3
	100	/	/	1.14	-1.69	6.80	4.08	-9.44	-12.5
Profits (billion yen)	-100	0	0	-89.5	76.2	-443	-51.5	364	229
	-50	0	0	-108	96.7	-470	-67.2	382	307
	0	0	0	-129	119	-522	-85.0	419	393
	50	0	0	-157	149	-604	-108	482	503
	100	0	0	-198	191	-736	-141	584	660
Distortion in SW (%)	-100	/		-0.279		-1.02		-2.13	
	-50	/		-0.200		-0.891		-2.13	
	0	/		-0.145		-0.805		-2.12	
	50	/		-0.104		-0.743		-2.12	
	100	/		-0.0731		-0.696		-2.12	

Table 2a. When B's travel demand is 80% of A's travel demand

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2490	2130	1630	1250	4170	3840
	-50	2880	1630	2470	2120	1620	1260	4160	3840
	0	2880	1630	2460	2120	1620	1260	4150	3840
	50	2880	1630	2450	2120	1610	1260	4150	3850
	100	2880	1630	2450	2110	1610	1260	4150	3850
τ (yen)	-100	1300	378	885		0		2610	
	-50	1300	378	874		0		2610	
	0	1300	378	868		0		2610	
	50	1300	378	864		0		2610	
	100	1300	378	861		0		2610	
x (1000 vehicles)	-100	38.0	30.3	41.1	27.2	43.9	29.5	35.7	22.7
	-50	43.3	36.5	45.6	34.2	48.8	36.9	39.4	28.8
	0	51.4	44.9	53.3	43.0	57.0	46.3	45.8	36.4
	50	64.1	57.2	65.6	55.6	70.3	59.8	56.2	47.2
	100	85.9	77.9	87.2	76.6	93.4	82.2	74.6	65.0
K (1000 vehicles)	-100	40.1	49.5	42.5	45.7	44.6	48.5	38.3	40.0
	-50	45.7	59.8	47.5	57.0	49.9	60.3	42.6	50.2
	0	54.3	73.4	55.7	71.2	58.6	75.2	49.8	62.9
	50	67.6	93.6	68.8	91.7	72.4	96.7	61.4	81.2
	100	90.6	127	91.7	126	96.5	133	81.7	112
Congestion Rate (%)	-100	94.7	61.1	96.7	59.4	98.4	60.7	93.2	56.7
	-50	94.7	61.1	96.0	60.1	97.8	61.3	92.4	57.4
	0	94.7	61.1	95.6	60.4	97.3	61.6	91.9	57.8
	50	94.7	61.1	95.3	60.7	97.1	61.8	91.6	58.1
	100	94.7	61.1	95.1	60.8	96.9	62.0	91.3	58.3
Distortion in K (%)	-100	/	/	5.94	-7.67	11.2	-1.95	-4.58	-19.2
	-50	/	/	3.94	-4.75	9.19	0.800	-6.79	-16.1
	0	/	/	2.67	-3.09	7.93	2.36	-8.20	-14.4
	50	/	/	1.79	-2.02	7.05	3.37	-9.17	-13.3
	100	/	/	1.15	-1.27	6.41	4.08	-9.88	-12.5
Profits (billion yen)	-100	0	0	-116	97.3	-398	-81.1	332	361
	-50	0	0	-135	121	-445	-101	363	459
	0	0	0	-162	151	-522	-126	419	581
	50	0	0	-204	194	-645	-162	513	754
	100	0	0	-274	266	-859	-222	679	1040
Distortion in SW (%)	-100	/		-0.360		-0.928		-2.51	
	-50	/		-0.231		-0.785		-2.41	
	0	/		-0.154		-0.700		-2.35	
	50	/		-0.102		-0.642		-2.31	
	100	/		-0.0647		-0.602		-2.28	

Table 2b. When B's travel demand is 20% of A's travel demand

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2780	2430	1621	1250	4160	3840
	-50	2880	1630	2750	2400	1620	1260	4160	3840
	0	2880	1630	2720	2380	1620	1260	4150	3840
	50	2880	1630	2700	2360	1620	1260	4150	3850
	100	2880	1630	2680	2340	1620	1260	4150	3850
τ (yen)	-100	1300	378	1190		0		2610	
	-50	1300	378	1160		0		2610	
	0	1300	378	1130		0		2610	
	50	1300	378	1110		0		2610	
	100	1300	378	1090		0		2610	
x (1000 vehicles)	-100	48.5	6.57	49.3	5.72	54.2	6.39	43.6	4.92
	-50	49.4	8.86	50.2	8.08	55.0	8.95	44.2	6.98
	0	51.4	11.2	52.1	10.5	57.0	11.6	45.8	9.11
	50	54.5	13.9	55.1	13.2	60.2	14.5	48.3	11.4
	100	58.9	16.9	59.5	16.3	64.9	17.9	52.0	14.1
K (1000 vehicles)	-100	51.2	10.7	51.8	9.70	55.5	10.5	47.3	8.68
	-50	52.2	14.5	52.8	13.5	56.5	14.6	48.1	12.2
	0	54.3	18.4	54.8	17.5	58.6	18.8	49.8	15.7
	50	57.5	22.7	58.0	21.9	61.9	23.4	52.6	19.7
	100	62.2	27.7	62.6	26.9	66.8	28.8	56.7	24.2
Congestion Rate (%)	-100	94.7	61.1	95.2	58.9	97.5	60.7	92.1	56.7
	-50	94.7	61.1	95.1	59.7	97.4	61.3	92.0	57.4
	0	94.7	61.1	95.1	60.1	97.3	61.6	91.9	57.8
	50	94.7	61.1	95.0	60.3	97.3	61.8	91.8	58.1
	100	94.7	61.1	95.0	60.5	97.2	62.0	91.7	58.3
Distortion in K (%)	-100	/	/	1.29	-9.73	8.49	-2.01	-7.57	-19.3
	-50	/	/	1.16	-6.59	8.20	0.792	-7.90	-16.1
	0	/	/	1.03	-4.78	7.93	2.36	-8.20	-14.4
	50	/	/	0.907	-3.59	7.68	3.37	-8.47	-13.3
	100	/	/	0.783	-2.75	7.45	4.07	-8.73	-12.5
Profits (billion yen)	-100	0	0	-38.2	32.9	-495	-17.6	400	78.2
	-50	0	0	-49.9	45.0	-503	-24.4	406	111
	0	0	0	-61.4	56.9	-522	-31.4	419	145
	50	0	0	-73.7	69.5	-552	-39.2	442	183
	100	0	0	-87.7	83.8	-595	-48.1	476	226
Distortion in SW (%)	-100	/		-0.123		-1.14		-1.58	
	-50	/		-0.106		-1.08		-1.62	
	0	/		-0.0915		-1.02		-1.66	
	50	/		-0.0779		-0.972		-1.69	
	100	/		-0.0656		-0.931		-1.72	

Table 2c. When B's travel demand is 10% of A's travel demand

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2830	2490	1620	1250	4160	3840
	-50	2880	1630	2810	2470	1620	1260	4150	3840
	0	2880	1630	2790	2460	1620	1260	4150	3840
	50	2880	1630	2780	2440	1620	1260	4150	3850
	100	2880	1630	2760	2430	1620	1260	4150	3850
τ (yen)	-100	1300	378	1240		0		2610	
	-50	1300	378	1230		0		2610	
	0	1300	378	1210		0		2610	
	50	1300	378	1190		0		2610	
	100	1300	378	1180		0		2610	
x (1000 vehicles)	-100	50.0	3.21	50.4	2.78	55.6	3.12	44.7	2.40
	-50	50.4	4.40	50.8	3.98	56.0	4.44	45.0	3.46
	0	51.4	5.61	51.8	5.21	57.0	5.79	45.8	4.55
	50	52.9	6.88	53.3	6.50	58.6	7.20	47.0	5.68
	100	55.1	8.26	55.4	7.89	60.9	8.71	48.8	6.89
K (1000 vehicles)	-100	52.8	5.25	53.1	4.72	57.1	5.14	48.6	4.23
	-50	53.2	7.19	53.5	6.69	57.5	7.25	48.9	6.03
	0	54.3	9.18	54.6	8.69	58.6	9.39	49.8	7.86
	50	55.9	11.3	56.2	10.8	60.2	11.6	51.2	9.77
	100	58.1	13.5	58.4	13.1	62.6	14.1	53.2	11.8
Congestion Rate (%)	-100	94.7	61.1	95.0	58.9	97.4	60.7	92.0	56.7
	-50	94.7	61.1	94.9	59.6	97.4	61.3	92.0	57.4
	0	94.7	61.1	94.9	60.0	97.3	61.6	91.9	57.8
	50	94.7	61.1	94.9	60.2	97.3	61.8	91.9	58.1
	100	94.7	61.1	94.9	60.4	97.3	62.0	91.8	58.3
Distortion in K (%)	-100	/	/	0.635	-10.1	8.19	-2.02	-7.90	-19.3
	-50	/	/	0.604	-7.03	8.06	0.790	-8.05	-16.1
	0	/	/	0.568	-5.27	7.93	2.36	-8.20	-14.4
	50	/	/	0.530	-4.11	7.80	3.37	-8.34	-13.3
	100	/	/	0.490	-3.29	7.68	4.07	-8.47	-12.5
Profits (billion yen)	-100	0	0	-19.7	17.1	-509	-8.58	410	38.2
	-50	0	0	-26.7	24.1	-512	-12.1	413	55.3
	0	0	0	-33.5	31.0	-522	-15.7	419	72.6
	50	0	0	-40.4	38.1	-537	-19.4	431	90.7
	100	0	0	-47.8	45.5	-558	-23.5	447	110
Distortion in SW (%)	-100	/		-0.0643		-1.18		-1.41	
	-50	/		-0.0599		-1.14		-1.44	
	0	/		-0.0552		-1.11		-1.47	
	50	/		-0.0506		-1.08		-1.49	
	100	/		-0.0459		-1.05		-1.52	

Table 3a. When the price elasticity of travel demand is 0.6

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2670	2290	1660	1240	4160	3820
	-50	2880	1630	2590	2230	1640	1250	4150	3830
	0	2880	1630	2550	2200	1630	1260	4140	3840
	50	2880	1630	2520	2180	1630	1260	4130	3840
	100	2880	1630	2500	2170	1620	1260	4130	3840
τ (yen)	-100	1300	378	1060		0		2610	
	-50	1300	378	989		0		2610	
	0	1300	378	954		0		2610	
	50	1300	378	932		0		2610	
	100	1300	378	918		0		2610	
x (1000 vehicles)	-100	43.1	16.2	47.3	12.0	52.7	14.0	39.3	9.18
	-50	45.9	24.1	48.8	21.2	54.2	24.0	40.0	16.7
	0	53.9	33.1	56.1	30.9	62.2	34.5	45.6	24.5
	50	69.4	46.6	71.2	44.8	78.8	49.9	57.4	35.7
	100	102	73.1	104	71.6	115	79.5	83.5	57.1
K (1000 vehicles)	-100	45.5	26.6	48.7	21.3	52.8	23.8	42.5	17.4
	-50	48.4	39.5	50.7	35.9	54.7	39.3	43.7	30.0
	0	56.9	54.1	58.6	51.4	63.2	55.9	50.2	43.3
	50	73.2	76.3	74.6	74.1	80.4	80.2	63.7	62.6
	100	108	120	109	118	118	127	93.0	99.6
Congestion Rate (%)	-100	94.7	61.1	97.1	56.5	99.9	58.8	92.5	52.7
	-50	94.7	61.1	96.3	59.1	99.0	61.0	91.4	55.5
	0	94.7	61.1	95.7	60.0	98.4	61.8	90.7	56.5
	50	94.7	61.1	95.4	60.5	98.0	62.2	90.2	57.0
	100	94.7	61.1	95.1	60.8	97.7	62.5	89.8	57.3
Distortion in K (%)	-100	/	/	7.06	-19.8	16.0	-10.3	-6.56	-34.4
	-50	/	/	4.62	-9.04	13.0	-0.419	-9.70	-23.8
	0	/	/	3.02	-5.00	11.1	3.24	-11.7	-20.0
	50	/	/	1.91	-2.86	9.86	5.16	-13.0	-17.9
	100	/	/	1.09	-1.53	8.93	6.35	-14.0	-16.7
Profits (billion yen)	-100	0	0	-72.1	56.6	-470	-39.8	362	144
	-50	0	0	-103	91.6	-488	-65.6	364	264
	0	0	0	-136	127	-563	-93.3	411	389
	50	0	0	-185	178	-717	-134	516	568
	100	0	0	-284	278	-1050	-212	747	910
Distortion in SW (%)	-100	/		-0.792		-2.41		-4.24	
	-50	/		-0.465		-1.87		-4.22	
	0	/		-0.286		-1.59		-4.19	
	50	/		-0.173		-1.41		-4.17	
	100	/		-0.0962		-1.30		-4.16	

Table 3b. When the price elasticity of travel demand is 0.2

		FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
	k^3	A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2570	2230	1600	1250	4170	3850
	-50	2880	1630	2560	2220	1600	1260	4170	3850
	0	2880	1630	2540	2210	1600	1260	4170	3850
	50	2880	1630	2530	2200	1600	1260	4170	3850
	100	2880	1630	2530	2190	1600	1260	4170	3850
τ (yen)	-100	1300	378	980		0		2610	
	-50	1300	378	968		0		2610	
	0	1300	378	957		0		2610	
	50	1300	378	949		0		2610	
	100	1300	378	941		0		2610	
x (1000 vehicles)	-100	43.6	21.9	44.5	21.0	46.5	22.0	41.4	19.3
	-50	45.8	24.6	46.6	23.8	48.6	24.9	43.2	21.9
	0	48.5	27.6	49.2	26.8	51.3	28.1	45.6	24.7
	50	51.9	30.9	52.6	30.2	54.8	31.6	48.7	27.8
	100	56.2	34.9	56.9	34.2	59.2	35.8	52.6	31.5
K (1000 vehicles)	-100	46.1	35.8	46.8	34.7	48.2	35.9	44.3	32.6
	-50	48.3	40.2	48.9	39.2	50.5	40.6	46.3	36.9
	0	51.2	45.1	51.8	44.2	53.4	45.7	48.9	41.6
	50	54.8	50.6	55.3	49.8	57.0	51.4	52.3	46.8
	100	59.3	57.1	59.8	56.3	61.7	58.1	56.5	53.0
Congestion Rate (%)	-100	94.7	61.1	95.2	60.5	96.3	61.2	93.4	59.1
	-50	94.7	61.1	95.2	60.6	96.2	61.3	93.3	59.3
	0	94.7	61.1	95.1	60.7	96.2	61.4	93.3	59.4
	50	94.7	61.1	95.1	60.8	96.1	61.5	93.2	59.5
	100	94.7	61.1	95.0	60.8	96.1	61.5	93.1	59.5
Distortion in K (%)	-100	/	/	1.51	-3.04	4.70	0.427	-3.89	-8.89
	-50	/	/	1.31	-2.46	4.48	0.925	-4.15	-8.31
	0	/	/	1.14	-2.02	4.29	1.31	-4.37	-7.86
	50	/	/	0.986	-1.66	4.11	1.62	-4.58	-7.50
	100	/	/	0.848	-1.37	3.96	1.87	-4.76	-7.21
Profits (billion yen)	-100	0	0	-101	90.6	-430	-60.0	385	309
	-50	0	0	-110	101	-450	-67.8	402	351
	0	0	0	-121	112	-476	-76.3	424	396
	50	0	0	-133	124	-508	-85.9	453	447
	100	0	0	-147	139	-550	-97.1	489	506
Distortion in SW (%)	-100	/		-0.0582		-0.261		-0.618	
	-50	/		-0.0495		-0.247		-0.618	
	0	/		-0.0421		-0.236		-0.618	
	50	/		-0.0358		-0.226		-0.619	
	100	/		-0.0303		-0.218		-0.619	

Table 4a. When B's construction cost is 80% of A's construction cost

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2830	2740	1620	1540	4160	4070
	-50	2880	1630	2820	2740	1620	1540	4160	4080
	0	2880	1630	2810	2740	1620	1540	4150	4080
	50	2880	1630	2810	2730	1620	1540	4150	4080
	100	2880	1630	2800	2730	1620	1540	4150	4080
τ (yen)	-100	1300	378	1240		0		2610	
	-50	1300	378	1230		0		2610	
	0	1300	378	1230		0		2610	
	50	1300	378	1220		0		2610	
	100	1300	378	1220		0		2610	
x (1000 vehicles)	-100	44.2	16.3	44.6	15.9	49.1	17.8	39.7	13.7
	-50	46.6	21.8	47.0	21.4	51.7	23.9	41.7	18.6
	0	51.4	27.8	51.7	27.5	57.0	30.6	45.8	24.0
	50	59.3	35.5	59.5	35.3	65.7	39.2	52.6	30.9
	100	72.0	46.6	72.3	46.3	79.7	51.4	63.8	40.6
K (1000 vehicles)	-100	46.6	18.3	47.0	17.9	50.4	19.5	43.1	16.0
	-50	49.2	24.3	49.5	24.0	53.1	26.1	45.3	21.7
	0	54.3	31.1	54.5	30.9	58.6	33.4	49.8	27.9
	50	62.6	39.8	62.8	39.5	67.5	42.7	57.3	35.8
	100	76.0	52.1	76.2	51.9	81.9	56.0	69.5	47.1
Congestion Rate (%)	-100	94.7	89.4	95.0	88.7	97.4	91.5	92.1	85.4
	-50	94.7	89.4	94.9	89.0	97.4	91.6	92.0	85.8
	0	94.7	89.4	94.9	89.1	97.3	91.6	91.9	86.0
	50	94.7	89.4	94.9	89.2	97.3	91.7	91.8	86.1
	100	94.7	89.4	94.8	89.2	97.3	91.7	91.8	86.2
Distortion in K (%)	-100	/	/	0.757	-2.06	8.10	6.81	-7.57	-12.2
	-50	/	/	0.590	-1.27	8.00	7.15	-7.92	-11.0
	0	/	/	0.452	-0.838	7.93	7.33	-8.20	-10.3
	50	/	/	0.340	-0.568	7.86	7.45	-8.42	-9.92
	100	/	/	0.247	-0.382	7.81	7.52	-8.60	-9.64
Profits (billion yen)	-100	0	0	-18.4	14.8	-449	-139	365	144
	-50	0	0	-22.2	19.2	-473	-186	382	196
	0	0	0	-26.6	24.1	-522	-238	419	254
	50	0	0	-32.4	30.2	-601	-305	482	326
	100	0	0	-41.0	39.0	-730	-399	583	430
Distortion in SW (%)	-100	/		-0.0131		-1.18		-1.43	
	-50	/		-0.00952		-1.17		-1.45	
	0	/		-0.00697		-1.16		-1.46	
	50	/		-0.00506		-1.16		-1.47	
	100	/		-0.00357		-1.15		-1.48	

Table 4b. When B's construction cost is 50% of A's construction cost

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2730	2520	1620	1400	4160	3960
	-50	2880	1630	2710	2510	1620	1410	4160	3970
	0	2880	1630	2690	2500	1620	1410	4150	3970
	50	2880	1630	2680	2490	1620	1410	4150	3980
	100	2880	1630	2680	2490	1620	1410	4150	3980
τ (yen)	-100	1300	378	1140		0		2610	
	-50	1300	378	1120		0		2610	
	0	1300	378	1110		0		2610	
	50	1300	378	1100		0		2610	
	100	1300	378	1090		0		2610	
x (1000 vehicles)	-100	43.6	17.6	44.8	16.4	48.9	18.2	39.6	14.0
	-50	46.3	22.9	47.3	21.9	51.6	24.2	41.6	18.9
	0	51.4	29.0	52.2	28.1	57.0	31.0	45.8	24.3
	50	59.5	36.7	60.2	36.0	65.7	39.5	52.7	31.1
	100	72.6	47.9	73.2	47.2	79.9	51.8	63.9	40.9
K (1000 vehicles)	-100	46.0	22.3	47.0	21.1	50.1	22.9	42.8	18.8
	-50	48.9	29.0	49.7	28.1	53.0	30.2	45.2	25.1
	0	54.3	36.7	54.9	35.9	58.6	38.5	49.8	32.2
	50	62.8	46.5	63.4	45.8	67.6	49.1	57.4	41.1
	100	76.6	60.6	77.1	60.0	82.3	64.2	69.7	54.0
Congestion Rate (%)	-100	94.7	79.0	95.4	77.6	97.6	79.8	92.4	74.4
	-50	94.7	79.0	95.3	78.1	97.5	80.2	92.1	75.1
	0	94.7	79.0	95.1	78.4	97.3	80.4	91.9	75.5
	50	94.7	79.0	95.0	78.6	97.2	80.6	91.8	75.7
	100	94.7	79.0	95.0	78.7	97.2	80.7	91.6	75.8
Distortion in K (%)	-100	/	/	2.05	-5.14	8.83	2.65	-6.95	-15.5
	-50	/	/	1.57	-3.21	8.32	4.19	-7.66	-13.4
	0	/	/	1.20	-2.14	7.93	5.04	-8.20	-12.2
	50	/	/	0.895	-1.46	7.61	5.58	-8.63	-11.5
	100	/	/	0.647	-0.984	7.36	5.95	-8.98	-10.9
Profits (billion yen)	-100	0	0	-49.5	40.8	-446	-102	364	180
	-50	0	0	-59.6	52.4	-472	-135	382	244
	0	0	0	-71.3	65.2	-522	-172	419	315
	50	0	0	-86.8	81.6	-602	-219	482	404
	100	0	0	-110	105	-733	-286	584	531
Distortion in SW (%)	-100	/		-0.0901		-1.05		-1.69	
	-50	/		-0.0651		-1.00		-1.71	
	0	/		-0.0474		-0.963		-1.73	
	50	/		-0.0343		-0.936		-1.74	
	100	/		-0.0241		-0.916		-1.75	

Table 4c. When B's construction cost is 10% of A's construction cost

	k^3	FB		SB1		SB2 (τ=0)		SB3 (τ=2610)	
		A	B	A	B	A	B	A	B
p (yen)	-100	2880	1630	2570	2160	1630	1200	4160	3800
	-50	2880	1630	2520	2130	1620	1200	4160	3800
	0	2880	1630	2490	2100	1620	1210	4150	3800
	50	2880	1630	2470	2090	1610	1210	4150	3800
	100	2880	1630	2460	2070	1610	1210	4150	3800
τ (yen)	-100	1300	378	964		0		2610	
	-50	1300	378	927		0		2610	
	0	1300	378	902		0		2610	
	50	1300	378	884		0		2610	
	100	1300	378	871		0		2610	
x (1000 vehicles)	-100	42.7	19.8	45.2	17.2	48.6	18.8	39.3	14.5
	-50	45.9	24.9	47.9	22.9	51.5	24.8	41.5	19.3
	0	51.4	30.9	53.1	29.2	57.0	31.5	45.8	24.7
	50	60.0	38.7	61.4	37.2	65.9	40.1	52.8	31.6
	100	73.5	50.0	74.8	48.7	80.2	52.4	64.1	41.4
K (1000 vehicles)	-100	45.0	38.1	47.0	34.5	49.6	36.8	42.4	30.3
	-50	48.4	48.0	50.0	45.1	52.7	47.9	45.0	39.8
	0	54.3	59.6	55.6	57.1	58.6	60.4	49.8	50.6
	50	63.3	74.6	64.4	72.5	67.8	76.6	57.6	64.3
	100	77.6	96.5	78.6	94.6	82.8	99.8	70.2	83.9
Congestion Rate (%)	-100	94.7	51.9	96.2	50.0	98.1	51.2	92.7	47.8
	-50	94.7	51.9	95.8	50.7	97.6	51.8	92.3	48.5
	0	94.7	51.9	95.6	51.1	97.3	52.1	91.9	48.9
	50	94.7	51.9	95.3	51.3	97.1	52.3	91.6	49.2
	100	94.7	51.9	95.2	51.5	96.9	52.5	91.4	49.4
Distortion in K (%)	-100	/	/	4.33	-9.60	10.1	-3.47	-5.84	-20.4
	-50	/	/	3.27	-6.14	8.87	-0.323	-7.19	-17.0
	0	/	/	2.46	-4.14	7.93	1.47	-8.20	-15.1
	50	/	/	1.82	-2.85	7.19	2.63	-8.98	-13.9
	100	/	/	1.31	-1.93	6.61	3.44	-9.60	-13.0
Profits (billion yen)	-100	0	0	-104	89.4	-442	-32.8	364	247
	-50	0	0	-125	113	-470	-42.7	382	329
	0	0	0	-149	139	-522	-53.8	419	421
	50	0	0	-182	173	-604	-68.2	482	539
	100	0	0	-230	222	-737	-88.9	584	706
Distortion in SW (%)	-100	/		-0.368		-1.03		-2.31	
	-50	/		-0.263		-0.878		-2.29	
	0	/		-0.190		-0.772		-2.28	
	50	/		-0.137		-0.696		-2.26	
	100	/		-0.0958		-0.638		-2.26	

Figure 1: Comparison among SB1, SB2, and SB3

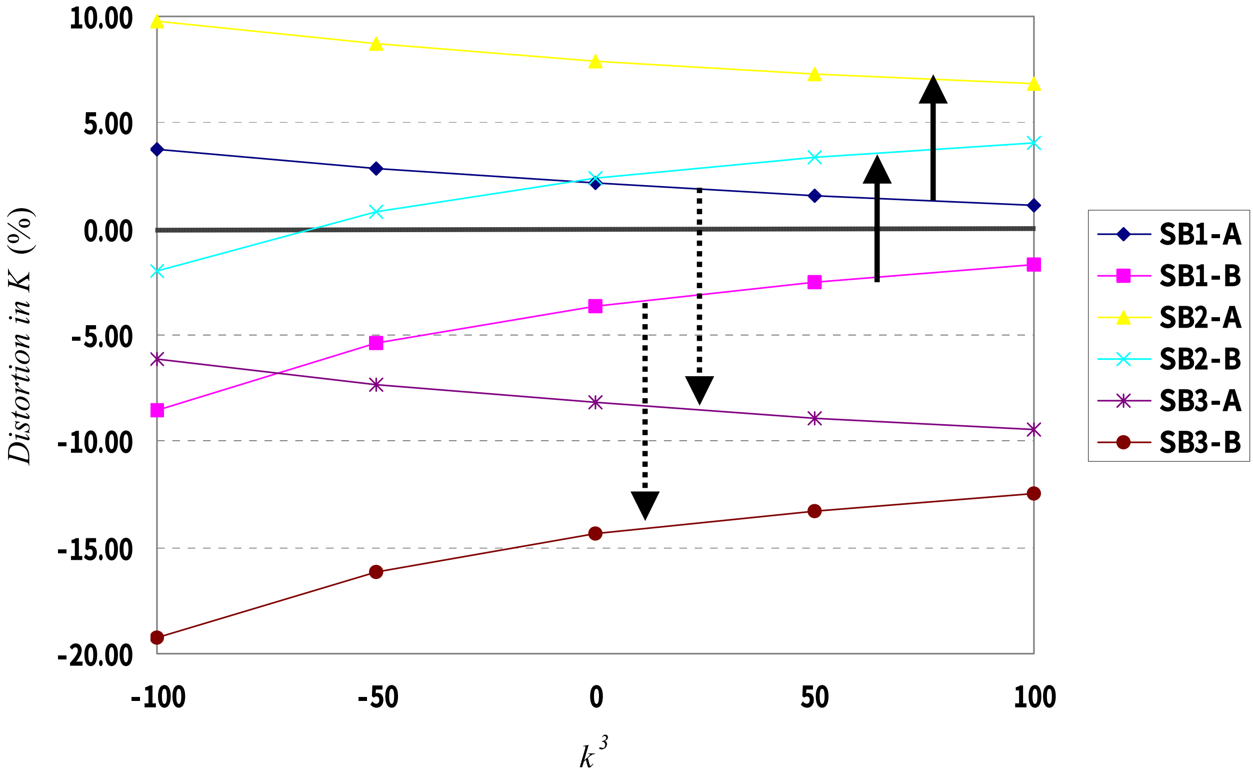


Figure 2. Varying B's Travel Demand in SB1: Distortion in K

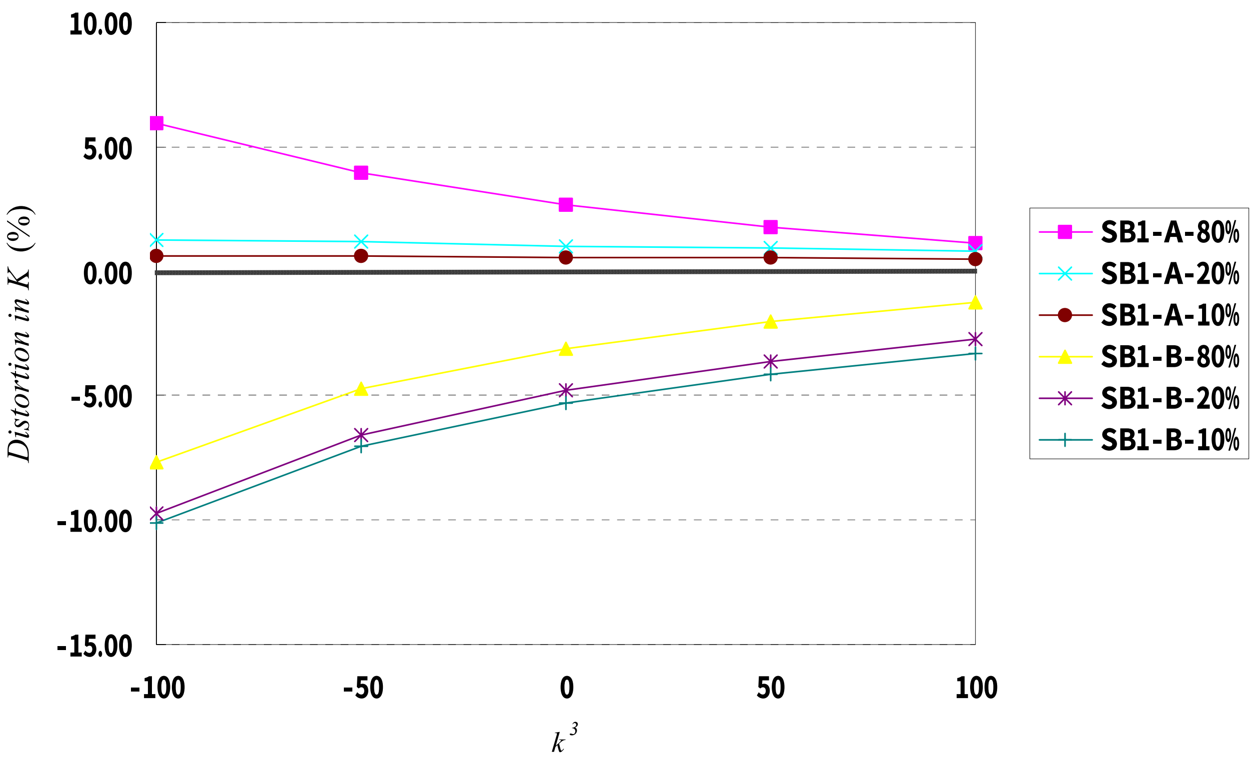


Figure 3. Varying the Price Elasticity of Travel Demand in SB1: Distortion in *K*

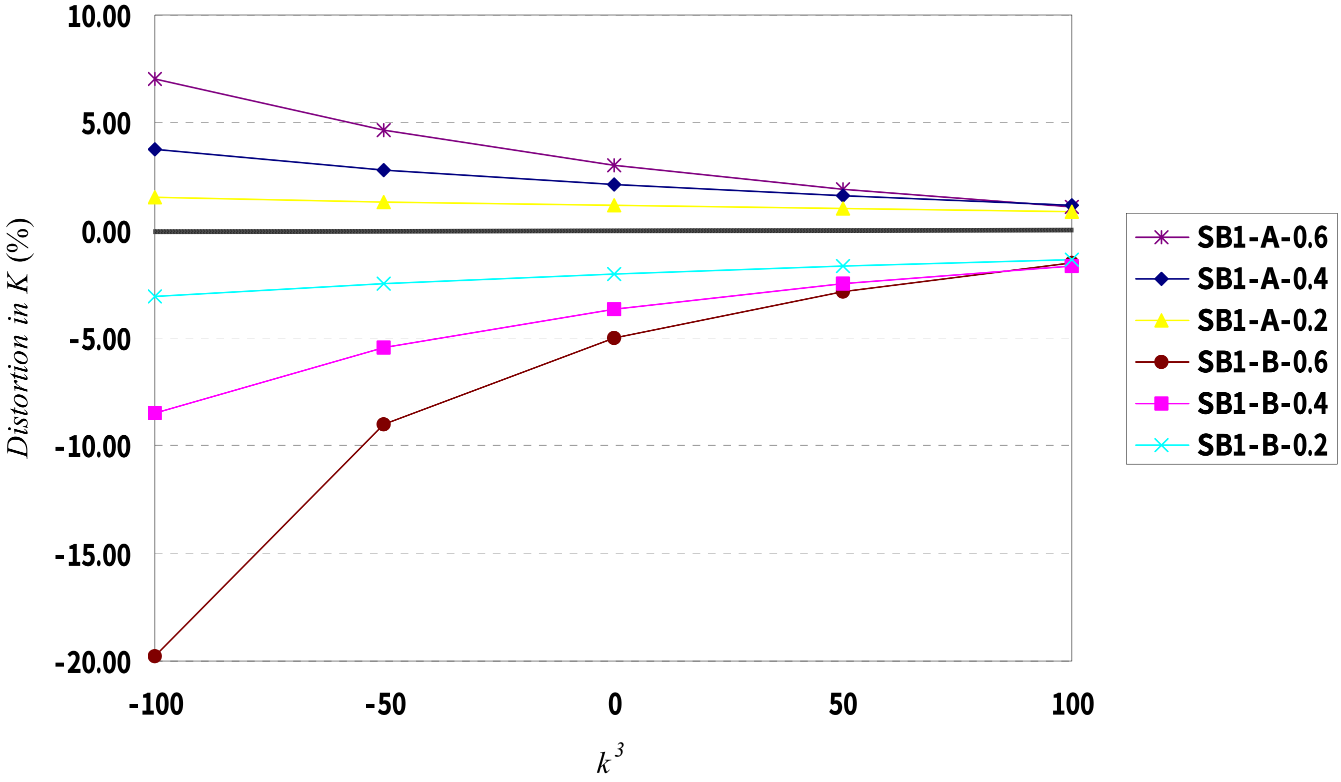
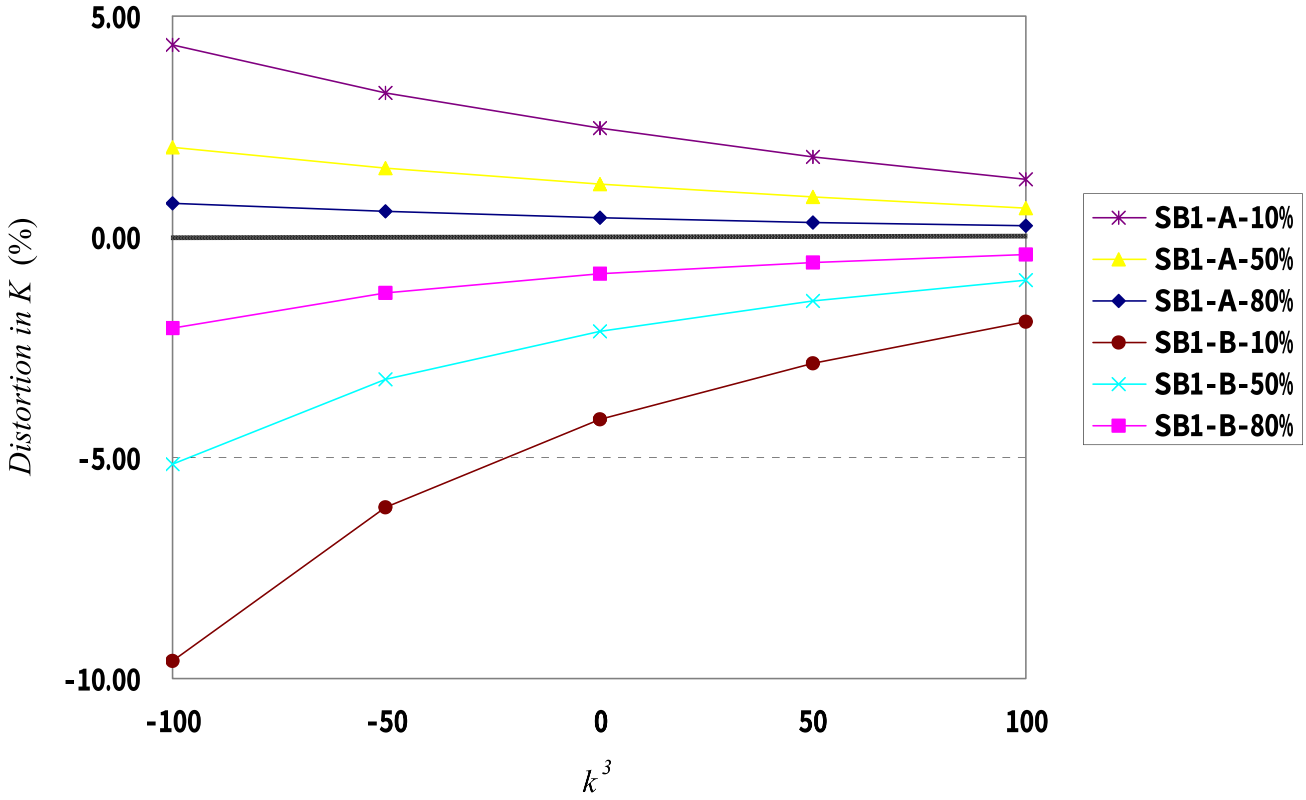


Figure 4. Varying A's Construction Cost in SB1: Distortion in *K*



Appendix

Derivation of (16) to (21)

Totally differentiating (3), (4), (9), and (10) yields:

$$\begin{pmatrix} u_{x^A x^A} - c^A_{x^A} & u_{x^A x^B} \\ u_{x^A x^B} & u_{x^B x^B} - c^B_{x^B} \end{pmatrix} \begin{pmatrix} dx^A \\ dx^B \end{pmatrix} = \begin{pmatrix} d\tau^A + c^A_{K^A} dK^A \\ d\tau^B + c^B_{K^B} dK^B \end{pmatrix}. \tag{A1}$$

From (A1), we obtain:

$$\frac{dx^A}{d\tau^A} = \frac{u_{x^B x^B} - c^B_{x^B}}{D} < 0, \quad \frac{dx^A}{dK^A} = \frac{(u_{x^B x^B} - c^B_{x^B}) c^A_{K^A}}{D} > 0, \quad \frac{dx^A}{d\tau^B} = \frac{dx^B}{d\tau^A} = \frac{-u_{x^A x^B}}{D},$$

$$\frac{dx^A}{dK^B} = \frac{-u_{x^A x^B} c^B_{K^B}}{D}, \quad \frac{dx^B}{dK^A} = \frac{-u_{x^A x^B} c^A_{K^A}}{D}, \quad \frac{dx^B}{d\tau^B} = \frac{u_{x^A x^A} - c^A_{x^A}}{D} < 0,$$

$$\frac{dx^B}{dK^B} = \frac{(u_{x^A x^A} - c^A_{x^A}) c^B_{K^B}}{D} > 0, \tag{A2}$$

where

$$\begin{aligned} D &\equiv (u_{x^A x^A} - c^A_{x^A})(u_{x^B x^B} - c^B_{x^B}) - (u_{x^A x^B})^2 \\ &= u_{x^A x^A} u_{x^B x^B} - (u_{x^A x^B})^2 - c^B_{x^B} u_{x^A x^A} - c^A_{x^A} u_{x^B x^B} + c^A_{x^A} c^B_{x^B} > 0 \end{aligned} \tag{A3}$$

from (8), $u_{x^A x^A} < 0$, $u_{x^B x^B} < 0$, $c^A_{x^A} > 0$, and $c^B_{x^B} > 0$.

Using (11) and (12), we can rewrite (15) as:

$$
\begin{aligned}
SW = y - c^A(x^A(\tau^A,\tau^B,K^A,K^B),K^A)x^A(\tau^A,\tau^B,K^A,K^B) \\
-c^B(x^B(\tau^A,\tau^B,K^A,K^B),K^B)x^B(\tau^A,\tau^B,K^A,K^B) \\
+u(x^A(\tau^A,\tau^B,K^A,K^B),x^B(\tau^A,\tau^B,K^A,K^B)) - c^{AK}K^A - c^{BK}K^B.
\end{aligned} \tag{A4}
$$

Maximizing (A4) with respect to τ^A, τ^B, K^A, and K^B yields:

$$
\frac{\partial SW}{\partial \tau^A} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_{\tau^A} + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_{\tau^A} = 0, \tag{A5}
$$

$$
\frac{\partial SW}{\partial \tau^B} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_{\tau^B} + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_{\tau^B} = 0, \tag{A6}
$$

$$
\frac{\partial SW}{\partial K^A} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_{K^A} + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_{K^A} - c^A_{K^A}x^A - c^{AK} = 0, \tag{A7}
$$

$$
\frac{\partial SW}{\partial K^B} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_{K^B} + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_{K^B} - c^B_{K^B}x^B - c^{BK} = 0. \tag{A8}
$$

From (3), (4), (A5), and (A6):

$$
(\tau^A - c^A_{x^A}x^A)(x^A_{\tau^A}x^B_{\tau^B} - x^A_{\tau^B}x^B_{\tau^A}) = 0. \tag{A9}
$$

Rearranging (A9) using (A2) and (A3) yields:

$$
\frac{\tau^A - c^A_{x^A}x^A}{D} = 0. \tag{A10}
$$

Since $D > 0$ from (A3), we obtain:

$$
\tau^A = c^A_{x^A}x^A, \tag{A11}
$$

which is (16). Substituting (A11) into (A5) yields:

$$\tau^B = c^B_{x^B} x^B , \tag{A12}$$

which is (17). Substituting (A11) and (A12) into (A7) and (A8) yields:

$$-c^A_{K^A} x^A = c^{AK} , \tag{A13}$$

$$-c^B_{K^B} x^B = c^{BK} , \tag{A14}$$

which are (18) and (19), respectively.

The assumption that $c^A(x^A, K^A)$ and $c^B(x^B, K^B)$ are homogeneous of degree zero implies:

$$c^A_{x^A} x^A + c^A_{K^A} K^A = 0 , \tag{A15}$$

$$c^B_{x^B} x^B + c^B_{K^B} K^B = 0 . \tag{A16}$$

Rearranging (A11), (A13), and (A15), we obtain:

$$\tau^A x^A = c^{AK} K^A , \tag{A17}$$

which is (20). Rearranging (A12), (A14), and (A16) yields:

$$\tau^B x^B = c^{BK} K^B , \tag{A18}$$

which is (21).

Derivation of the results in subsection 4.1

Substituting $d\tau^A = d\tau^B = d\tau$ into (A1), we obtain the following properties:

$$\frac{dx^A}{d\tau} = \frac{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}}{D}, \quad \frac{dx^A}{dK^A} = \frac{(u_{x^B x^B} - c^B_{x^B})c^A_{K^A}}{D} > 0, \quad \frac{dx^A}{dK^B} = \frac{-u_{x^A x^B} c^B_{K^B}}{D},$$

$$\frac{dx^B}{d\tau} = \frac{u_{x^A x^A} - c^A_{x^A} - u_{x^A x^B}}{D}, \quad \frac{dx^B}{dK^A} = \frac{-u_{x^A x^B} c^A_{K^A}}{D}, \quad \frac{dx^B}{dK^B} = \frac{(u_{x^A x^A} - c^A_{x^A})c^B_{K^B}}{D} > 0. \qquad \text{(A19)}$$

In the second-best case, (A4) is:

$$SW = y - c^A(x^A(\tau, K^A, K^B), K^A)x^A(\tau, K^A, K^B) - c^B(x^B(\tau, K^A, K^B), K^B)x^B(\tau, K^A, K^B)$$
$$+u(x^A(\tau, K^A, K^B), x^B(\tau, K^A, K^B)) - c^{AK}K^A - c^{BK}K^B.$$
(A20)

Maximizing (A20) with respect to τ, K^A, and K^B yields:

$$\frac{\partial SW}{\partial \tau} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_\tau + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_\tau = 0, \qquad \text{(A21)}$$

$$\frac{\partial SW}{\partial K^A} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_{K^A} + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_{K^A} - c^A_{K^A}x^A - c^{AK} = 0, \qquad \text{(A22)}$$

$$\frac{\partial SW}{\partial K^B} = (-c^A - c^A_{x^A}x^A + u_{x^A})x^A_{K^B} + (-c^B - c^B_{x^B}x^B + u_{x^B})x^B_{K^B} - c^B_{K^B}x^B - c^{BK} = 0. \qquad \text{(A23)}$$

Rearranging (A21) using $\theta^i \equiv -\frac{\partial x^i}{\partial \tau}\frac{\tau}{x^i}$ ($i = A, B$) yields:

$$\tau = \frac{\theta^A x^A (c^A_{x^A} x^A) + \theta^B x^B (c^B_{x^B} x^B)}{\theta^A x^A + \theta^B x^B}, \qquad \text{(A24)}$$

which is (25).

Derivation of the results in subsection 4.2

Rearranging (A22) using (3), (4), (A19), and (A21) yields:

$$
\begin{aligned}
-c^A_{K^A} x^A &= c^{AK} - \frac{(\tau - c^B_{x^B} x^B)(x^A_\tau x^B_{K^A} - x^B_\tau x^A_{K^A})}{x^A_\tau} \\
&= c^{AK} - \frac{(\tau - c^B_{x^B} x^B)\left(\dfrac{-c^A_{K^A}}{D}\right)}{\dfrac{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}}{D}} \\
&= c^{AK} + \frac{(\tau - c^B_{x^B} x^B) c^A_{K^A}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}}.
\end{aligned}
\tag{A25}
$$

When $c^A_{x^A} x^A \geq c^B_{x^B} x^B$ and $\theta^i > 0$, we obtain $\tau > c^B_{x^B} x^B$ from (A24). Since $\theta^i > 0$ implies $\frac{dx^A}{d\tau} = \frac{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}}{D} < 0$, it follows that $u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B} < 0$ from (A3). Given $\tau > c^B_{x^B} x^B$, $c^A_{K^A} < 0$, and $u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B} < 0$, we have:

$$
-c^A_{K^A} x^A = c^{AK} + \frac{(\tau - c^B_{x^B} x^B) c^A_{K^A}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}} > c^{AK}, \tag{A26}
$$

which is (26). Similarly, rearranging (A23) using (3), (4), (A19), and (A21) yields:

$$-c^B_{K^B}x^B = c^{BK} - \frac{(\tau - c^B_{x^B}x^B)(x^A_\tau x^B_{K^B} - x^B_\tau x^A_{K^B})}{x^A_\tau}$$

$$= c^{BK} - \frac{(\tau - c^B_{x^B}x^B)\left(\dfrac{c^B_{K^B}}{D}\right)}{\dfrac{u_{x^Bx^B} - c^B_{x^B} - u_{x^Ax^B}}{D}} \tag{A27}$$

$$= c^{BK} - \frac{(\tau - c^B_{x^B}x^B)c^B_{K^B}}{u_{x^Bx^B} - c^B_{x^B} - u_{x^Ax^B}}.$$

Given $\tau > c^B_{x^B}x^B$, $c^B_{K^B} < 0$, and $u_{x^Bx^B} - c^B_{x^B} - u_{x^Ax^B} < 0$, we have:

$$-c^B_{K^B}x^B = c^{BK} - \frac{(\tau - c^B_{x^B}x^B)c^B_{K^B}}{u_{x^Bx^B} - c^B_{x^B} - u_{x^Ax^B}} < c^{BK}, \tag{A28}$$

which is (27).

Derivation of the results in subsection 4.3

When $c^A_{x^A}x^A \geq c^B_{x^B}x^B$ and $\theta^i > 0$, (A24) implies:

$$c^B_{x^B}x^B < \tau < c^A_{x^A}x^A. \tag{A29}$$

(A15), (A26), and (A29) imply:

$$\tau < c^A_{x^A}x^A = -c^A_{K^A}K^A = \frac{(c^{AK} + SBDWL^A)K^A}{x^A}, \tag{A30}$$

where $SBDWL^A \equiv \dfrac{(\tau - c^B_{x^B}x^B)c^A_{K^A}}{u_{x^Bx^B} - c^B_{x^B} - u_{x^Ax^B}} > 0$. Rearranging (A30) yields:

$$\tau x^A < (c^{AK} + SBDWL^A)K^A, \tag{A31}$$

which is (28). Similarly, from (A16), (A28), and (A29), we derive:

$$\tau > c^B_{x^B} x^B = -c^B_{K^B} K^B = \frac{(c^{BK} - SBDWL^B) K^B}{x^B}, \tag{A32}$$

where $SBDWL^B \equiv \dfrac{(\tau - c^B_{x^B} x^B) c^B_{K^B}}{u_{x^B x^B} - c^B_{x^B} - u_{x^A x^B}} > 0$. Rearranging (A32) yields:

$$\tau x^B > (c^{BK} - SBDWL^B) K^B, \tag{A33}$$

which is (29).

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