Revenue-recycling within Transport Networks

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Abstract

This paper analyzes the second-best pricing and investment policy for transport networks with a revenue-recycling mechanism in which the toll revenue is used as transport investments or subsidies, as in London's congestion charging scheme. The results of this paper demonstrate that the way toll revenue is used significantly modifies the usual results, where a lump-sum transfer is assumed. First, revenue-recycling as investment has an effect that works to increase the second-best toll when the benefits from it are larger than the costs. Revenue-recycling as a subsidy does not have such an effect. Second, 'partial' cost–benefit analysis that focuses only on the targeted transport mode would usually lead to a false conclusion as to whether the toll revenues should be used as transport investments, subsidies, or general tax revenues. The 'full' cost–benefit analysis, which includes changes in consumer surplus and producer surplus in all transport modes, is necessary.

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1 Introduction

In many large cities throughout the world, motorization causes severe road congestion. For instance, Transport for London (2003, p.53) reports that the average all-day speed had declined gradually before the congestion charging scheme was introduced, and was 14.2 km per hour in central London in 2002. One of the economic solutions proposed for such road congestion, at least since Walters (1961) and Vickery (1963), has been a congestion tax. The standard argument for the congestion tax asserts that given no distortion in other parts of the economy, the congestion tax policy can attain a first-best situation if the congestion tax is set equal to the congestion externality, which is the difference between the average cost of auto transport and the marginal cost. The cost recovery theorem[2], originally derived by Mohring and Harwitz (1962) and Strotz (1965), shows that the revenue from the first-best congestion tax is just sufficient to finance optimal capacity. However, congestion tax policies are rarely adopted, although recent developments in information and technology make the technological barrier to introducing them much lower.

In actual situations, there are reasons why introducing the first-best congestion tax policies is difficult, even if technological problems are completely resolved. First, congestion tax policies are unpopular among citizens. They may be unaware of the benefits from reduced travel costs by decreased congestion, but they are aware of the increased price. Congestion tax policies are also vulnerable to the criticism that the government wants to introduce them as excuses for another stable revenue source. Second, in the trend of privatization, it becomes common for different transport modes

[2] This naming is based on De Palma and Lindsey (2007). Other recent articles on this issue (e.g., Bichsel (2001) and Verhoef and Rouwendal (2004)) call it the revenue-recycling result (or theorem).

to be run by different organizations. For instance, the ownership and operation structure of the transport network in Tokyo is very complicated. Railways, other than some subways, are owned and run by private firms on a stand-alone basis. Highways were privatized in 2005. Highway assets are owned by the national government, but the operation and maintenance are delegated to the privatized firm, Metropolitan Expressway Co., Ltd., which leases the highway assets and pays fees from collected highway tolls. Ordinary roads are owned and operated by the national and local governments, which collect fuel taxes and construct roads. Such a complex ownership and operation structure would make it difficult to implement the first-best policy for the entire transport network.

The congestion charging scheme introduced in London in 2003 is noteworthy. One of the important features of this is that it has a clear link between the revenue from the charge and the use of the revenue, which is by law limited to spending on improving transport in London. However, the analyses of congestion taxes so far have not formerly dealt with how to use the revenue from congestion tax; that is, past studies have at least implicitly assumed that the revenue is returned via lump-sum transfer, although some articles (e.g., Small (1992) and Goodwin (1994)) have proposed practical suggestions on how to use it.[3] Therefore, the existing literature cannot give us direct insights on how to evaluate a London-type congestion charging scheme.

The purpose of this paper is to analyze the second-best pricing and investment policy for transport networks with a built-in mechanism where the revenue from the pricing is

[3] Small (1992) suggests that one-third of the revenues should be allocated to each of the following categories: (i) monetary reimbursement to travelers as a group; (ii) substitution for general taxes; and (iii) new transportation services. Goodwin's (1994) suggestion is that one-third of the revenues should be allocated to: (i) improvements to the effectiveness of the alternative methods of transport, especially public transport; (ii) improvements in the quality of roads; and (iii) general tax revenue.

used as an investment or subsidy, which is called a 'revenue-recycling' mechanism within transport networks, adopting terminology similar to that introduced by Bovenberg and Goulder (2002), and to clarify the difference from the standard argument using a simple stylized model. The model in this paper has the following features. A representative consumer demands transport services on two routes: route 1 and route 2. The relationship between the two routes may be substitutes or complements. For instance, they may be roads and substitute public transit. Another example is an urban highway and a complementary rural highway. For the transport authority, the price of route 2 is exogenous, possibly because route 2 is operated by another body based on its own principle or route 2 is untolled transport mode (e.g., rural road). The transport authority collects the revenue from route 1 and uses part of it for revenue-recycling within transport networks, which includes investment in route 1 and investment and a subsidy for route 2 in this paper. The remaining revenue is assumed to be returned via lump-sum transfer. The ratio of the revenue that is used as investments or subsidies within transport networks is called the degree of revenue-recycling.

The main results of this paper are summarized as follows. For concreteness, the results are explained here following a typical case in which routes 1 and 2 are roads and substitute public transit whose price is higher than its marginal cost.

First, suppose that the transport authority can determine both the road price and the degree of revenue-recycling. Controlling the degree of revenue-recycling is equivalent to controlling the amount of the investment or subsidy. Therefore, the problem considered here is reduced to that of the second-best policy with overpriced public transport. In the case of revenue-recycling as investment in roads, the road price is higher than the first-best, influenced by overpriced public transit, but given this road price, the investment in roads is the first-best level. In the case of revenue-recycling as investment in public transit, the result is the same regarding the road price. However, the investment is made in overpriced public transit and consequently is distorted. When the revenue is recycled as subsidies for public transit with investments in roads and public transport fixed, the prices of roads and public transit are at their first-best level. This is because a high price in public transit is completely corrected by a subsidy for it.

Second, suppose that the transportation authority can change the road price; however, the degree of revenue-recycling is fixed. An example is London's congestion charging scheme, where the revenue is used to improve transport in London by law. When the marginal benefit of investment in roads or public transit is larger than its marginal cost, the road price is higher. This will be called the second-best investment effect. The second-best investment effect makes the road price higher, if the revenue from roads is used as investment in roads or public transit whose marginal benefit is larger than the marginal cost. If the revenue is recycled as subsidies for public transit with investments in roads and public transit fixed, the second-best investment effect disappears, because such subsidies do not correct the distortion in investment.

Third, consider a choice as to whether the road revenue should be returned via the revenue-recycling mechanism in the form of investments or subsidies within transport networks or via general-purpose taxes, given the fixed road price. For example, there has been an active debate in Japan about whether the revenue from fuel taxes should be used for purposes other than construction of roads or not, although all the revenue is now purported to be used for construction of roads. A 'full' cost–benefit analysis including all the parts of the transport network can deal with this issue. A 'partial' cost–benefit analysis, which only takes into account the transport mode for which the revenue is recycled, is invalid, unless the price equals the marginal cost in all the parts of the transport networks or the demand in each route is fixed.

The structure of the paper is as follows. In section 2, a basic model is presented. Section 3 deals with the case where the revenue from route 1 is used for an investment in route 1. In section 4, the revenue from route 1 is used for an investment in route 2. Section 5 focuses on the case where the revenue is used to provide a subsidy for route 2. Section 6 concludes the analysis.

2 Model

A representative consumer demands the composite consumer good z, a transport service in route 1, and a transport service in route 2. The transport demand in each route is x^1 and x^2. The superscripts denote routes throughout the paper. We assume that both routes are congestible through their own demand and that congestion increases travel time.

The utility function of a representative consumer is:

(1) $$U = z + u(x^1, x^2),$$

which is assumed to be strictly concave. The quasilinear utility function of (1) implies that income effects are ignored. This simplifying assumption can be justified in that the share of transport expenditure in total household expenditure is usually low. The price of the composite consumer good, z, is normalized to unity. Denoting the monetary price of each route by τ^1 and τ^2, the budget constraint of the representative consumer is:

(2) $$wl = z + \tau^1 x^1 + \tau^2 x^2,$$

where w is an hourly wage rate and l is hours of labor. For the sake of simplicity, we assume that the consumption of the composite consumer good, z, does not require time.

Denoting travel times in routes 1 and 2 by t^1 and t^2, the time constraint is:

(3) $\bar{L} = l + t^1 x^1 + t^2 x^2$,

where $\bar{L}$ is fixed available time, exclusive of leisure, for the representative consumer. Erasing l from (2) and (3), we obtain a generalized budget constraint, including a time constraint:

(4) $\bar{y} = z + p^1 x^1 + p^2 x^2$,

where $\bar{y}(\equiv w\bar{L})$ is maximum income and

(5) $p^i \equiv \tau^i + wt^i$

is a generalized price of route i ($i = 1,2$).

The travel time in each route, t^i, is longer when congestion is more severe and the capacity investment, I^i, is smaller, that is:

(6) $t^i = t^i(x^i, I^i)$ where $t^i_{x^i} > 0$ and $t^i_{I^i} < 0$ $i = 1,2$.

Throughout the paper, the subscripts denote partial derivatives unless otherwise noted. Because our analysis is unaffected by the level of the unit rental price of the capacity investment, we set it at one. For the same reason, the monetary cost in each route is set at zero. Therefore, the average cost per transport service in each route, c^i, is:

(7) $c^i(x^i, I^i) \equiv wt^i(x^i, I^i)$ $i = 1,2$,

where $c^i_{x^i} > 0$ and $c^i_{I^i} < 0$. Substituting (7) into (5), we rewrite the generalized price in each route as:

(8) $p^i = \tau^i + c^i(x^i, I^i)$.

A representative consumer maximizes his or her utility, (1), subject to the generalized budget constraint, (4). Maximization yields the following first-order conditions:

(9) $u_{x^i}(x^1, x^2) = p^i \quad i = 1,2$.

From (9), we derive the demand functions $x^1(p^1, p^2)$ and $x^2(p^1, p^2)$, which satisfy:

(10) $x^1_{p^2} = x^2_{p^1} = -u_{x^1x^2}$.

When x^1 and x^2 are substitutes with respect to the generalized prices, $x^1_{p^2} = x^2_{p^1} = -u_{x^1x^2} > 0$, which implies $u_{x^1x^2} < 0$. On the contrary, when they are complements, $x^1_{p^2} = x^2_{p^1} = -u_{x^1x^2} < 0$, which implies $u_{x^1x^2} > 0$.

Substituting (8) for $x^1(p^1, p^2)$ and $x^2(p^1, p^2)$ and rearranging, we obtain $x^1(\tau^1, \tau^2, I^1, I^2)$ and $x^2(\tau^1, \tau^2, I^1, I^2)$. Therefore, from (1), (4), and (8), the total surplus, TS, can be written as:

(11)
$$\begin{aligned} TS &= U + \tau^1 x^1 + \tau^2 x^2 - I^1 - I^2 \\ &= y - p^1 x^1 - p^2 x^2 + u(x^1, x^2) + \tau^1 x^1 + \tau^2 x^2 - I^1 - I^2 \\ &= y + u(x^1(\tau^1, \tau^2, I^1, I^2), x^2(\tau^1, \tau^2, I^1, I^2)) \\ &\quad -c^1(x^1(\tau^1, \tau^2, I^1, I^2), I^1) x^1(\tau^1, \tau^2, I^1, I^2) \\ &\quad -c^2(x^2(\tau^1, \tau^2, I^1, I^2), I^2) x^2(\tau^1, \tau^2, I^1, I^2) - I^1 - I^2. \end{aligned}$$

Maximizing (11) with respect to τ^1, τ^2, I^1, and I^2 yields the following first-best results:

(12) $\tau^i = c^i_{x^i} x^i \quad i = 1,2$, and

(13) $-c^i_{I^i} x^i = 1 \quad i = 1,2$.

(12) shows that the monetary price of each route equals the marginal congestion externality, which is the (social) marginal cost. (13) shows that the marginal benefit of investment, which stems from reduced congestion, equals the marginal cost of it.

Actual situations commonly differ from the first-best case. Government policies are implemented not only for efficiency but also for equity or other purposes. Even if the government only cared about efficiency, it would be difficult to implement integrated pricing and investment policies unless it owned and operated all transport networks where minute pricing was technically feasible. This requirement is usually difficult to satisfy, however.

From the following section, we focus on the second-best situation where at least the monetary price in route 2 is fixed, possibly because route 2 is operated by another body based on its own principle or route 2 is untolled transport mode (e.g., rural road). $100a$ % of the revenue from the monetary price (toll, fare, and taxes) in route 1 is assumed to be used within transport networks as investments or subsidies, and the remaining $100(1-a)$ % of the revenue is assumed to be returned via a lump-sum transfer, where a is a parameter that shows the degree of revenue-recycling within transport networks. When $a = 0$, all the revenue is returned via lump-sum transfer. To exclude this uninteresting case, we assume $0 < a \le 1$. It is useful to summarize the cases to be analyzed in Table 1, delineating control variables, which the transport authority can change, and exogenous variables. In Table 1, S^2 denotes the subsidy for route 2. We do not analyze a trivial case where the revenue from route 1 is used as a subsidy for route 1.

Section	3-1	3-2	3-3	4-1	4-2	4-3	5-1	5-2	5-3
Type of Revenue-recycling	$I^1 = a\tau^1 x^1$			$I^2 = a\tau^1 x^1$			$S^2 = a\tau^1 x^1$		
Control Variables	τ^1, a	τ^1	a	τ^1, a	τ^1	a	τ^1, a	τ^1	a
Exogenous Variables	τ^2, I^2	τ^2, I^2, a	τ^1, τ^2, I^2	I^1, τ^2	I^1, τ^2, a	τ^1, τ^2, I^1	τ^2, I^1, I^2	τ^2, I^1, I^2, a	τ^1, τ^2, I^1, I^2

Table 1 The cases to be analyzed

3 Revenue-recycling from Route 1 to Route 1 as Investments

In this section, we consider pricing and investment policies in route 1, given that route 2 is independently operated on its own standard, including full-cost basis, price-cap regulation, simple profit maximizing, etc. Therefore, the analysis in this section is that of second-best in which the monetary price and investment in route 2, τ^2 and I^2, are fixed with $\overline{\tau^2}$ and $\overline{I^2}$ under a revenue-recycling mechanism within route 1. Denote the revenue from the monetary price (e.g., toll, fare, and taxes) of route 1 by R^1:

(14) $R^1 = \tau^1 x^1$.

$100a$ % of the revenue is assumed to be used for an investment in route 1, and the remaining $100(1-a)$ % of the revenue is assumed to be returned via a lump-sum transfer. Therefore, we have:

(15) $I^1 = aR^1 = a\tau^1 x^1$.

From (8), (9), and (15), $x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2})$ and $x^2(\tau^2, a; \overline{\tau^2}, \overline{I^2})$ are derived. Modifying (11), the total surplus can be written as:

$$
\begin{aligned}
TS = {} & y + u(x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2}), x^2(\tau^1, a; \overline{\tau^2}, \overline{I^2})) \\
& - c^1(x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2}), a\tau^1 x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2}))x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2}) \\
& - c^2(x^2(\tau^1, a; \overline{\tau^2}, \overline{I^2}), \overline{I^2})x^2(\tau^1, a; \overline{\tau^2}, \overline{I^2}) - a\tau^1 x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2}) - \overline{I^2}.
\end{aligned} \tag{16}
$$

3-1 Second-best pricing and investment when the monetary price of route 1 and the degree of revenue-recycling are controllable

First, we consider the case where the transport authority can control both the monetary price of route 1, τ^1, and the degree of revenue-recycling, a. Controlling the degree of revenue-recycling means controlling the level of investments, but the maximum amount of investments is constrained by the revenue from route 1. Generally, an interior solution is not guaranteed to exist in the range of $0 < a < 1$. We assume here that an interior solution exists in that range and delegate the analysis of corner solution of $a = 1$ to the next section. Maximizing (16) with respect to τ^1 and a yields:

(17) $\tau^1 = c^1_{x^1} x^1 - (\overline{\tau^2} - c^2_{x^2} x^2)\dfrac{x^2_{\tau^1} I^1_a - x^2_a I^1_{\tau^1}}{x^1_{\tau^1} I^1_a - x^1_a I^1_{\tau^1}}$ and

(18) $-c^1_{I^1} x^1 = 1$,

where, from (A8) in Appendix 1, $\dfrac{x^2_{\tau^1} I^1_a - x^2_a I^1_{\tau^1}}{x^1_{\tau^1} I^1_a - x^1_a I^1_{\tau^1}} < 0$ if routes 1 and 2 are substitutes regarding p^i and $\dfrac{x^2_{\tau^1} I^1_a - x^2_a I^1_{\tau^1}}{x^1_{\tau^1} I^1_a - x^1_a I^1_{\tau^1}} > 0$ if they are complements regarding p^i.

The first term on the right-hand side of (17) represents the marginal congestion externality in the same way as (12). The second term on the right-hand side of (17) stems from the second-best situation where the monetary price of route 2 cannot be optimally adjusted. The monetary price of route 1 must be set to take into account the preexisting price distortions in route 2. The second term on the right-hand side of (17) is hereafter called the 'congestion spill-over effect' following Verhoef et al. (1996). For example, suppose that routes 1 and 2 are a congested highway and a substitute less-congested railway, and that the railway fare is higher than its congestion externality, because of full-cost basis pricing including the railway construction cost. In this case, the congestion spill-over effect is positive, because it is socially desirable to make use of less congested railways in route 2 by setting a high price in route 1 and converting the demand from routes 1 to 2.

In Verhoef et al. (1996), the congestion spill-over effect is represented by $-c_{x^2}^2 x^2 \left(\frac{-u_{x^1x^1}}{c_{x^2}^2 - u_{x^1x^1}} \right)$. The second term on the right-hand side of (17) coincides with their expression for a special case. If (i) routes 1 and 2 are perfect substitutes and (ii) there exists no revenue-recycling, that is,

(19) $U = z + u(x^1 + x^2)$

in (1) and $a = 0$, the second term of the right-hand side of (17) is reduced to

$$-c_{x^2}^2 x^2 \left(\frac{-u_{x^1x^1}}{c_{x^2}^2 - u_{x^1x^1}} \right).$$

Controlling the degree of revenue-recycling, a, means controlling the investment level in route 1, I^1. (18) coincides with (13), which demonstrates that the degree of revenue-recycling must be set so that the marginal benefit of investment in route 1, I^1, equals the marginal cost even in the second-best case. This result relies on the fact that investment is made for route 1 where the monetary price of route 1 is adjusted. The result will be changed in the analysis in section 4 where the investment is made for route 2 whose price is unadjusted.

3-2 Second-best pricing when the degree of revenue-recycling as investment in route 1 is fixed

Second, we focus on the case where the degree of revenue-recycling is fixed. The analysis includes the case where the revenue allocation between general tax revenue and investment in route 1 is predetermined but the monetary price of route 1 is controllable for the transport authority. The analysis also includes the case of corner solution ($a = 1$), in which all the revenue is used for the investment in route 1. Maximizing (16) with respect to τ^1 yields:

$$(20) \quad \tau^1 = c^1_{x^1} x^1 - (\overline{\tau^2} - c^2_{x^2} x^2)\frac{x^2_{\tau^1}}{x^1_{\tau^1}} - \frac{(-c^1_{I^1} x^1 - 1) I^1_{\tau^1}}{x^1_{\tau^1}}{}^4,$$

where, from (A8) in Appendix 1, $\frac{x^2_{\tau^1}}{x^1_{\tau^1}} < 0$ if routes 1 and 2 are substitutes regarding p^i and $\frac{x^2_{\tau^1}}{x^1_{\tau^1}} > 0$ if they are complements regarding p^i, and $\frac{I^1_{\tau^1}}{x^1_{\tau^1}} < 0$ from (A6).

The first and second terms of the right-hand side of (20) can be interpreted in the same way as that of (17). The third term of the right-hand side of (20) shows the effects of revenue-recycling as investment in route 1 when the degree of revenue-recycling is fixed. This effect stems from the fact that the investment in route 1 can not be adjusted. We call this effect the second-best investment effect. When $-c^1_{I^1} x^1 > 1$, that is, the marginal benefit of the investment in route 1 is larger than its marginal cost, which is

[4] A simpler version of this equation is derived in Kidokoro (2005).

unity, the second-best investment effect works to make the monetary price of route 1 higher. If $\overline{\tau^2} = c^2_{x^2} x^2$, that is, the congestion spill-over effect is zero, the second-best investment effect makes the monetary price of route 1 higher than the first-best level, as long as $-c^1_{I^1} x^1 > 1$. The higher monetary price than the first-best is justified, because the investment in route 1 through revenue-recycling additionally magnifies the total surplus. Whether the marginal benefit of investment is larger than its marginal cost or not determines the direction of the second-best investment effect, which is unaffected by the relationship between routes 1 and 2, i.e., whether they are substitutes or complements.

3-3 Second-best investment for route 1 when the monetary price of route 1 is fixed

Third, we analyze the case where the monetary price of route 1 is fixed. This analysis includes the case where the monetary price is politically predetermined at a certain level and difficult to adjust; however, the transport authority can adjust the budget for the investment in route 1. In this section, we focus on how to determine the degree of revenue-recycling.

Partially differentiating (16) with respect to a yields:

(21) $$TS_a = (\overline{\tau^1} - c^1_{x^1} x^1) x^1_a + (\overline{\tau^2} - c^2_{x^2} x^2) x^2_a + (-c^1_{I^1} x^1 - 1) I^1_a,$$

where $x^1_a > 0$ and $I^1_a > 0$ from (A2) and (A7) in Appendix 1. From (A4), $x^2_a < 0$ if routes 1 and 2 are substitutes regarding p^i and $x^2_a > 0$ if they are complements regarding p^i.

(21) clarifies that it is generally incorrect to determine the degree of revenue-recycling focusing only on the marginal benefit of investment and its marginal cost in

route 1, as Arnott and Yan (2000) point out. For example, suppose that the monetary price of highways is lower than its social marginal cost because of congestion, but for substitute railways, the reverse situation holds. In this case, the first and second terms of the right-hand side of (21) are negative, because the demand in route 1 is increased and that in route 2 is decreased. Therefore, if a naive transport authority implements investment up to the point where the marginal benefit of investment in highways equals its marginal cost, $TS_a < 0$, that is, overinvestment occurs. This result suggests that the total surplus is possibly higher if the revenue from the highway toll is returned not via highway investment but via general-purpose taxes, even when the cost–benefit analysis for highways is favorable. This 'partial' investment rule, which compares the marginal benefit of the invested route and its marginal cost, is true only when i) the monetary price of each route is its first-best level or ii) the transport demand in each route does not change.

The practical solution to this problem is to implement cost–benefit analysis including all the transport networks. Integrating (21) with respect to a and rearranging yields:

$$(22) \quad \Delta TS = \int_{p^{1W}}^{p^{1WO}} x^1 dp^1 + \int_{p^{2W}}^{p^{2WO}} x^2 dp^2 + \int_{a^{WO}}^{a^{W}} \frac{d(\overline{\tau^1} x^1)}{da} da + \int_{a^{WO}}^{a^{W}} \frac{d(\overline{\tau^2} x^2)}{da} da - \Delta I^1,$$

where $\Delta I^1 \equiv I^{1W} - I^{1WO}$. The superscripts W and WO represent 'the case where the degree of revenue-recycling is changed' and 'the case where the degree of revenue-recycling is not changed'.

The first term of the right-hand side in (26) is consumer surplus in route 1, the second term is consumer surplus in route 2, the third term is producer surplus in route 1, and the fourth term is producer surplus in route 2. From (22), in order to determine the degree of revenue-recycling, the usual procedure of cost–benefit analysis suffices, noting that each route corresponds to each market and that the correct benefits are the sum of consumer and producer surpluses in all routes.

4 Revenue-recycling from Route 1 to Route 2 as Investments

We turn our analysis to the case where the revenue from route 1 is used for the investment in route 2. For example, in London's congestion charging scheme, the revenue from congestion charging is used for the investment in public transit. This is the case where route 1 is roads and route 2 is public transit. Another example is to construct rural highways using the toll revenue from urban highways, where route 1 is urban highways and route 2 is rural highways.

In this section, the monetary price in route 2 and investment in route 1, τ^2 and I^1, are fixed with $\overline{\tau^2}$ and $\overline{I^1}$. $100a$ % of the revenue from route 1 is used for the investment in route 2:

(23) $I^2 = aR^1 = a\tau^1 x^1$.

The remaining $100(1-a)$ % is returned via a lump-sum transfer.

From (5), (9), and (23), $x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1})$ and $x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1})$ are derived. The total surplus in this case is as follows.

(24)
$$\begin{aligned} TS = {} & y + u(x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}), x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1})) \\ & - c^1(x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}), \overline{I^1}) x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}) \\ & - c^2(x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}), a\tau^1 x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1})) x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}) - a\tau^1 x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}) - \overline{I^1} \end{aligned}$$

4-1 Second-best pricing and investment when the monetary price of route 1 and the degree of revenue-recycling are controllable

First, we consider the case where the transport authority can control both the monetary price of route 1, τ^1, and the degree of revenue-recycling as investment in route 2, a. As in the analysis in section 3-1, controlling the degree of revenue-recycling means controlling the level of investment in route 2; however, an interior solution is not guaranteed to exist in the range $0 < a < 1$. We assume here that an interior solution exists in that range and delegate the analysis of the corner solution of $a = 1$ to section 4-2. Maximizing (24) with respect to τ^1 and a yields:

(25) $$\tau^1 = c^1_{x^1} x^1 - (\overline{\tau^2} - c^2_{x^2} x^2) \frac{x^2_{\tau^1} I^2_a - x^2_a I^2_{\tau^1}}{x^1_{\tau^1} I^2_a - x^1_a I^2_{\tau^1}}$$ and

(26) $$-c^2_{I^2} x^2 = 1 + (\overline{\tau^2} - c^2_{x^2} x^2) \frac{x^2_{\tau^1} x^1_a - x^2_a x^1_{\tau^1}}{x^1_{\tau^1} I^2_a - x^1_a I^2_{\tau^1}},$$

where from (A16) in Appendix 2, $\frac{x^2_{\tau^1} I^2_a - x^2_a I^2_{\tau^1}}{x^1_{\tau^1} I^2_a - x^1_a I^2_{\tau^1}} < 0$ if routes 1 and 2 are substitutes regarding p^i and $\frac{x^2_{\tau^1} I^2_a - x^2_a I^2_{\tau^1}}{x^1_{\tau^1} I^2_a - x^1_a I^2_{\tau^1}} > 0$ if they are complements regarding p^i. From (A17) in Appendix 2, $\frac{x^2_{\tau^1} x^1_a - x^2_a x^1_{\tau^1}}{x^1_{\tau^1} I^2_a - x^1_a I^2_{\tau^1}} < 0$.

From (25) and (26), the following four cases are possible, depending on the sign of $\overline{\tau^2} - c^2_{x^2} x^2$ and the relationship between routes 1 and 2:

i) $\tau^1 > c^1_{x^1} x^1$ and $-c^2_{I^2} x^2 < 1$ if routes 1 and 2 are substitutes and $\overline{\tau^2} > c^2_{x^2} x^2$,

ii) $\tau^1 < c^1_{x^1} x^1$ and $-c^2_{I^2} x^2 > 1$ if routes 1 and 2 are substitutes and $\overline{\tau^2} < c^2_{x^2} x^2$,

iii) $\tau^1 < c^1_{x^1}x^1$ and $-c^2_{I^2}x^2 < 1$ if routes 1 and 2 are complements and $\overline{\tau^2} > c^2_{x^2}x^2$,

iv) $\tau^1 > c^1_{x^1}x^1$ and $-c^2_{I^2}x^2 > 1$ if routes 1 and 2 are complements and $\overline{\tau^2} < c^2_{x^2}x^2$.

The results of i) to iv) can be understood intuitively. In the case of $\overline{\tau^2} > c^2_{x^2}x^2$, it is desirable to increase investment in route 2 to eliminate the distortion from a high price, and consequently, $-c^2_{I^2}x^2 < 1$ holds. On the contrary, in the case of $\overline{\tau^2} < c^2_{x^2}x^2$, a decrease in investment in route 2 is desirable to eliminate the distortion from a low price, and hence, $-c^2_{I^2}x^2 > 1$ holds. If routes 1 and 2 are substitutes, the congestion spill-over effect yields $\tau^1 > c^1_{x^1}x^1$ when $\overline{\tau^2} > c^2_{x^2}x^2$ and $\tau^1 < c^1_{x^1}x^1$ when $\overline{\tau^2} < c^2_{x^2}x^2$. If they are substitutes, the congestion spill-over brings $\tau^1 < c^1_{x^1}x^1$ when $\overline{\tau^2} > c^2_{x^2}x^2$, and $\tau^1 > c^1_{x^1}x^1$ when $\overline{\tau^2} < c^2_{x^2}x^2$. This result is an expansion of Wheaton (1978), which derives the second-best investment level under a distorted price for a single road.

4-2 Second-best pricing when the degree of revenue-recycling as investment in route 2 is fixed

Second, we examine the case where the degree of revenue-recycling as investment in route 2 is fixed. The analysis includes the case of a corner solution ($a = 1$). Maximizing (24) with respect to τ^1 yields:

(27) $$\tau^1 = c^1_{x^1}x^1 - (\overline{\tau^2} - c^2_{x^2}x^2)\frac{x^2_{\tau^1}}{x^1_{\tau^1}} - \frac{(-c^2_{I^2}x^2 - 1)I^2_{\tau^1}}{x^1_{\tau^1}},$$

where, from (A14) in Appendix 2, $\frac{I^2_{\tau^1}}{x^1_{\tau^1}} < 0$. The sign of $\frac{x^2_{\tau^1}}{x^1_{\tau^1}}$ does not correspond to whether routes 1 and 2 are substitutes or complements from (A9) and (A11) in

Appendix 2. An increase in the monetary price of route 1 causes three effects on route 2. The first effect is an increase or a decrease in demand in route 2 by the relationship of substitutes or complements between routes 1 and 2. This is the same as in the analysis in section 3-2. The second effect is an increase in demand in route 2 by an increase in investment in route 2. The third effect is a decrease in demand in route 2 through reduced revenue-recycling, because an increase in the monetary price of route 1 causes a decrease in the demand in route 1, which results in a decrease in the revenue from route 1 and investment in route 2 ceteris paribus. Because of the second and third effects, the relationship between the sign of $\frac{x^2_{\tau^1}}{x^1_{\tau^1}}$ and the substitute or complement relationship between routes 1 and 2 is ambiguous here.

The third term of the right-hand side of (27) represents the second-best investment effect in the same way as in (20). The second-best investment effect is positive if the marginal benefit of investment is larger than its marginal cost in route 2, not in route 1. That is, the second-best investment effect makes the monetary price of route 1 higher in this case. This property justifies an increase in the monetary price of route 1 in the situation where the degree of revenue-recycling as investment in route 2 is predetermined and the investment in route 2 is socially insufficient. The result suggests that a very high congestion charge in London, 8 GBP a day in 2007, can be justified under its implementation scheme where all the revenue from congestion charging is determined by law to be used to improve a transport network in London and investment is made for substitute public transit.

4-3 Second-best investment for route 2 when the monetary price of route 1 is fixed

Third, we analyze the case where the monetary price of route 1 is fixed. This includes the case where the monetary price is predetermined at a certain level and politically difficult to change but the transport authority can adjust the degree of revenue-recycling as investment in route 2.

Partially differentiating (24) with respect to a yields:

(28) $$TS_a = (\overline{\tau^1} - c^1_{x^1} x^1) x^1_a + (\overline{\tau^2} - c^2_{x^2} x^2) x^2_a + (-c^2_{I^2} x^2 - 1) I^2_a ,$$

where $x^2_a > 0$ and $I^2_a > 0$ from (A12) and (A15) in Appendix 2. From (A10), $x^1_a < 0$ if routes 1 and 2 are substitutes regarding p^i and $x^1_a > 0$ if they are complements regarding p^i.

(28) suggests that it is generally false to determine the degree of revenue-recycling focusing only on the marginal benefit of investment and the marginal cost of the invested route in the same way as the analysis in section 3-3. For example, suppose that the monetary price of highways is lower than its social marginal cost because of congestion; however, for substitute railways, the reverse situation holds. In this case, the first and second terms of the right-hand side of (28) are positive. Therefore, it is possible that $TS_a > 0$, i.e., underinvestment occurs, even if the marginal benefit of investment is smaller than its marginal cost in route 2. This result suggests that the total surplus is possibly higher if the revenue from route 1 is returned via railway investment, even when the cost–benefit analysis considering railways is unfavorable. The 'partial' investment decision rule, which compares the marginal benefit of the invested route and

its marginal cost, is valid only when i) the monetary price is the first-best level or ii) the transport demand in each route is fixed.

Integrating (28) with respect to a and rearranging yields:

$$(29) \quad \Delta TS = \int_{p^{1W}}^{p^{1WO}} x^1 dp^1 + \int_{p^{2W}}^{p^{2WO}} x^2 dp^2 + \int_{a^{WO}}^{a^W} \frac{d(\overline{\tau^1} x^1)}{da} da + \int_{a^{WO}}^{a^W} \frac{d(\overline{\tau^2} x^2)}{da} da - \Delta I^2 ,$$

where $\Delta I^2 \equiv I^{2W} - I^{2WO}$.

(29) can be interpreted in the same way as (22). The first, second, third, and fourth terms of the right-hand side in (29) are consumer surplus in route 1, consumer surplus in route 2, producer surplus in route 1, and producer surplus in route 2. (29) shows that the usual procedure of cost–benefit analysis is applicable to determine the degree of revenue-recycling, if the transport authority takes into account the fact that each route corresponds to each market, and the correct benefits are the sum of consumer and producer surpluses in all routes.

5 Revenue-recycling from Route 1 to Route 2 as a Subsidy

In this section, we consider the case where the revenue from route 1 is used as a subsidy for route 2 and make clear the difference between revenue-recycling as an investment and as a subsidy. In this section, the monetary price in route 2 and the investment levels in routes 1 and 2 are fixed with $\overline{\tau^2}$, $\overline{I^1}$, and $\overline{I^2}$. The monetary price of route 2 is now modified as:

$$(30) \quad p^2 = \overline{\tau^2} - s^2 + wt^2(x^2, \overline{I^2}) = \overline{\tau^2} - s^2 + c^2(x^2, \overline{I^2}) ,$$

where s^2 is a subsidy per transport service in route 2 and is endogenously determined to satisfy:

$$(31) \quad S^2 = aR^1 = a\tau^1 x^1 = s^2 x^2 .$$

From (5), (9), (30), and (31), $x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2})$ and $x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2})$ are derived. The total surplus can be written as:

$$
\begin{aligned}
TS = y + u(x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2}), x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2})) \\
-c^1(x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2}), \overline{I^1}) x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2}) \\
-c^2(x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}), \overline{I^2}) x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2}) - \overline{I^1} - \overline{I^2}.
\end{aligned}
\tag{32}
$$

5-1 Second-best pricing and subsidy when the monetary price of route 1 and the degree of revenue-recycling are controllable

First, we consider the case where the transport authority can set both the monetary price of route 1, τ^1, and the degree of revenue-recycling as a subsidy for route 2, a. Following the analysis in sections 3-1 and 3-2, an interior solution of a is not guaranteed in the range of $0 < a < 1$. We assume that an interior solution exists in that range and delegate the analysis of the corner solution of $a = 1$ to section 5-2.

Maximizing (32) with respect to τ^1 and a yields:

(33) $\tau^1 = c^1_{x^1} x^1$ and

(34) $\overline{\tau^2} - s^2 = c^2_{x^2} x^2$.

When the investment levels are fixed, the first-best result can be attained by controlling the monetary price of route 1, τ^1, and the degree of revenue-recycling as a subsidy for route 2, a. (34) demonstrates that s^2 should be set at the level where the *effective* monetary price of route 2 for a consumer is its social marginal cost. The monetary price of route 2, $\overline{\tau^2}$, is fixed, but a subsidy, s^2, is controllable by changing a. This means that the transport authority can implement the first-best price in route 2, by adjusting the degree of revenue-recycling as a subsidy for route 2. Given the first-best pricing in route 2, the transport authority should implement first-best pricing in route 1 too. This is why (33) is the same as (12).

5-2 Second-best pricing when the degree of revenue-recycling as a subsidy for route 2 is fixed

Second, we focus on the case where the degree of revenue-recycling as subsidy for route 2 is fixed. Maximizing (32) with respect to τ^1 yields:

$$(35) \quad \tau^1 = c^1_{x^1} x^1 - (\overline{\tau^2} - s^2 - c^2_{x^2} x^2) \frac{x^2_{\tau^1}}{x^1_{\tau^1}}.$$

The sign of $\frac{x^2_{\tau^1}}{x^1_{\tau^1}}$ does not correspond to whether routes 1 and 2 are substitutes or complements from (A18) and (A20) in Appendix 3, because a change in the monetary price of route 1 causes two additional effects in route 2, which are the same as (27), other than a change in its demand by the relationship of substitutes or complements.

Note that no second-best investment effect exists in (35), differently from (20) and (27). The investment level in route 2 is fixed here. A subsidy for route 2 therefore does not adjust the distortion in investment that causes the second-best investment effect.

5-3 Second-best subsidy when the monetary price of route 1 is fixed

Lastly, we examine how to determine the degree of revenue-recycling as the subsidy for route 2 when the monetary price of route 1 is fixed.

Partially differentiating (32) with respect to a yields:

$$(36) \quad TS_a = (\overline{\tau^1} - c^1_{x^1} x^1) x^1_a + (\overline{\tau^2} - c^2_{x^2} x^2) x^2_a,$$

where $x_a^2 > 0$ from (A21) in Appendix 3. From (A19) in Appendix 3, $x_a^1 < 0$ if routes 1 and 2 are substitutes regarding p^i and $x_a^1 > 0$ if they are complements.

(36) shows that the benefits from revenue-recycling as a subsidy for route 2 are affected by the price distortion in both routes. Consider the following two examples. First, suppose that the monetary price of highways is lower than their social marginal cost because of congestion, but for substitute railways, the reverse situation holds. In this case, the first and second terms of the right-hand side of (42) are positive, because a subsidy for route 2 decreases demand in congested route 1 and increases demand in uncongested route 2. Therefore, $TS_a > 0$, which means that this subsidy is welfare improving. Second, suppose that the monetary price of urban highways is lower than its social marginal cost because of congestion, but for complementary rural highways, the reverse situation is true. In this case, the first term of the right-hand side of (36) is negative but the second term is positive, because a subsidy for route 2 increases demand both in congested route 1 and in uncongested route 2. Therefore, it is undetermined whether the total surplus is increased or not by this revenue-recycling scheme.

Integrating (36) with respect to a and rearranging yields:

$$(37) \quad \Delta SS = \int_{p^{1W}}^{p^{1WO}} x^1 dp^1 + \int_{p^{2W}}^{p^{2WO}} x^2 dp^2 + \int_{a^{WO}}^{a^{W}} \frac{d(\overline{\tau^1} x^1)}{da} da + \int_{a^{WO}}^{a^{W}} \frac{d(\overline{\tau^2} x^2)}{da} da - \Delta(s^2 x^2),$$

where $\Delta(s^2 x^2) \equiv s^{2W} x^{2W} - s^{2WO} x^{2WO}$.

As in (22) and (29), the first, second, third, and fourth terms of the right-hand side in (37) represent consumer surplus in route 1, consumer surplus in route 2, producer surplus in route 1, and producer surplus in route 2. The cost–benefit formula is the same as the case of revenue-recycling as investments, and consequently, the transport authority does not need to be conscious of whether the revenue is used for investments or subsidies in implementing cost–benefit analysis.

6 Conclusion

This paper examines the effects of revenue-recycling in a situation where at least in a certain part of the transport network, its monetary price cannot be adjusted, taking into account the fact that various transportation modes are commonly operated without perfect coordination. The results have implications for actual policies. First, in a congestion charging scheme in London, where the transport authority is required to use all the revenue to improve London’s transportation system by law, a higher charge than the first-best level could be justified by the second-best investment effect, if the marginal benefit of investment in public transit is larger than its marginal cost. This is not true, however, if the revenue is used as a subsidy for public transit. Second, in Japan, there has been active political debate on whether the revenue from the fuel taxes should be used only for construction of roads or for general-purpose taxes. The cost recovery theorem supports the former, but the argument based on a simple cost recovery theorem is weak, because it ignores the pricing and investment distortions in at least some parts of the transportation networks. To analyze this issue, full cost–benefit analysis, which includes all the transport networks, is necessary. The current cost–benefit analysis for roads in Japan does not consider the effects on other transport modes. This implies that a false conclusion regarding the use of the revenue from fuel taxes can be derived if the debate is based on the current ‘partial’ cost–benefit analysis.

Two caveats are necessary to assess the results in this paper.

First, the analysis in this paper disregarded the marginal cost of public funds. Existing studies (e.g., Ballard (1985)) shows that the marginal cost of public funds differ by the type of tax. If the marginal cost of public funds by toll or tax for transport is larger compared with other taxes, the benefits from revenue-recycling will be reduced. On the contrary, if the reverse is true, the benefits will be enhanced. To examine these issues, we need empirical analysis of the marginal cost of public funds in transport sectors.

Second, our analysis focused on revenue-recycling within transport sectors, but revenue-recycling with other sectors is possible, although public acceptability would become more important in this case. This point relates to the argument of the 'double dividend' of environmental taxes. Bovenberg and Goulder (2002) and Salanie (2003, Chapter 10) prove that the double-dividend hypothesis generally fails in the case of exchange of labor taxes for environmental taxes. The intuitive explanation is as follows. Environmental taxes are more narrowly based than labor taxes. Swapping broad-based taxes with narrow-based taxes provides distortion, which yields a reduction in the real wage and a corresponding drop in employment. On the contrary, Parry and Bento (2001) assert that the congestion tax is one exception to this argument and that the double dividend does in fact exist. The reason why the double-dividend hypothesis fails is that labor supply decreases. They argue that the double dividend could arise in the case of a congestion tax, because the reduction in congestion associated with the congestion tax could increase labor supply. Following Parry and Bento (2001), it is possible that revenue-recycling with sectors other than transport could yield large benefits. The analysis of revenue-recycling between the transport and nontransport sectors is deferred to future research.

Appendices

Appendix 1 Comparative Statistics for the Model in Section 3

By totally differentiating (5), (9), and (15) and rearranging, it is shown that $x^1(\tau^1, a; \overline{\tau^2}, \overline{I^2})$ and $x^2(\tau^1, a; \overline{\tau^2}, \overline{I^2})$ satisfy the following relationship:

(A1) $x^1_{\tau^1} = |D1|^{-1}(u_{x^2x^2} - wt^2_{x^2})(1 + ax^1wt^1_{I^1})$,

(A2) $x^1_a = |D1|^{-1}(u_{x^2x^2} - wt^2_{x^2})x^1\tau^1wt^1_{I^1} > 0$,

(A3) $x^2_{\tau^1} = |D1|^{-1}(-u_{x^1x^2})(1 + ax^1wt^1_{I^1})$,

(A4) $x^2_a = |D1|^{-1}(-u_{x^1x^2})x^1\tau^1wt^1_{I^1} < 0$,

where:

(A5)
$$\begin{aligned} |D1| &= (u_{x^1x^1} - wt^1_{x^1})(u_{x^2x^2} - wt^2_{x^2}) - (u_{x^1x^2})^2 \\ &= u_{x^1x^1}u_{x^2x^2} - (u_{x^1x^2})^2 - wt^2_{x^2}u_{x^1x^1} - wt^1_{x^1}(u_{x^2x^2} - c^2_{x^2}). \end{aligned}$$

We assume that $t^1_{x^1} = t^1_1 + a\tau^1t^1_2 > 0$, where t^1_i ($i = 1, 2$) denotes the partial derivative of t^1 with respect to the i-th argument. (This is the only exceptional usage of subscripts in this paper.) Note that an increase in the demand in route 1 has two effects on travel time, t^1. One is the effect that high demand in route 1 increases congestion and increases travel time. The other is the effect that high demand in route 1 increases the revenue from route 1, increases investments in route 1, and reduces travel time. The above assumption implies that the former effect outweighs the latter effect and that the overall effect of an increase in the demand in route 1 is to increase travel time. This assumption is needed to exclude the situation where an increase in the demand in route 1 reduces the travel time in route 1. This assumption, together with the strict concavity of the utility function and $t^2_{x^2} > 0$, yields $|D1| > 0$. Likewise, an increase in the monetary price of route 1, τ^1, not only increases the generalized price in route 1 but also increases the investment in route 1. The latter effect results in a decrease in the generalized price in route 1, but this effect is assumed to be smaller than the former effect, that is, $p^1_{\tau^1} = 1 + ax^1wt^1_{I^1} > 0$. This assumption yields $x^1_{\tau^1} < 0$.

We denote the elasticity of demand in route 1 with respect to its monetary price by $\varepsilon \equiv -\dfrac{x^1_{\tau^1}\tau^1}{x^1}$. Because it is natural to consider that this should be lower than one[5], $\varepsilon < 1$ is assumed to hold. Because $x^1_{\tau^1} < 0$ implies $\varepsilon > 0$, we obtain:

(A6) $$\frac{I^1_{\tau^1}}{x^1_{\tau^1}} = \frac{ax^1 + a\tau^1 x^1_{\tau^1}}{x^1_{\tau^1}} = a\tau^1\left(1 - \frac{1}{\varepsilon}\right) < 0.$$

From (A2), we also have:

(A7) $$I^1_a = \tau^1 x^1 + a\tau^1 x^1_a > 0.$$

From (A1)–(A4), (A6), and (A7), we derive:

(A8) $$\frac{x^2_{\tau^1}I^1_a - x^2_a I^1_{\tau^1}}{x^1_{\tau^1}I^1_a - x^1_a I^1_{\tau^1}} = \frac{x^2_{\tau^1}}{x^1_{\tau^1}} = \frac{-u_{x^1x^2}}{u_{x^2x^2} - wt^2_{x^2}}.$$

If routes 1 and 2 are substitutes regarding the generalized prices, $u_{x^1x^2} < 0$ implies that (A8) is negative. If they are complements regarding them, $u_{x^1x^2} > 0$ implies that (A8) is positive.

[5] In a survey paper on the price elasticities of transport demand by Oum et al. (1992, Tables 1 and 2), the price elasticities of automobile usage are shown to range from 0.09 to 0.52 and that of urban transit are shown to range from 0.1 to 0.6 with only a few exceptions.

Appendix 2 Comparative Statistics for the Model in Section 4

By totally differentiating (5), (9), and (23) and rearranging, it is shown that $x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1})$ and $x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1})$ satisfy the following relationship:

(A9) $x^1_{\tau^1} = |D2|^{-1}\left\{(u_{x^2x^2} - wt^2_{x^2}) - ax^1wt^2_{I^2}u_{x^1x^2}\right\}$,

(A10) $x^1_a = |D2|^{-1}(-u_{x^1x^2})x^1\tau^1wt^2_{I^2}$,

(A11) $x^2_{\tau^1} = |D2|^{-1}\left[-u_{x^1x^2} + awt^2_{I^2}\left\{(u_{x^1x^1} - wt^1_{x^1})x^1 + \tau^1\right\}\right]$,

(A12) $x^2_a = |D2|^{-1}(u_{x^1x^1} - wt^1_{x^1})x^1\tau^1wt^2_{I^2} > 0$,

where:

(A13)
$$\begin{aligned} |D2| &= (u_{x^1x^1} - wt^1_{x^1})(u_{x^2x^2} - wt^2_{x^2}) - u_{x^1x^2}(u_{x^1x^2} - a\tau^1wt^2_{I^2}) \\ &= u_{x^1x^1}u_{x^2x^2} - (u_{x^1x^2})^2 - wt^1_{x^1}(u_{x^2x^2} - wt^2_{x^2}) - wt^2_{x^2}u_{x^1x^1} + a\tau^1wt^2_{I^2}u_{x^1x^2}. \end{aligned}$$

If routes 1 and 2 are substitutes regarding the generalized price, that is, $u_{x^1x^2} < 0$, then $|D2| > 0$ and $x^1_{\tau^1} < 0$ from the strict concavity of the utility function, $t^1_{x^1} > 0$, $t^2_{x^2} > 0$, and $t^2_{I^2} < 0$. If they are complements regarding the generalized price, that is, $u_{x^1x^2} > 0$, then the signs of $|D2|$ and $x^1_{\tau^1}$ are ambiguous. This is because an increase in the monetary price of route 1 has the effect of increasing the demand in route 1, which is caused by an increase in demand in complement route 2, through an increase in investment in route 2. We assume that this effect is so small that $|D2| > 0$ and $x^1_{\tau^1} < 0$ hold even if routes 1 and 2 are complements.

By the assumption that the elasticity of demand in route 1 with respect to its monetary price is lower than one, we have:

(A14) $\dfrac{I^2_{\tau^1}}{x^1_{\tau^1}} = \dfrac{ax^1 + a\tau^1 x^1_{\tau^1}}{x^1_{\tau^1}} = a\tau^1\left(1 - \dfrac{1}{\varepsilon}\right) < 0$,

where $0 < \varepsilon < 1$ from $x^1_{\tau^1} < 0$. From (A10), we obtain:

(A15) $I^2_a = \tau^1 x^1 + a\tau^1 x^1_a = \dfrac{\tau^1 x^1 \left\{u_{x^1x^1}u_{x^2x^2} - (u_{x^1x^2})^2 - wt^1_{x^1}(u_{x^2x^2} - wt^2_{x^2}) - wt^2_{x^2}u_{x^1x^1}\right\}}{|D2|} > 0$.

From (A9)–(A12), (A14), and (A15), we obtain:

(A16) $\dfrac{x^2_{\tau^1}I^2_a - x^2_a I^2_{\tau^1}}{x^1_{\tau^1}I^2_a - x^1_a I^2_{\tau^1}} = \dfrac{-u_{x^1x^2}}{u_{x^2x^2} - wt^2_{x^2}}$.

If routes 1 and 2 are substitutes regarding the generalized prices, $u_{x^1x^2} < 0$ implies that (A16) is negative. If they are complements regarding them, $u_{x^1x^2} > 0$ implies that (A16) is positive. We also obtain:

(A17) $\dfrac{x^2_{\tau^1}x^1_a - x^2_a x^1_{\tau^1}}{x^1_{\tau^1}I^2_a - x^1_a I^2_{\tau^1}} = \dfrac{-wt^2_{I^2}}{u_{x^2x^2} - wt^2_{x^2}} < 0$.

Appendix 3 Comparative Statistics for the Model in Section 5

By totally differentiating (5), (9), (30), and (31) and rearranging, it is shown that $x^1(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2})$ and $x^2(\tau^1, a; \overline{\tau^2}, \overline{I^1}, \overline{I^2})$ satisfy the following relationship:

(A18) $x^1_{\tau^1} = |D3|^{-1}\left\{u_{x^2x^2} - wt^2_{x^2} + \dfrac{ax^1}{x^2}\left(u_{x^1x^2} - \dfrac{\tau^1}{x^2}\right)\right\}$,

(A19) $x^1_a = |D3|^{-1}(-u_{x^1x^2})\left(-\dfrac{\tau^1 x^1}{x^2}\right) < 0$,

(A20) $x^2_{\tau^1} = |D3|^{-1}\left\{-u_{x^1x^2} - \dfrac{ax^1}{x^2}\left(u_{x^1x^1} - wt^1_{x^1} + \dfrac{\tau^1}{x^1}\right)\right\}$, (A21) $x_a^2 = |D3|^{-1}(u_{x^1x^1} - wt_{x^1}^1)\left(-\dfrac{\tau^1 x^1}{x^2}\right) > 0$,

where:

(A22)
$$\begin{aligned} |D3| &= (u_{x^1x^1} - wt_{x^1}^1)\left\{u_{x^2x^2} - wt_{x^2}^2 - \frac{a\tau^1 x^1}{(x^2)^2}\right\} - u_{x^1x^2}\left(u_{x^1x^2} + \frac{a\tau^1}{x^2}\right) \\ &= u_{x^1x^1}u_{x^2x^2} - (u_{x^1x^2})^2 - wt_{x^1}^1 u_{x^2x^2} - (u_{x^1x^1} - wt_{x^1}^1)\left\{wt_{x^2}^2 + \frac{a\tau^1 x^1}{(x^2)^2}\right\} - u_{x^1x^2}\frac{a\tau^1}{x^2}. \end{aligned}$$

If routes 1 and 2 are substitutes regarding the generalized price, that is, $u_{x^1x^2} < 0$, then $|D3| > 0$ and $x_{\tau^1}^1 < 0$ from the strict concavity of the utility function, $t_{x^1}^1 > 0$, and $t_{x^2}^2 > 0$. If they are complements regarding the generalized price, that is, $u_{x^1x^2} > 0$, then the signs of $|D3|$ and $x_{\tau^1}^1$ are ambiguous. This is because an increase in the monetary price of route 1 has the effect of increasing demand in route 1, which is caused by an increase in demand in complement route 2, through an increase in the subsidy for route 2. As in Appendix 2, we assume that this effect is so small that $|D3| > 0$ and $x_{\tau^1}^1 < 0$ hold even if routes 1 and 2 are complements.

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