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# Transport efficiency, downstream R&D, and spillovers

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## Abstract

This study examines the effects of higher transport efficiency on cost-reducing R&D investment and welfare in a two-way duopoly trade model with an imperfectly competitive transport sector. We show that, corresponding to the degree of the R&D spillover, higher transport efficiency can affect investment in a U-shaped fashion. We also show that higher transport efficiency can reduce total output and consumer surplus. By comparing the two cases of firm-specific carriers and duopoly carriers, we demonstrate that total output in the case of duopoly carriers is lower than that in the case of firm-specific carriers if the spillover is sufficiently large. Higher transport efficiency and competition in the transport sector may harm consumers.

**Key words:** Transport efficiency; Imperfectly competitive transport sector; Cost-reducing R&D; R&D spillover

**JEL classification:** F12; L13

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# 1 Introduction

For the past several decades, technical improvements in the transportation industry have contributed to transport cost reductions and growth in world trade. As reported by Levinson (2006), products that traditionally take considerable money and time to carry can be transported within shorter time periods and at lower cost because of containerization.<sup>1</sup> Such improvements in transport efficiency due to containerized shipping have sharply increased imports and imported items and brought higher benefit to consumers. According to Broda and Weinstein (2004), U.S. imported items increased four-fold between 1972 and 2001, raising real income by about 3%. As improvements in transport efficiency have continued,<sup>2</sup> industrial R&D spending in some OECD countries has also rapidly increased. For instance, the ratio of industrial R&D spending to GDP in the United States was about 1.12% in 1981, about 1.42% in 1995, and about 1.73% in 2008.

This study examines the effect of higher transport efficiency on a firm's R&D investment and welfare. Although some studies examine the relationship between a firm's R&D investment and transport (or trade) cost reductions in oligopoly models, the transport cost is exogenously given and hence the role of carriers and technical efficiency of transportation have garnered insufficient attention (e.g., Ghosh and Lim 2013; Haaland and Kind 2008; Long, Raff, and Stahler 2011; Morita 2012). Some authors find that R&D investment always decreases or increases with transport cost reductions (Ghosh and Lim 2013; Haaland and Kind 2008; Morita 2012); others find that transport cost reductions have a non-monotonic effect on investment (Long, Raff, and Stahler 2011). In contrast to existing studies, by considering an imperfectly competitive transport sector and R&D spillovers, we show that, in a single framework, a transport cost reduction that results from an improvement in efficiency can lead to both more and less

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<sup>1</sup>Talley (2000) indicates that technological improvements in ocean shipping through containerization reduced ocean freight rates, and increased containerized trade by 433% between 1980 and 1996 (in TEUs). Hummels (2007) also emphasizes the cost-saving effect of containerized shipping.

<sup>2</sup>For example, containerships continued to grow in size in the 1980s. According to Kuby and Reid (1992), in 1969 no fleets were larger than 1,600 TEU; by contrast, about 20% of the containerships built and ordered between 1980 and 1985 exceeded 2,600 TEU. They also emphasize that line-haul costs per ton-mile decrease with ship size.

investment according to the degree of the spillover.

Following Takauchi (2015), who considers international R&D rivalry with a monopoly carrier, we provide a two-way Cournot duopoly model with an imperfectly competitive transport sector. We consider two symmetric regions: each region has a homogeneous product market and a single producing firm. While neither firm charges fees for local supply, it must use carriers and pay a per-unit transport charge to export its product. To ship cargoes, these carriers incur a quadratic operation cost. We consider the slope of carriers' cost to be the degree of transport efficiency—a steeper cost represents lower technical efficiency in the transport industry. Firms engage in cost-reducing R&D activities with exogenous spillovers. The sequence of events is as follows: first, each firm invests in cost-reducing R&D. Second, the transport charge is determined in the transport market. Lastly, each firm decides its export and local supply.

We firstly examine the case that in each region a single carrier exists that ships the local firm's product (the firm-specific carrier hereafter). We show that higher transport efficiency always raises R&D investment if there is no R&D spillover. Further, it affects investment in a U-shaped fashion if the spillover is intermediate and always reduces investment if the spillover is sufficiently high. The transport charge decreases as transport efficiency improves; it also decreases as spillovers decrease. For smaller spillovers, the export cost is low and the effect of the transport charge reduction is dominant. For larger spillovers, the export cost is high and the effect of the transport charge reduction weakens. However, higher transport efficiency reduces the transport charge, meaning the positive effect becomes stronger as transport efficiency improves. For this reason, as long as the spillover is intermediate, the investment is U-shaped for transport efficiency. We also show that higher transport efficiency can reduce total output and consumer surplus. A larger spillover reduces the production cost, increasing the firm's output and raising the transport charge. Imports are thus lower for larger spillovers. Then, higher transport efficiency does not sufficiently increase imports and the decline in local supply is large; hence, total output falls.

We further investigate the quantity competition of the two carriers and show that,

for sufficiently high R&D spillovers, each region's total output and consumer surplus in the case of multiple carriers is lower than that in the case of firm-specific carriers. This competition between carriers makes demand more elastic—a small rise in the transport charge decreases demand markedly. For this reason, the transport charge and output are inverted U-shaped for the spillover. While total output in the case of firm-specific carriers always increases with spillovers, that in the case of duopoly carriers decreases when the spillover rises above a certain level. This result suggests that competition in the transport sector may harm consumers. We believe that our model offers a new insight into the context of trade and transportation.

This study is related to research that introduces the transport sector in various trade models (Abe, Hattori, and Kawagoshi 2014; Behrens, Gaigne, and Thisse 2009; Behrens and Picard 2011; Francois and Wooton 2001; Ishikawa and Tarui 2015; Takauchi 2015).<sup>3</sup> Francois and Wooton (2001) incorporate an imperfectly competitive transport sector into a competitive trade model and examine the effect of tariff reductions. Abe, Hattori, and Kawagoshi (2014) examine trade and environmental policies in a two-way duopoly where transportation generates pollution. Behrens, Gaigne, and Thisse (2009) and Behrens and Picard (2011) examine the effects of endogenous freight rates on the agglomeration of firms. While Behrens, Gaigne, and Thisse (2009) focus on the carrier's market power, Behrens and Picard (2011) focus on a logistics problem associated with roundtrips. Ishikawa and Tarui (2015) also examine the logistics problem and consider the role of trade policies in oligopoly markets. While all these studies use different models to provide useful insights, they do not consider the R&D activities of firms. The present study is closely related to Takauchi (2015), which considers downstream cost-reducing R&D rivalry with monopoly carriers. Although Takauchi (2015) focuses on the efficiency of R&D technology, the author does not consider the role of R&D spillovers, the carrier's operation cost, and competition in the transport sector.

This study is also related to several works that examine exogenous transport cost reductions in various oligopoly models (Ghosh and Lim 2013; Gurtzgen 2002; Haaland

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<sup>3</sup>Matsushima and Takauchi (2014) consider the effect of the privatization of seaports on port usage fees and welfare in a two-way duopoly model.

and Kind 2008; Liu and Mukherjee 2013; Long, Raff, and Stahler 2011; Marjit and Mukherjee 2015; Morita 2012). Ghosh and Lim (2013), Haaland and Kind (2008), and Morita (2012) examine the relationship between exogenous transport (trade) costs and R&D investment in different oligopoly settings; however, they do not consider upstream agents that have market power. By contrast, Gurtzgen (2002), Liu and Mukherjee (2013) and Marjit and Mukherjee (2015) consider the role of upstream agents that have market power (i.e., labor unions and input suppliers) under different market structures. However, they do not consider the R&D activities of firms. Therefore, we believe that the model presented herein complements existing studies of endogenous/exogenous transport costs and R&D investment.

The remainder of this paper is organized as follows. Section 2 describes the baseline model and timing of the game. Section 3 derives the results of the baseline model. Section 4 examines the case that two carriers compete in the transport sector and compares the results of the baseline model with those of the extended model. Section 5 concludes. All proofs are shown in the appendices.

## 2 Model

We consider a two-way duopoly trade model with firm-specific carriers, as in Takauchi (2015). By incorporating two factors—R&D spillovers and carriers' quadratic operation costs—into Takauchi's (2015) model, we examine the effects of transport efficiency on firm behavior and welfare under cost-reducing R&D rivalry.<sup>4</sup>

There are two symmetric regions,  $H$  and  $F$ , whose markets are segmented. In region  $i$  ( $i = H, F$ ), a single downstream firm produces a homogeneous product for local supply and exports.<sup>5</sup> We call the downstream producing firm *firm  $i$*  ( $i = H, F$ ). These two firms compete *à la* Cournot in both the local and the other region's markets. The inverse market demand function in region  $i$  is  $p_i = a - q_{ii} - q_{ji}$  ( $i \neq j$ ), where  $p_i$  is the product price in market  $i$ ,  $q_{ii}$  is the local supply of firm  $i$ ,  $q_{ji}$  is the exports of

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<sup>4</sup>In Section 4, we further examine quantity competition in the transport sector.

<sup>5</sup>In other words, we consider a type of Brander and Krugman's (1983) duopoly model.

firm  $j$ , and  $a$  is a positive constant. Before the production stage, firms engage in cost-reducing R&D competition with spillovers. To reduce the unit production cost,  $c$ , firm  $i$  undertakes investment,  $x_i$ . Owing to the positive spillovers of developed knowledge, some ratio of firm  $j$ 's R&D results flows into firm  $i$ , and thus firm  $i$ 's unit production cost after investment is  $c - x_i - \beta x_j$  ( $i \neq j$ ), where  $\beta \in [0, 1]$  is the exogenous spillover rate.<sup>6</sup> R&D spillovers are not considered in Takauchi (2015). We assume that firm  $i$  does not pay the transport charge when it supplies the local market. By contrast, firm  $i$  must pay a per-unit transport charge,  $t_i$ , to export its product because it does not have suitable facilities to carry out long-distance transportation and must use a firm-specific carrier to transport its product to the other region's market. We call this upstream agent *carrier  $i$*  ( $i = H, F$ ). The profit of firm  $i$  is defined by  $\Pi_i \equiv \pi_{ii} + \pi_{ij} - x_i^2$ : the local supply profit is  $\pi_{ii} \equiv (a - q_{ii} - q_{ji} - (c - x_i - \beta x_j))q_{ii}$ , the export profit is  $\pi_{ij} \equiv (a - q_{jj} - q_{ij} - (c - x_i - \beta x_j) - t_i)q_{ij}$ , and the R&D cost is  $x_i^2$ , for  $i = H, F$  and  $i \neq j$ .<sup>7</sup>

Carrier  $i$  makes a take-it-or-leave-it offer to firm  $i$  and determines its transport charge,  $t_i$ . The profit of carrier  $i$  is defined by

$$u_i \equiv t_i q_{ij} - \frac{\lambda}{2} (q_{ij})^2,$$

where  $\lambda \in [0, \infty[$  denotes the efficiency of carriers' transport technology. When carriers have higher cargo-handling ability (e.g., improvements in marine engines and adoption of large ships), they have a lower transportation cost: a lower  $\lambda$  thus corresponds to higher transport technology. This transport technology is also ignored in Takauchi (2015).<sup>8</sup>

We consider the following three-stage game. In the first stage of the game, each firm decides its level of R&D investment,  $x_i$ . In the second stage, each carrier decides

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<sup>6</sup>This specification is popular and frequently used in the literature on cost-reducing R&D rivalry. See, for example, D'Aspremont and Jacquemin (1988), Ghosh and Lim (2013), and Kamien, Muller, and Zang (1992).

<sup>7</sup>To focus on the role of transport efficiency and downstream firms' R&D spillovers, we do not consider the technical efficiency in R&D investment; that is, we set the coefficient of the R&D cost to unity (i.e.,  $k = 1$  in  $kx_i^2$ ).

<sup>8</sup>In Takauchi (2015), the carrier's profit is defined by  $u_i \equiv t_i q_{ij}$ .

its transport charge,  $t_i$ . In the third stage, each firm decides its local supply,  $q_{ii}$ , and exports,  $q_{ij}$ . We use the sub-game perfect Nash equilibrium (SPNE) as the equilibrium concept.

### 3 Firm-specific Carriers

The SPNE of the game is solved by using backward induction.

**Third stage:** The first-order conditions (FOCs) for the profit maximization of firm  $i$  are  $\partial\Pi_i/\partial q_{ii} = \alpha - 2q_{ii} - q_{ji} + x_i + \beta x_j = 0$  and  $\partial\Pi_i/\partial q_{ij} = \alpha - q_{jj} - 2q_{ij} + x_i + \beta x_j - t_i = 0$ , where  $\alpha \equiv a - c > 0$ . These yield the following output in the production sub-game:

$$q_{ii}(t_j, \mathbf{x}) = \frac{\alpha + (2-\beta)x_i + (2\beta-1)x_j + t_j}{3}, \quad q_{ij}(t_i, \mathbf{x}) = \frac{\alpha + (2-\beta)x_i + (2\beta-1)x_j - 2t_i}{3}.$$

Here,  $\mathbf{x}$  denotes the vector of R&D investment, i.e.,  $\mathbf{x} = (x_i, x_j)$ .

**Second stage:** Carrier  $i$ 's transport demand is  $TD_i = q_{ij}(t_i, \mathbf{x})$ , that is,

$$TD_i = \frac{\alpha + (2-\beta)x_i + (2\beta-1)x_j}{3} - \frac{2}{3}t_i. \quad (1)$$

From the carrier's profit and (1), the FOC for the profit maximization<sup>9</sup> of each carrier is

$$\frac{\partial u_i(t_i, \mathbf{x})}{\partial t_i} = \frac{1}{9}[\alpha(3+2\lambda) + (3+2\lambda)(2-\beta)x_i + (3+2\lambda)(2\beta-1)x_j - 4(3+\lambda)t_i] = 0.$$

This yields the transport charge in the transportation sub-game.

$$t_i(\mathbf{x}) = \frac{(3+2\lambda)[\alpha + (2-\beta)x_i + (2\beta-1)x_j]}{4(3+\lambda)}. \quad (2)$$

**First stage:** By using the third-stage output, second-stage transport charge (2), and firm's profit, we obtain the following FOC for the profit maximization of each firm:<sup>10</sup>

$$\begin{aligned} \frac{\partial\Pi_i(\mathbf{x})}{\partial x_i} &= -\frac{128x_i}{8} + \frac{4(2-\beta)[\alpha + (2-\beta)x_i + (2\beta-1)x_j]}{8(3+\lambda)^2} \\ &+ \frac{(7-2\beta+2\lambda)[\alpha(5+2\lambda) + (7-2\beta+2\lambda)x_i - (2-(7+2\lambda)\beta)x_j]}{8(3+\lambda)^2} = 0. \end{aligned}$$

<sup>9</sup>The second-order condition (SOC) is satisfied, i.e.,  $\partial^2 u_i(t_i, \mathbf{x})/\partial t_i^2 = -4(3+\lambda)/9 < 0$ .

<sup>10</sup>The SOC for the firm's profit maximization is satisfied, i.e.,  $\partial^2\Pi_i(\mathbf{x})/\partial x_i^2 = (-79 - 44\beta + 8\beta^2 - 68\lambda - 8\beta\lambda - 12\lambda^2)/(8(3+\lambda)^2) < 0$ .



By solving  $\partial\Pi_i(\mathbf{x})/\partial x_i = 0$  for  $x_i$ , we obtain R&D investment in SPNE. Hereafter, the variables with an asterisk “\*” denote those in SPNE:

$$x_i^* = \frac{\alpha[43 + 24\lambda + 4\lambda^2 - 2(7 + 2\lambda)\beta]}{D}, \quad (3)$$

where  $D \equiv 101 + 72\lambda + 12\lambda^2 - (29 + 20\lambda + 4\lambda^2)\beta + 2(7 + 2\lambda)\beta^2 > 0$ .

From (3), outputs, total output, and consumer surplus in SPNE are

$$q_{ii}^* = \frac{4\alpha(3 + \lambda)(5 + 2\lambda)}{D}; \quad q_{ij}^* = \frac{8\alpha(3 + \lambda)}{D}, \quad (4)$$

$$Q_i^* = q_{ii}^* + q_{ji}^* = \frac{4\alpha(21 + 13\lambda + 2\lambda^2)}{D}; \quad CS_i^* = \frac{(Q_i^*)^2}{2}. \quad (5)$$

Firm  $i$ 's profit is

$$\Pi_i^* = \frac{\alpha^2}{D^2} [A + 4(7 + 2\lambda)(43 + 24\lambda + 4\lambda^2)\beta - 4(7 + 2\lambda)^2\beta^2],$$

where  $A \equiv 2327 + 3600\lambda + 2040\lambda^2 + 512\lambda^3 + 48\lambda^4$ .

Each carrier's transport charge and profit are

$$t_i^* = \frac{4\alpha(3 + \lambda)(3 + 2\lambda)}{D}; \quad u_i^* = \frac{32\alpha^2(3 + \lambda)^3}{D^2}. \quad (6)$$

We set the following assumption.

**Assumption 1.** *The unit production cost after R&D investment has a positive value, i.e.,  $c > x_i^* + \beta x_j^*$ .<sup>11</sup>*

From (4) and (6), we obtain Lemma 1.

**Lemma 1.** *(i)  $\partial t_i^*/\partial\lambda > 0$ ,  $\partial q_{ii}^*/\partial\lambda > 0$ , and  $\partial q_{ij}^*/\partial\lambda < 0$ ; (ii)  $\partial t_i^*/\partial\beta > 0$ ,  $\partial q_{ii}^*/\partial\beta > 0$ , and  $\partial q_{ij}^*/\partial\beta > 0$ .*

Part (i) is explained as follows. When transport efficiency improves, the carrier's cost curve is flatter and its cost falls; hence, each carrier tries to decrease its charge to raise its profit (i.e.,  $\partial t_i^*/\partial\lambda > 0$ ). Since the export cost falls as  $\lambda$  decreases, firms increase those exports as  $\lambda$  decreases (i.e.,  $\partial q_{ij}^*/\partial\lambda < 0$ ). Through the strategic substitutability in market competition, an increase in firm  $j$ 's exports reduces firm  $i$ 's local

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<sup>11</sup>For example, suppose  $a - c = 1$  and  $c = 1$ . Then,  $1 > x_i^* + \beta x_j^* = (1 + \beta)[43 + 24\lambda + 4\lambda^2 - 2(7 + 2\lambda)\beta]/D$  holds for  $\beta \in [0, 1]$  and  $\lambda \in [0, \infty[$ .

supply (i.e.,  $\partial q_{ii}^*/\partial\lambda > 0$ ). Part (ii) of Lemma 1 is intuitive: a higher R&D spillover reduces firm  $i$ 's production cost and thus increases its output (i.e.,  $\partial q_{ii}^*/\partial\beta > 0$  and  $\partial q_{ij}^*/\partial\beta > 0$ ). Since total output in region  $i$  is  $Q_i^* = q_{ii}^* + q_{ji}^*$ , total output increases with the spillover. Furthermore, an increase in firm  $i$ 's exports implies that carrier  $i$ 's transport demand increases. Corresponding to this demand expansion, each carrier raises its charge (i.e.,  $\partial t_i^*/\partial\beta > 0$ ).

The equilibrium R&D investment, (3), yields the following result.

**Proposition 1.** (i) An improvement in transport efficiency, i.e., a decrease in  $\lambda$ , increases a firm's investment if and only if  $\lambda > (7 - 8\beta)/2\beta$ . (ii) A rise in R&D spillover increases a firm's investment if and only if

$$\beta < \delta(\lambda) \equiv \frac{301 + 254\lambda + 76\lambda^2 + 8\lambda^3 - 4\sqrt{2(3+\lambda)^2(7+2\lambda)^3}}{2(7+2\lambda)^2}.$$

Fig. 1 shows Proposition 1.

[Fig. 1 around here]

Here, we consider part (i). Some studies of trade with R&D investment consider the effect of a trade or transport cost reduction on a firm's R&D activities (Ghosh and Lim 2013; Haaland and Kind 2008; Long, Raff, and Stahler 2011; Morita 2012) and they offer contrasting results. Although our model differs from these studies, we can relate those results to ours corresponding to the degree of R&D spillovers. Higher transport efficiency reduces the transport charge, which has two effects: one is the positive effect that encourages investment through a reduction in the export cost, while the other is the negative effect that discourages investment through increased competition in the local market. The positive effect depends on the export cost itself: if  $\beta$  is lower, exports are larger and the positive effect is stronger. If  $\beta = 0$ , R&D investment always rises as  $\lambda$  decreases (see the curve evaluated  $\beta = 0$  in panel (b) of Fig. 1). This case corresponds to Ghosh and Lim (2013) and Haaland and Kind (2008). In their two-way duopoly models, there is no upstream agent and the positive effect of transport cost reductions is always dominant.

For  $0 < \beta < 7/8$ ,<sup>12</sup> R&D investment is U-shaped for  $\lambda$ . Since a rise in  $\beta$  raises the transport charge and dampens exports, the positive effect goes down as  $\beta$  goes up. On the one hand, the export cost is larger when  $\lambda$  is larger, meaning that the positive effect is dominated by the negative one when  $\lambda$  is sufficiently large. However, as  $\lambda$  decreases, the export volume increases and hence the positive effect is stronger again (see the curve evaluated  $\beta = 0.5$  in panel (b) of Fig. 1). This case corresponds to the result of Long, Raff, and Stahler (2011), who consider firm heterogeneity (productivity is stochastically distributed among firms). In their oligopoly model, if the transport cost is sufficiently low, the chance of becoming an exporter is large and R&D spending rises with the transport cost reduction. However, if the transport cost is sufficiently high, the chance of becoming an exporter is small, the marginal benefit of R&D is small, and hence investment decreases as the transport cost falls.

For  $\beta \geq 7/8$ , the positive effect is dominated by the negative one (see the curve evaluated  $\beta = 0.9$  in panel (b) of Fig. 1). This case corresponds to the result of Morita (2012), who incorporates skilled and unskilled labor in a general equilibrium setting. In his duopoly model, a trade cost (specific tariff) reduction sharply raises the wage for skilled labor and this makes the negative effect dominant.

The logic behind part (ii) is as follows. Whether a rise in spillovers increases R&D investment depends on the level of transport efficiency (see panel (c) of Fig. 1). Investment decreases with  $\beta$  if  $\lambda < \lambda_1 \simeq 0.50$ ; it has an inverted U-shape for  $\beta$  if  $\lambda_1 \leq \lambda \leq \lambda_2 \simeq 2.80787$ ; and it increases with  $\beta$  if  $\lambda > \lambda_2$ .<sup>13</sup> A rise in  $\beta$  has two effects: one is the positive effect that encourages firm  $i$ 's investment through a reduction in its production cost and the other is the negative effect that discourages firm  $i$ 's investment through a reduction in its rival's production cost. The negative effect depends on the size of the rival's exports. From Lemma 1, higher transport efficiency reduces the transport charge. Since a lower export cost increases exports, exports are sufficiently large if  $\lambda$  is sufficiently small. Then, an expansion of exports due to a rise

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<sup>12</sup>The threshold  $(7 - 8\beta)/2\beta = 0$  if  $\beta = 7/8$ . Also,  $\lambda = (7 - 8\beta)/2\beta = 0 \Leftrightarrow \beta = 7/(2(4 + \lambda))$ ;  $\beta = 7/(2(4 + \lambda)) \rightarrow 0$  as  $\lambda \rightarrow \infty$  (see panel (a) of Fig. 1).

<sup>13</sup>Note that  $\lambda_1 \simeq 0.50$  is the solution of  $\delta(\lambda) = 0$  and  $\lambda_2 \simeq 2.80787$  is the solution of  $\delta(\lambda) = 1$ .

in  $\beta$  is stronger, implying that the negative effect dominates the positive one. When  $\lambda_1 \leq \lambda \leq \lambda_2$ , investment is an inverted U-shape for  $\beta$ .<sup>14</sup> Because  $\lambda$  has a larger value and exports are lower than those in the case of  $\lambda < \lambda_1$ , the negative effect that results from a rising spillover becomes weaker. A lower  $\beta$  also reduces the rival's exports, meaning that the negative effect weakens further. When  $\lambda > \lambda_2$ , the transport charge is sufficiently high and this strongly dampens the firm's export activity. Because the positive effect is dominant, investment increases with the spillover.

Let us examine the effect of an improvement in transport efficiency on welfare.<sup>15</sup> We firstly consider the effects of  $\lambda$  on the consumers in each region. From (5), we obtain the following result.

**Proposition 2.** *An improvement in transport efficiency, i.e., a decrease in  $\lambda$ , reduces total output and consumer surplus in each region if and only if*

$$\lambda > \frac{25 - 13\beta - 14\beta^2 + 2\sqrt{(1 + \beta)(1 + 2\beta)(7 - 2\beta)}}{2(2\beta^2 + 3\beta - 3)}.$$

Fig. 2 illustrates Proposition 2.

[Fig. 2 around here]

Proposition 2 implies that an increase in the transport cost can raise total output and consumer surplus if the degree of the R&D spillover is high.<sup>16</sup> To understand this result, the carrier and its charge play a key role. Since the transport charge decreases as the spillover decreases, a lower (higher) export cost corresponds to a smaller (larger) spillover. When the spillover is smaller, the imports of region  $i$  have a larger volume and thus the effect of the export cost reduction on the exporter (firm  $j$ ) is stronger. An improvement in transport efficiency largely increases imports, meaning that total

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<sup>14</sup>The results in the case " $\lambda_1 \leq \lambda$ " largely differ from those of Ghosh and Lim (2013).

<sup>15</sup>Since a rise in the R&D spillover reduces production costs, welfare in each region monotonically increases with  $\beta$ .

<sup>16</sup>Although Gurtzgen (2002) and Marjit and Mukherjee (2015) do not consider R&D rivalry, they also find a similar result. Gurtzgen (2002) assumes a two-way duopoly model in which firms engage in differentiated Bertrand competition with labor unions. Marjit and Mukherjee (2015) assume a one-way trade model in which downstream is differentiated Cournot competition with free entry and upstream is a perfect/imperfect labor market.

output increases (see the curve evaluated  $\beta = 0.6$  in panel (b) of Fig. 2). When the spillover is large, total output is U-shaped for the level of transport efficiency. The transport charge has a higher value for a larger  $\beta$  as well as a higher value for a larger  $\lambda$ . Imports in region  $i$  are significantly small when  $\beta$  and  $\lambda$  become larger. Then, the effect of a reduction in firm  $i$ 's local supply is stronger and total output decreases as  $\lambda$  decreases. However, under a larger  $\beta$ , total output rises when transport efficiency exceeds a certain level. Although  $\beta$  is high, a decrease in  $\lambda$  sufficiently increases firm  $j$ 's exports if  $\lambda$  is sufficiently low. For this reason, total output is U-shaped for  $\lambda$  (see the two curves evaluated  $\beta = 0.9$  and  $\beta = 1$  in panel (b) of Fig. 2).<sup>17</sup>

Welfare in region  $i$  is defined as the sum of consumer surplus, firm  $i$ 's profit, and carrier  $i$ 's profit,  $SW_i^* \equiv CS_i^* + \Pi_i^* + u_i^*$ :

$$SW_i^* = \frac{\alpha^2}{D^2} [E + 4(7 + 2\lambda)(43 + 24\lambda + 4\lambda^2)\beta - 4(7 + 2\lambda)^2\beta^2], \quad (7)$$

where  $E \equiv 6719 + 8832\lambda + 4352\lambda^2 + 960\lambda^3 + 80\lambda^4$ .

From (7), we obtain Proposition 3.

**Proposition 3.** *An improvement in transport efficiency, i.e., a decrease in  $\lambda$ , reduces welfare in each region if and only if  $\lambda > g(\beta)$ , where*

$$g^{-1}(\lambda) \equiv \frac{1211 + 384\lambda - 36\lambda^2 - 16\lambda^3 + \sqrt{G}}{4(1099 + 912\lambda + 256\lambda^2 + 24\lambda^3)}$$

and  $G \equiv 256\lambda^6 + 37248\lambda^5 + 590608\lambda^4 + 3917408\lambda^3 + 13164552\lambda^2 + 22324032\lambda + 15296337$ .

Fig. 3 shows Proposition 3.

[Fig. 3 around here]

Welfare has three shapes: (i) an increase for a decrease in  $\lambda$ ; (ii) U-shaped when  $\lambda = 0$  (the highest transport efficiency) is maximized; and (iii) U-shaped but  $\lambda = 0$  is not maximized (see panel (b) of Fig. 3). To consider the result, let us decompose

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<sup>17</sup>By plugging  $\beta = 1$  into  $\mu(\beta)$ , we obtain  $(\sqrt{30} - 1)/2$ . See panel (a) of Fig. 2.

“ $\partial SW_i^*/\partial\lambda$ ” into three parts:

$$\frac{\partial SW_i^*}{\partial\lambda} = \underbrace{\frac{\partial CS_i^*}{\partial\lambda}}_{(+)/(-)} + \underbrace{\frac{\partial \Pi_i^*}{\partial\lambda}}_{(+)} + \underbrace{\frac{\partial u_i^*}{\partial\lambda}}_{(-)},$$

where “(+)” denotes a *positive* sign, “(-)” denotes a *negative* sign, and “(+)/(-)” is both a positive and a negative sign. As seen in Proposition 2, an improvement in transport efficiency (i.e., a decrease in  $\lambda$ ) increases consumer surplus as long as the spillover is not too large. Each firm’s profit decreases as  $\lambda$  decreases ( $\partial \Pi_i^*/\partial\lambda > 0$ ).<sup>18</sup> The reason is as follows. While firms do not incur a transport cost for local supply, they must pay it to export. Thus, exports are less efficient compared with local supply. Since an improvement in transport efficiency increases less-efficient exports but reduces efficient local supply, profit decreases. By contrast, each carrier’s profit increases as  $\lambda$  decreases ( $\partial u_i^*/\partial\lambda < 0$ ). A lower  $\lambda$  increases exports, meaning that the carrier’s demand expands and its profit rises.

The degree of the spillover affects the sign and intensity of these three parts. When there is no spillover ( $\beta = 0$ ), imports are larger and the effect of import expansion due to a decrease in  $\lambda$  becomes sufficiently strong. Because the carrier’s profit and consumer surplus increase markedly, welfare also rises as  $\lambda$  decreases (see the curve evaluated  $\beta = 0$  in panel (b) of Fig. 3).

When there is a spillover ( $\beta \neq 0$ ), welfare is U-shaped for  $\lambda$ . For a larger  $\lambda$  (i.e.,  $\lambda > g(\beta)$ ), the effect of import expansion that results from a decrease in  $\lambda$  is lower. Since the reduction in the firm’s profit is relatively large, welfare decreases as  $\lambda$  decreases. However, if  $\lambda$  is below a threshold level, imports become larger again and the carrier’s profit and consumer surplus sufficiently rise as  $\lambda$  decreases (see the curve evaluated  $\beta = 0.7$  in panel (b) of Fig. 3). On the one hand, if  $\beta$  is larger, the area in which a decrease in  $\lambda$  reduces consumer surplus appears and that area expands with  $\beta$  (see Proposition 2). For extremely high  $\beta$ , the welfare-enhancing effect of a decrease in  $\lambda$  is small and thus a decrease in  $\lambda$  does not sufficiently raise welfare even if  $\lambda$  is sufficiently low (see the curve evaluated  $\beta = 1$  in panel (b) of Fig. 3).

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<sup>18</sup>The effect of a change in  $\lambda$  on the firm’s and carrier’s profit is calculated in Appendix B.1.

## 4 Competition in the Transport Sector

Section 3 showed the effects of transport efficiency for firm-specific carriers. Hence, it is necessary to examine the case of competition in the transport sector. We thus relax the assumption of a “monopoly carrier for each firm” and introduce quantity competition.<sup>19</sup> Consequently, the welfare change that results from improving transport efficiency is the same as the case for firm-specific carriers.<sup>20</sup> On the contrary, we find that R&D investment and total output (i.e., consumer surplus) in the case of a firm-specific carrier *can be larger* than that in the case of the duopoly transport sector.

There are two carriers in the transport sector; carrier  $i$  belongs to region  $i$  ( $i = H, F$ ) and competes *à la Cournot* in the transport market. The profit of carrier  $i$  is given by  $u_i \equiv tz_i - (\lambda z_i^2)/2$  for  $i = H, F$ , where  $t$  is the transport charge and  $z_i$  is carrier  $i$ 's transport volume. The timing of the game is the same as described in the previous section and we solve the game in a similar way to before.<sup>21</sup>

From the market-clearing condition  $z_H + z_F = TD = q_{HF} + q_{FH}$ , each carrier faces the following transport demand:

$$TD = \frac{2\alpha + (1 + \beta)(x_H + x_F)}{3} - \frac{4}{3}t. \quad (8)$$

Under (8), each carrier decides its transport volume to maximize its profit. The second-stage transport charge is

$$t(\mathbf{x}) = \frac{(3 + 4\lambda)[2\alpha + (1 + \beta)(x_H + x_F)]}{4(9 + 4\lambda)}. \quad (9)$$

By solving the firm's profit maximization problem  $\max_{x_i} \Pi_i(\mathbf{x}) = \max_{x_i} \{\pi_{ii}(\mathbf{x}) + \pi_{ij}(\mathbf{x}) - x_i^2\}$ , we obtain the following R&D investment in SPNE:

$$x_i^{**} = \frac{\alpha}{J} [263 + 216\lambda + 48\lambda^2 - (7 + 4\lambda)(19 + 4\lambda)\beta], \quad (10)$$

where  $J \equiv 5(7+4\lambda)(11+4\lambda) - 2(65+56\lambda+16\lambda^2)\beta + (7+4\lambda)(19+4\lambda)\beta^2 > 0$ . Hereafter, variables with a double asterisk “\*\*” denote the variables in the SPNE of the game in

<sup>19</sup>Abe, Hattori, and Kawagoshi (2014), Behrens, Gaigné, and Thisse (2009), Francois and Wooton (2001), and Ishikawa and Tarui (2015) also assume quantity competition in the transport sector.

<sup>20</sup>Similar to the case of firm-specific carriers, an improvement in transport efficiency affects welfare in a U-shaped fashion. This is also the same for the firm's profit. See Appendices B.2 and B.3.

<sup>21</sup>We derive the equilibrium outcome in each sub-game in Appendix C.

which the transport sector is a Cournot duopoly.

Outputs, transport volume, and consumer surplus in SPNE are

$$q_{ii}^{**} = \frac{4\alpha(7+4\lambda)(9+4\lambda)}{J}; \quad q_{ij}^{**} = z_i^{**} = \frac{16\alpha(9+4\lambda)}{J}, \quad (11)$$

$$Q_i^{**} = \frac{4\alpha(9+4\lambda)(11+4\lambda)}{J}; \quad CS_i^{**} = \frac{(Q_i^{**})^2}{2}. \quad (12)$$

The transport charge and each carrier's profit are

$$t^{**} = \frac{4\alpha(3+4\lambda)(9+4\lambda)}{J}; \quad u_i^{**} = \frac{64\alpha^2(9+4\lambda)^2(3+2\lambda)}{J^2}. \quad (13)$$

Eqs. (11) and (13) yield the following result.

**Lemma 2.** (i)  $\partial t^{**}/\partial\lambda > 0$ ,  $\partial q_{ii}^{**}/\partial\lambda > 0$ , and  $\partial q_{ij}^{**}/\partial\lambda < 0$ . (ii) If  $\beta \leq \frac{65+56\lambda+16\lambda^2}{(7+4\lambda)(19+4\lambda)}$ ,  $\partial t^{**}/\partial\beta \geq 0$ ,  $\partial q_{ii}^{**}/\partial\beta \geq 0$ , and  $\partial q_{ij}^{**}/\partial\beta \geq 0$ ; otherwise,  $\partial t^{**}/\partial\beta < 0$ ,  $\partial q_{ii}^{**}/\partial\beta < 0$ , and  $\partial q_{ij}^{**}/\partial\beta < 0$ .

Part (i) in Lemma 2 is the same as the result for Lemma 1. Because transport efficiency directly affects export activity (i.e., a lower  $\lambda$  reduces the transport cost and charge), it increases imports but decreases local supply by increasing local market competition. Part (ii) states that the transport charge and output (as well as total output) are inverted U-shaped for the spillover.<sup>22</sup> This is because, in the case of duopoly carriers, transport demand is more elastic than that in the case of firm-specific carriers. Although a rise in  $\beta$  reduces the production cost and can increase output, this demand expansion also raises the transport charge and can reduce output. In the case of duopoly carriers, transport demand drops markedly as  $\beta$  increases when the transport charge becomes sufficiently high. If  $\beta$  rises above a certain level and the transport charge sufficiently rises, the charge begins to fall to avoid decreasing transport demand. Hence, (inverse) transport demand in the case of duopoly carriers is flatter (more elastic) than that in the case of firm-specific carriers. From (1) and (8),

$$\underbrace{|\partial t_i / \partial TD_i|}_{\text{Firm-specific carrier}} = 3/2 > 3/4 = \underbrace{|\partial t / \partial TD|}_{\text{Duopoly carriers}}.$$

<sup>22</sup>Whether the change in the spillover increases output depends on the sign of  $\partial t^{**}/\partial\beta$ . See Appendix A.5.



On the one hand, when  $\lambda$  is larger, exports are lower ( $\partial q_{ij}^{**}/\partial\lambda < 0$ ). Because the negative effects of a higher transport charge weaken, the range in which output and the transport charge rise expands (i.e., the threshold  $\frac{65+56\lambda+16\lambda^2}{(7+4\lambda)(19+4\lambda)}$  increases) as  $\lambda$  increases.

From (10), we obtain the following.

**Lemma 3.** (i)  $\partial x_i^{**}/\partial\beta > 0$  if and only if

$$\beta < \frac{(7+4\lambda)(19+4\lambda)(263+216\lambda+48\lambda^2) - 2\sqrt{2(9+4\lambda)^2(7+4\lambda)^3(19+4\lambda)^3}}{(7+4\lambda)^2(19+4\lambda)^2}.$$

(ii)  $\partial x_i^{**}/\partial\lambda > 0$  if and only if  $\lambda > (5 - 4\beta)/4\beta$ .

Fig. 4 illustrates Lemma 3.

[Fig. 4 around here]

In contrast to the result of Proposition 1, in the case of duopoly carriers, the negative effect of investment (i.e., the effect of a decrease in its rival's production cost) is stronger compared with the case of firm-specific carriers. The key factor to this result is that, as previously explained in Lemma 2, a higher  $\beta$  affects the transport charge markedly, which is inverted U-shaped for  $\beta$ . By contrast, the transport charge always increases with  $\beta$  in the case of firm-specific carriers (see Lemma 1). That is, in the case of duopoly carriers, a rise in  $\beta$  can sufficiently reduce a rival's exports and weaken the positive effect of a rise in  $\beta$ . For this reason, the area in which a rise in  $\beta$  always increases R&D investment does not appear (see panel (a) of Fig. 4). Part (ii) is the same as the result of Proposition 1. Since a change in transport efficiency on output and the transport charge is the same as the case of firm-specific carriers (Lemmas 1 and 2), a similar result holds for R&D investment (see panel (b) of Fig. 4).

Finally, we consider whether competition in the transport sector raises the firm's R&D investment and each region's total output (consumer surplus). From eqs. (3) and (10), for the ranking of R&D investment, we obtain the following.

**Proposition 4.** *Firm  $i$ 's R&D investment in the case of Cournot duopoly carriers,*

$x_i^{**}$ , is lower than that in the case of firm-specific carriers,  $x_i^*$ , if and only if

$$\beta > \frac{1251 + 2004\lambda + 1242\lambda^2 + 336\lambda^3 + 32\lambda^4}{2(15 + 4\lambda)(42 + 60\lambda + 27\lambda^2 + 4\lambda^3)}.$$

Fig. 5 shows Proposition 4.

[Fig. 5 around here]

The result of Proposition 4 can be explained by those of Proposition 1 and Lemma 3. From Proposition 1, in the case of firm-specific carriers, R&D investment increases with the spillover except for the case that transport efficiency is not too high (also see panel (a) of Fig. 1). On the contrary, in the case of duopoly carriers, the area in which investment increases with  $\beta$  is limited to the case that  $\beta$  is sufficiently small and  $\lambda$  is relatively large (see Lemma 3 and panel (a) of Fig. 4). That is, in many cases, R&D investment decreases with  $\beta$ . Therefore, for a sufficiently high  $\beta$ , investment in the case of firm-specific carriers can exceed that in the case of duopoly carriers.

From (5) and (12), for the ranking of total output, we obtain the following.

**Proposition 5.** *Total output in the case of Cournot duopoly carriers,  $Q_i^{**}$ , is lower than that in the case of firm-specific carriers,  $Q_i^*$ , if and only if*

$$\beta > \frac{\sqrt{(9+4\lambda)N} - (141 + 258\lambda + 72\lambda^2)}{2(7 + 2\lambda)(201 + 285\lambda + 120\lambda^2 + 16\lambda^3)},$$

where  $N \equiv 1199097 + 3166956\lambda + 3513960\lambda^2 + 2145888\lambda^3 + 781200\lambda^4 + 169408\lambda^5 + 20224\lambda^6 + 1024\lambda^7$ .

The result of Proposition 5 is illustrated in Fig. 6.

[Fig. 6 around here]

While total output in the case of firm-specific carriers increases with R&D spillovers (Lemma 1), that in the case of duopoly carriers decreases when the degree of the spillover rises above a certain level (Lemma 2). Therefore, as in Proposition 4, total output (and consumer surplus) in the case of duopoly carriers can be lower than that in the case of firm-specific carriers if the degree of the spillover is sufficiently high. This

result implies that if the fruit of R&D largely flows (i.e.,  $\beta$  is close to 1), competition in the transport sector may harm consumers.<sup>23</sup>

## 5 Conclusion

This study considers the effects of an improvement in transport efficiency on a firm's R&D investment and welfare. Although industrial R&D investment has rapidly expanded as improvements in transport efficiency have continued, previous works have paid insufficient attention to the relationship between the technical efficiency of transportation and R&D investment. In a simple two-region duopolistic R&D rivalry model with an imperfect competitive transport sector, we show that R&D investment rises as transport efficiency improves if there is no R&D spillover; is U-shaped for transport efficiency if the spillover is intermediate; and always decreases as transport efficiency improves if the spillover is sufficiently high. We also show that although higher transport efficiency reduces the transport charge, it can reduce total output and consumer surplus in each region. We further extend the case of firm-specific carriers to the case of the Cournot competition of duopoly carriers. The spillover affects the transport charge and output in a U-shaped fashion in the case of duopoly carriers, but it always increases the transport charge and total output in the case of firm-specific carriers. For this reason, total output and consumer surplus in the case of duopoly carriers can be lower than those in the case of firm-specific carriers if the spillover is sufficiently high. That is, competition in the transport sector can harm consumers. Our model gives heed to the results brought about by technology improvements in the transport sector, and hence we believe that our work provides a new insight into studies of trade and transportation.

In this study, we do not consider the role of public investment. While the government may invest to enhance the quality of transportation and its relevant facilities, this aspect is beyond the scope of our analysis. In the situation of international trade

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<sup>23</sup>It can also be found, by using Mathematica plotting, that when  $\beta$  is close to 1 and  $\lambda$  is not too small, the welfare level in duopoly carriers is lower than that in firm-specific carriers.

within the transport sector, it may be fruitful for future research to examine governments' investment strategies for transport facilities.

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## Appendices

### Appendix A. Proofs

**A.1. Proof of Lemma 1.** The comparative statics analysis of (4) and (6) yields

$$\begin{aligned}\frac{\partial t_i^*}{\partial \lambda} &= \frac{4\alpha}{D^2} [261+188\lambda+36\lambda^2 - (81+44\lambda+4\lambda^2)\beta + (90+56\lambda+8\lambda^2)\beta^2] > 0, \\ \frac{\partial q_{ii}^*}{\partial \lambda} &= \frac{4\alpha}{D^2} [31+44\lambda+12\lambda^2 - (19-4\lambda-4\lambda^2)\beta + (94+56\lambda+8\lambda^2)\beta^2] > 0, \\ \frac{\partial q_{ij}^*}{\partial \lambda} &= \frac{8\alpha}{D^2} [-(115+72\lambda+12\lambda^2) + (31+24\lambda+4\lambda^2)\beta - 2\beta^2] < 0, \\ \frac{\partial t_i^*}{\partial \beta} &= \frac{4\alpha(3+\lambda)(3+2\lambda)}{D^2} [29+20\lambda+4\lambda^2 - 4(7+2\lambda)\beta] > 0, \\ \frac{\partial q_{ii}^*}{\partial \beta} &= \left(\frac{5+2\lambda}{3+2\lambda}\right) \frac{\partial t_i^*}{\partial \beta} > 0, \quad \frac{\partial q_{ij}^*}{\partial \beta} = \left(\frac{2}{3+2\lambda}\right) \frac{\partial t_i^*}{\partial \beta} > 0. \quad \text{Q.E.D.}\end{aligned}$$

**A.2. Proof of Proposition 1.** (i) By differentiating (3) wrt.  $\lambda$ , we have  $\partial x_i^*/\partial \lambda = \{32(a-c)(3+\lambda)[2\beta(4+\lambda)-7]\}/D^2$ . Thus,  $\partial x_i^*/\partial \lambda \geq 0$  if  $\lambda \geq (7-8\beta)/2\beta$ . (ii) By differentiating (3) wrt.  $\beta$ , we have

$$\frac{\partial x_i^*}{\partial \beta} = \frac{\alpha}{D^2} [B_1 - 4(7+2\lambda)(43+24\lambda+4\lambda^2)\beta + 4(7+2\lambda)^2\beta^2],$$

where  $B_1 \equiv -167 + 144\lambda + 312\lambda^2 + 128\lambda^3 + 16\lambda^4$ . We solve  $\partial x_i^*/\partial \beta \geq 0$  for  $\beta$  and have  $\beta \leq \frac{301+254\lambda+76\lambda^2+8\lambda^3-4\sqrt{2(3+\lambda)^2(7+2\lambda)^3}}{2(7+2\lambda)^2}$ . Q.E.D.

**A.3. Proof of Proposition 2.**  $CS_i^* = (Q_i^*)^2/2$  and  $\partial CS_i^*/\partial \lambda = Q_i^*(\partial Q_i^*/\partial \lambda)$ , meaning that  $\text{sign}(\partial CS_i^*/\partial \lambda)$  depends on the sign of  $\partial Q_i^*/\partial \lambda$ . By differentiating (5) wrt.  $\lambda$ , we have

$$\frac{\partial Q_i^*}{\partial \lambda} = \frac{4\alpha}{D^2} [4(2\beta^2 + 3\beta - 3)\lambda^2 + 4(14\beta^2 + 13\beta - 25)\lambda + 98\beta^2 + 43\beta - 199].$$

We solve  $\partial Q_i^*/\partial\lambda \geq 0$  for  $\lambda$  and have  $\lambda \geq \frac{25-13\beta-14\beta^2+2\sqrt{(1+\beta)(1+2\beta)(7-2\beta)}}{2(2\beta^2+3\beta-3)}$ . Q.E.D.

**A.4. Proof of Proposition 3.** By differentiating (7) wrt.  $\lambda$ , we have

$$\frac{\partial SW_i^*}{\partial\lambda} = \frac{16\alpha^2(3+\lambda)}{D^3} (2E_2\beta^2 - E_3\beta - 1573 - 1128\lambda - 188\lambda^2),$$

where  $E_2 \equiv 1099 + 912\lambda + 256\lambda^2 + 24\lambda^3$  and  $E_3 \equiv 1211 + 384\lambda - 36\lambda^2 - 16\lambda^3$ . We solve  $\partial SW_i^*/\partial\lambda \geq 0$  for  $\beta$  and have  $\beta \geq g^{-1}(\lambda) \equiv \frac{1211+384\lambda-36\lambda^2-16\lambda^3+\sqrt{G}}{4(1099+912\lambda+256\lambda^2+24\lambda^3)}$ , where  $G \equiv 256\lambda^6 + 37248\lambda^5 + 590608\lambda^4 + 3917408\lambda^3 + 13164552\lambda^2 + 22324032\lambda + 15296337$ . Q.E.D.

**A.5. Proof of Lemma 2.** (i) By differentiating (11) and (13) wrt.  $\lambda$ , we have

$$\begin{aligned} \frac{\partial t^{**}}{\partial\lambda} &= \frac{32\alpha}{J^2} [S + 8(125 - 38\beta + 53\beta^2)\lambda + 16(15 - 2\beta + 7\beta^2)\lambda^2] > 0, \\ \frac{\partial q_{ii}^{**}}{\partial\lambda} &= \frac{32\alpha}{J^2} [5(1 + \beta^2)(7 + 4\lambda)^2 - 2(79 + 8\lambda - 16\lambda^2)\beta] > 0, \\ \frac{\partial q_{ij}^{**}}{\partial\lambda} &= -\frac{64\alpha}{J^2} [425 - 122\beta + 101\beta^2 + 8(5 - 2\beta + \beta^2)\lambda(9 + 2\lambda)] < 0, \end{aligned}$$

where  $S \equiv 3(365 - 134\beta + 149\beta^2) > 0$ .

(ii) By differentiating (11) and (13) wrt.  $\beta$ , we have

$$\begin{aligned} \frac{\partial t^{**}}{\partial\beta} &= \frac{8\alpha(3+4\lambda)(9+4\lambda)}{J^2} [65 + 56\lambda + 16\lambda^2 - (7+4\lambda)(19+4\lambda)\beta], \\ \frac{\partial q_{ii}^{**}}{\partial\beta} &= \left(\frac{7+4\lambda}{3+4\lambda}\right) \frac{\partial t^{**}}{\partial\beta}, \quad \frac{\partial q_{ij}^{**}}{\partial\beta} = \left(\frac{4}{3+4\lambda}\right) \frac{\partial t^{**}}{\partial\beta}. \end{aligned}$$

The signs of  $\partial q_{ii}^{**}/\partial\beta$  and  $\partial q_{ij}^{**}/\partial\beta$  depend on the sign of  $\partial t^{**}/\partial\beta$ . By solving  $\partial t^{**}/\partial\beta \geq 0$ , we have  $\beta \leq \frac{65+56\lambda+16\lambda^2}{(7+4\lambda)(19+4\lambda)}$ . Q.E.D.

**A.6. Proof of Lemma 3.** By differentiating (10) wrt.  $\beta$ , we have

$$\frac{\partial x_i^{**}}{\partial\beta} = \frac{\alpha}{J^2} [L_x + (7+4\lambda)^2(19+4\lambda)^2 - 2(7+4\lambda)(19+4\lambda)(263+216\lambda+48\lambda^2)\beta],$$

where  $L_x \equiv -17015 - 30384\lambda - 15392\lambda^2 - 1792\lambda^3 + 256\lambda^4$ . By solving  $\partial x_i^{**}/\partial\beta \geq 0$  for  $\beta$ , we have  $\beta \leq \frac{(7+4\lambda)(19+4\lambda)(263+216\lambda+48\lambda^2)-2\sqrt{2(9+4\lambda)^2(7+4\lambda)^3(19+4\lambda)^3}}{(7+4\lambda)^2(19+4\lambda)^2}$ . By differentiating (10) wrt.  $\lambda$ , we have  $\partial x_i^{**}/\partial\lambda = \frac{256\alpha(9+4\lambda)}{J^2} (4\beta - 5 + 4\beta\lambda)$ . Therefore,  $\partial x_i^{**}/\partial\lambda \geq 0$  iff  $\lambda \geq (5 - 4\beta)/4\beta$ . Q.E.D.

**A.7. Proof of Proposition 4.** From (3) and (10),  $x_i^{**} - x_i^* = \frac{8\alpha}{DJ} [1251 + 2004\lambda +$

$1242\lambda^2 + 336\lambda^3 + 32\lambda^4 - 2(15 + 4\lambda)(42 + 60\lambda + 27\lambda^2 + 4\lambda^3)\beta]$ . By solving  $x_i^{**} - x_i^* \leq 0$  for  $\beta$ , we have  $\beta \geq \frac{1251+2004\lambda+1242\lambda^2+336\lambda^3+32\lambda^4}{2(15+4\lambda)(42+60\lambda+27\lambda^2+4\lambda^3)}$ . Q.E.D.

**A.8. Proof of Proposition 5.** From (5) and (12),  $Q_i^{**} - Q_i^* = \frac{4\alpha}{DJ} [(11 + 4\lambda)(174 + 177\lambda + 66\lambda^2 + 8\lambda^3) - 3(47 + 86\lambda + 24\lambda^2)\beta - (7 + 2\lambda)(201 + 285\lambda + 120\lambda^2 + 16\lambda^3)\beta^2]$ . By solving  $Q_i^{**} - Q_i^* \leq 0$  for  $\beta$ , we have  $\beta \geq \frac{\sqrt{(9+4\lambda)N} - (141+258\lambda+72\lambda^2)}{2(7+2\lambda)(201+285\lambda+120\lambda^2+16\lambda^3)}$  and  $N \equiv 1199097 + 3166956\lambda + 3513960\lambda^2 + 2145888\lambda^3 + 781200\lambda^4 + 169408\lambda^5 + 20224\lambda^6 + 1024\lambda^7$ . Q.E.D.

## Appendix B. Derivation of the other results

**B.1. The signs of  $\partial\Pi_i^*/\partial\lambda$  and  $\partial u_i^*/\partial\lambda$ .** By differentiating  $\Pi_i^*$  and (6) wrt.  $\lambda$ , we have  $\partial\Pi_i^*/\partial\lambda = \{32\alpha^2(3 + \lambda)[2(9 + 2\lambda)(39 + 24\lambda + 4\lambda^2)\beta^2 - (15 + 2\lambda)(57 + 28\lambda + 4\lambda^2)\beta]\}/D^3 + [96\alpha^2(3 + \lambda)(99 + 110\lambda + 52\lambda^2 + 8\lambda^3)]/D^3 > 0$  and  $\partial u_i^*/\partial\lambda = \{32\alpha^2(3 + \lambda)^2[2(9 + 2\lambda)\beta^2 + (33 + 28\lambda + 4\lambda^2)\beta - 3(43 + 24\lambda + 4\lambda^2)]\}/D^3 < 0$ .

**B.2. Sign of  $\partial\Pi_i^{**}/\partial\lambda$ .** When the transport sector is a duopoly, a decrease in  $\lambda$  can raise the profits of firms. Each firm's profit in Section 4 is

$$\Pi_i^{**} = \frac{\alpha^2(7 + 4\lambda)}{J^2} [L_p + 2(19+4\lambda)(263+216\lambda+48\lambda^2)\beta - (7+4\lambda)(19+4\lambda)^2\beta^2], \quad (\text{A1})$$

where  $L_p \equiv 2153 + 3604\lambda + 2224\lambda^2 + 448\lambda^3$ . By differentiating (A1) wrt.  $\lambda$ , we have  $\partial\Pi_i^{**}/\partial\lambda = \{256\alpha^2(9 + 4\lambda)^2[5(3 + 4\lambda)(7 + 4\lambda) - 4(9 + 4\lambda)(11 + 4\lambda)\beta + (3 + 4\lambda)(73 + 28\lambda)\beta^2]\}/J^2$ . We solve  $\partial\Pi_i^{**}/\partial\lambda \leq 0$  for  $\beta$  and have  $k_l \leq \beta \leq k_u$ , where  $k_l \equiv \frac{(198+160\lambda+32\lambda^2)-\sqrt{K}}{(3+4\lambda)(73+28\lambda)}$ ,  $k_u \equiv \frac{(198+160\lambda+32\lambda^2)+\sqrt{K}}{(3+4\lambda)(73+28\lambda)}$ , and  $K \equiv 16209 - 19920\lambda - 66208\lambda^2 - 42240\lambda^3 - 7936\lambda^4$ .  $K \leq 0$  for  $\lambda \geq \bar{\lambda} \simeq 0.340202$ , meaning that  $k_l$  (increasing for  $\lambda$ ) and  $k_u$  (decreasing for  $\lambda$ ) do not have a real value for  $\lambda > \bar{\lambda}$ ;  $k_l = k_u$  if  $\lambda = \bar{\lambda}$ .

**B.3. Signs of  $\partial Q_i^{**}/\partial\lambda$  and  $\partial SW_i^{**}/\partial\lambda$ .** By differentiating  $Q_i^{**}$  wrt.  $\lambda$ , we have  $\partial Q_i^{**}/\partial\lambda = \frac{32\alpha}{J^2} [\beta(2 + \beta)(43 + 136\lambda + 48\lambda^2) - 5(11 + 4\lambda)^2]$ . We solve  $\partial Q_i^{**}/\partial\lambda \geq 0$  for  $\beta$  and have  $\beta \geq \phi_q \equiv \frac{2\sqrt{2(9+4\lambda)^2(43+136\lambda+48\lambda^2)} - (43+136\lambda+48\lambda^2)}{43+136\lambda+48\lambda^2}$ . The threshold  $\phi_q$  is decreasing for  $\lambda$  and  $\lim_{\lambda \rightarrow \infty} \phi_q = -1 + 2\sqrt{2/3} \simeq 0.632993$ .

The equilibrium welfare level in Section 4,  $SW_i^{**} = CS_i^{**} + \Pi_i^{**} + u_i^{**}$ , is

$$SW_i^{**} = \frac{\alpha^2}{J^2} [M + (7+4\lambda)(19+4\lambda)(263+216\lambda+48\lambda^2)\beta - (7+4\lambda)^2(19+4\lambda)^2\beta^2], \quad (\text{A2})$$

where  $M \equiv 109031 + 184752\lambda + 118816\lambda^2 + 34560\lambda^3 + 3840\lambda^4$ . By differentiating (A2) wrt.  $\lambda$ , we have  $\partial SW_i^{**}/\partial\lambda = \frac{2048\alpha^2(9+4\lambda)}{J^3} [R\beta^2 - 4(92+69\lambda+12\lambda^2)\beta - 40(2+\lambda)(5+2\lambda)]$ , where  $R \equiv 275 + 624\lambda + 368\lambda^2 + 64\lambda^3$ . We solve  $\partial SW_i^{**}/\partial\lambda \geq 0$  for  $\beta$  and have  $\beta \geq \phi_{sw} \equiv \frac{2(92+69\lambda+12\lambda^2)+2\sqrt{(9+4\lambda)^2(444+838\lambda+469\lambda^2+80\lambda^3)}}{275+624\lambda+368\lambda^2+64\lambda^3}$ . The threshold  $\phi_{sw}$  is decreasing for  $\lambda$  and  $\lim_{\lambda \rightarrow \infty} \phi_{sw} = 0$ , meaning that  $SW_i^{**}$  is monotonically decreasing for  $\lambda$  iff  $\beta = 0$ .

### Appendix C. Outcomes of each sub-game in Section 4.

**Third stage:** The firm's third-stage output is  $q_{ii}(t, \mathbf{x}) = \frac{1}{3}[\alpha + (2-\beta)x_i + (2\beta-1)x_j + t]$  and  $q_{ij}(t, \mathbf{x}) = \frac{1}{3}[\alpha + (2-\beta)x_i + (2\beta-1)x_j - 2t]$ .

**Second stage:** From the market-clearing condition  $TD = q_{HF}(t, \mathbf{x}) + q_{FH}(t, \mathbf{x})$ , inverse transport demand is  $t = \frac{2\alpha+(1+\beta)(x_H+x_F)}{4} - \frac{3(z_H+z_F)}{4}$ . By using this equation and the profit of carrier  $i$ , we obtain carrier  $i$ 's reaction function:  $z_i = \frac{2\alpha+(1+\beta)(x_H+x_F)}{2(3+2\lambda)} - \frac{3}{2(3+2\lambda)}z_j$  ( $i \neq j$ ). From this, the second-stage transport volume is  $z_i(\mathbf{x}) = \frac{2\alpha+(1+\beta)(x_H+x_F)}{9+4\lambda}$ . This yields (9).

**First stage:** The maximization problem  $\max_{x_i} \Pi_i(\mathbf{x}) = \max_{x_i} \{\pi_{ii}(\mathbf{x}) + \pi_{ij}(\mathbf{x}) - x_i^2\}$  yields the following FOC<sup>24</sup>:  $\partial \Pi_i(\mathbf{x})/\partial x_i = 0 \Leftrightarrow -2x_i + \frac{1}{2(9+4\lambda)^2} \{4\alpha + \eta_1 x_i - [7 + 4\lambda - (11 + 4\lambda)\beta]x_j\} \eta_1 + \frac{1}{8(9+4\lambda)^2} \{2\alpha(7 + 4\lambda) + \eta_2 x_i - [(11 + 4\lambda) - (25 + 12\lambda)\beta]x_j\} \eta_2 = 0$ , where  $\eta_1 \equiv (11 + 4\lambda) - (7 + 4\lambda)\beta$  and  $\eta_2 \equiv 25 + 12\lambda - (11 + 4\lambda)\beta$ . From the FOC, we obtain (10).

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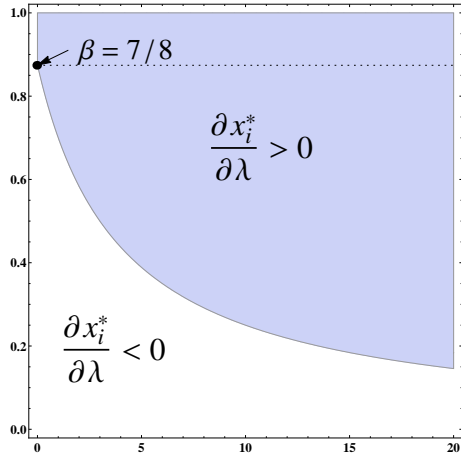
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<sup>24</sup>The SOC is always satisfied, i.e.,  $\partial^2 \Pi_i(\mathbf{x})/\partial x_i^2 = -[(11 + 4\lambda)(17 + 12\lambda) + 2(11 + 4\lambda)(53 + 2\lambda)\beta - (317 + 312\lambda + 80\lambda^2)\beta^2]/8(9 + 4\lambda)^2 < 0$ .

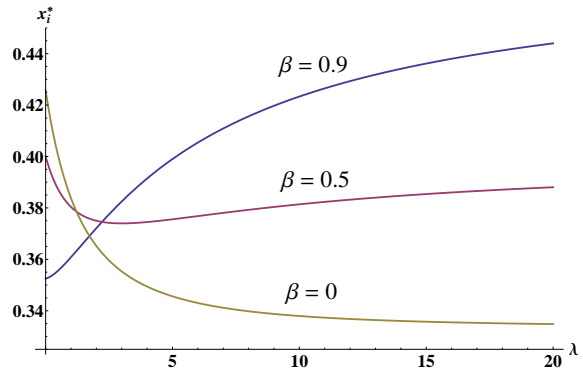
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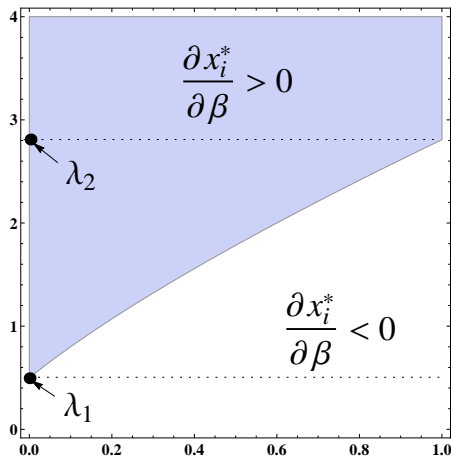
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Panel (a): The area of  $\partial x_i^*/\partial \lambda > 0$ . (the horizontal axis is  $\lambda$  and the vertical axis is  $\beta$ )

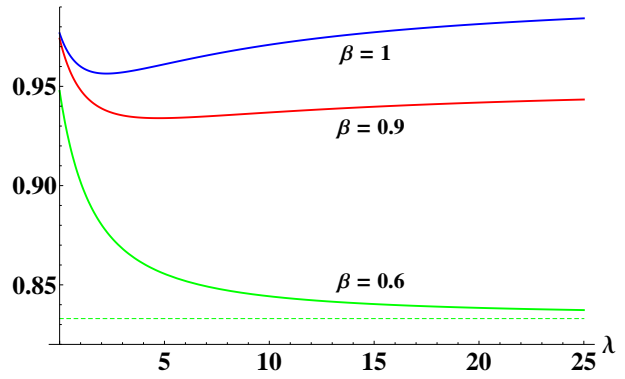
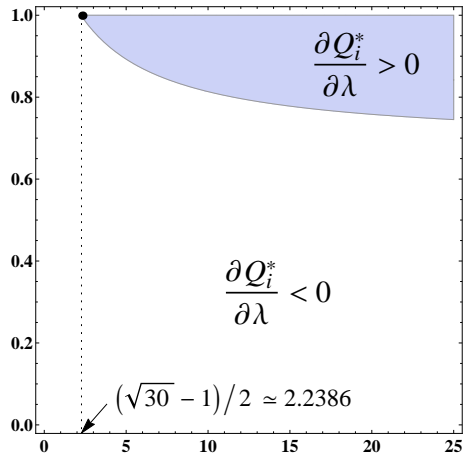


Panel (b): Graph of  $\partial x_i^*/\partial \lambda$ .



Panel (c): The area of  $\partial x_i^*/\partial \beta > 0$ . (the horizontal axis is  $\beta$  and the vertical axis is  $\lambda$ )

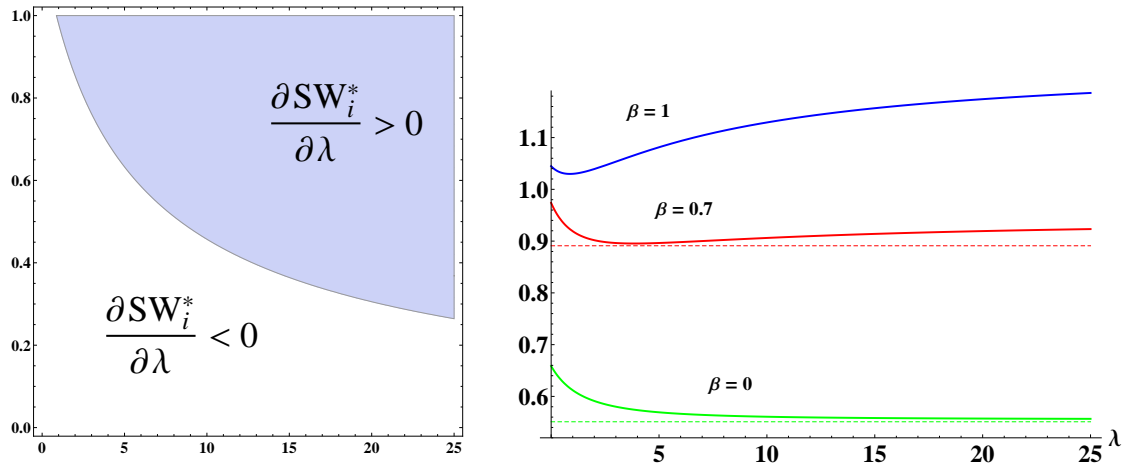
Figure 1: Illustration of Proposition 1.



Panel (a): The area of  $\partial Q_i^*/\partial \lambda > 0$ . (the horizontal axis is  $\lambda$  and the vertical axis is  $\beta$ )

Panel (b): Graph of  $Q_i^*$  for  $\lambda$ .

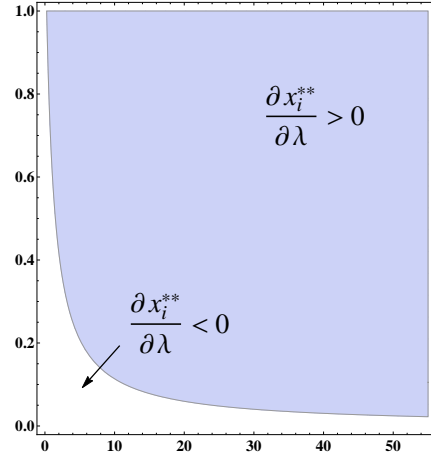
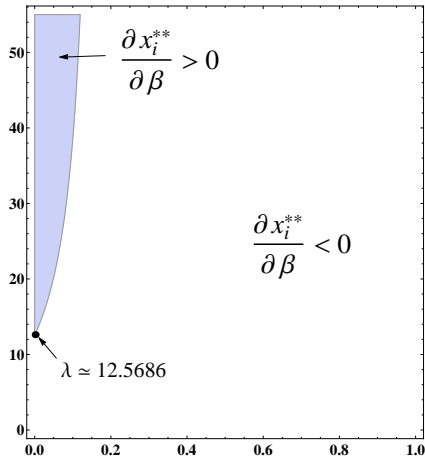
Figure 2: Illustration of Proposition 2.



Panel (a): The area of  $\partial SW_i^*/\partial \lambda > 0$ . (the horizontal axis is  $\lambda$  and the vertical axis is  $\beta$ )

Panel (b): Graph of  $SW_i^*$  for  $\lambda$ .

Figure 3: Illustration of Proposition 3.



Panel (a): The area of  $\frac{\partial x_i^{**}}{\partial \beta} > 0$ . (the horizontal axis is  $\beta$  and the vertical axis is  $\lambda$ ) Panel (b): The area of  $\frac{\partial x_i^{**}}{\partial \lambda} > 0$ . (the horizontal axis is  $\lambda$  and the vertical axis is  $\beta$ )

Figure 4: Illustration of Lemma 3.

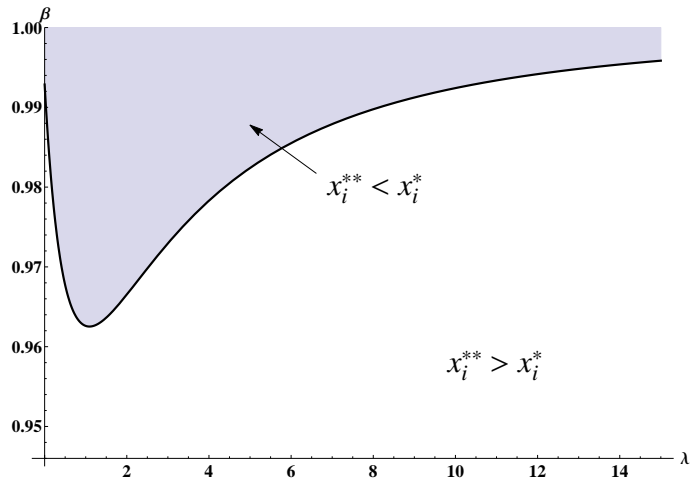


Figure 5: The ranking of  $x_i^*$  and  $x_i^{**}$

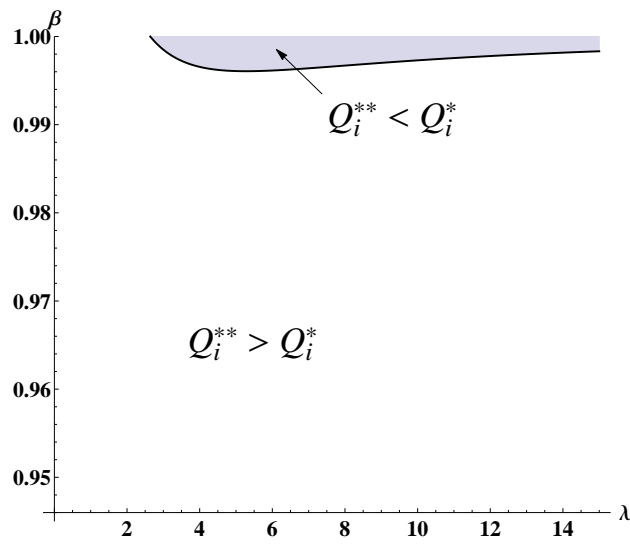


Figure 6: The ranking of  $Q_i^*$  and  $Q_i^{**}$