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Abstract

Efficient distribution has a considerable influence on the sales volume of firms, and thus affects the firms' research and development (R&D) activities. This paper analyzes the relationship between competition in the transport sector and R&D of firms using the transportation services. We consider a two-region reciprocal market in which firms invest in cost-reducing R&D and use carriers that engage in price competition to supply their products to the foreign market. We show that, corresponding to the degree of R&D spillover, a transport cost (or price) reduction due to an increase in the number of carriers can increase or decrease the firms' R&D investments. This result is consistent with the finding in previous studies that trade liberalization can hinder R&D. Because inefficient firms lead to high prices in the market, an increase in the number of carriers may reduce consumer surplus. We further discuss a case in which firms have monopsony power in transportation services and show that our main results are robust to the extension.

Key words: Transport price; R&D spillovers; Price competition; Monopsony power

JEL classification: F12; L13; R40

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1 Introduction

It is well known that trade barriers, such as transport costs and tariffs affect firms' innovation incentives.[1] In particular, transport cost is a major trade barrier;[2] and the level of this cost affects firms' innovation activities. For example, a high freight rate imposes high shipment costs and limits the market access of exporting firms. This restricts production activities, and hence can diminish the incentives for innovation, such as cost-reducing research and development (R&D).

To consider the relation between trade barriers and innovation activities, many researchers have been analyzed it until now. However, there are conflicting views among them. Whereas some studies empirically find that trade liberalization can promote firms' R&D activity (Aw et al., 2011; Bustos, 2011; Lileeva & Trefler, 2010), other studies find that R&D investment can decrease due to a reduction in trade barriers (Scherer & Huh, 1992; Funk, 2003). There are also sharp differences among theoretical works. Especially, such difference is remarkable among studies that employ oligopoly flamework. Some studies find that R&D investment always decreases or increases with a reduction in trade barriers (Ghosh & Lim, 2013; Haaland & Kind, 2008; Hwang et

[1] Trade barriers also affect factors of competition, such as market size and intensity of the exporting market competition. Innovation incentives depend on these factors of competition, such that the level of trade barriers (low and high) affects a firm's innovation incentives. See, for example, Aghion et al. (2004, 2005).

[2] For industrialized countries, transport cost is at least as large a barrier as policy barriers. According to Anderson and Van Wincoop (2004), the ad-valorem tax equivalent of transport cost is 10.7%, and that of tariff and non-tariff barriers is 7%.

al., 2018; Takauchi & Mizuno, 2019b), while others find a U-shaped effect (Long et al., 2011).

Hence, it might be difficult to predict that a reduction in trade barriers such as transport cost always strengthens innovation incentives for firms. Sometimes, trade liberalization may promote firm's R&D investment while in other cases, it may inhibit them.

In this paper, we propose a model in which a reduction in transport cost causes both a rise and fall in the firm's R&D investment. By considering a market structure consisting of many carriers (transporting firms) and two innovative exporting firms, we demonstrate that a reduction in the transport price caused by a rise in the number of carriers can bring about both an increase and decrease in the exporters' R&D investment.

We base our model on a Brander and Krugman (1983)-type reciprocal market. While each region's exporting firm uses inter-regional transport services and pays a freight charge to export overseas, it can freely supply its local market. To reduce their production costs, exporting firms engage in R&D activity involving knowledge spillovers.[3] Inter-regional transportation is a homogenous service, and carriers compete on price *à la* Dastidar (1995).

We show that a rise in the number of carriers increases (decreases) the exporters' R&D investment under a low (high) spillover rate of R&D. A higher spillover rate

[3] Prior empirical studies demonstrate positive international spillovers in R&D. See Coe and Helpman (1995) and Keller (1998). Xu and Wang (1999) further find that capital goods trade is an important conduit for international R&D spillovers.

reduces production costs, stimulating production. The transport demand rises due to the expanded production, and so carriers lower their prices as the spillover rate rises. Furthermore, the larger number of carriers promotes exports through the reduced transport price, but this lower price decreases domestic supply. If the spillover rate is low, the transport price is low; and thus, exports face lower restriction. Then, because the degree of export increase due to the transport price reduction exceeds the range of reduction of the domestic supply, the export promotion due to the rise in the number of carriers encourages R&D. Conversely, if the spillover rate is high, the transport price is high and the trade barrier is also high. Then, because the range of reduction of the domestic supply due to the lower transport price exceeds the degree of export increase, the export promotion due to the rise in the number of carriers discourages R&D.

We also show that a higher number of carriers harms consumers under a high R&D spillover rate.[4] A rise in the number of carriers lowers the transport price, and its effect strengthens as the spillover rate increases. The transport price reduction increases the foreign rival's exports and decreases the domestic supply. Hence, when the transport price reduction begins to have a large impact on the extent to which domestic supply decreases, aggregate output falls because the decline in the domestic supply exceeds the increase in the foreign rival's exports. In general, the promotion of competition due to an increase in the number of firms reduces prices and enhances consumer benefit. In contrast to this standard view, our result indicates that the promotion of competition in

[4] We place the considerations of total surplus in the Supplementary Material because we focus here on the firm's R&D investment and consumer surplus. In addition, our model does not significantly change Brander and Krugman's (1983) result with respect to the total surplus.

the transport sector can reduce consumer surplus.[5] Hence, we believe that our analysis provides a new insight into the context of the relation between competition and welfare.

To avoid criticism of the assumption such that downstream firms are price takers in the upstream transport market and to examine the welfare effect of competition in the transportation industry, we further consider the case in which exporting firms have monopsony power with respect to the transport service. This extension moderates the negative effect of an increased number of carriers on the domestic supply. However, since the domestic supply drops sharply as the number of carriers increases if the spillover rate is sufficiently high, a higher number of carriers can reduce consumer surplus.

This paper is most closely related to those of Takauchi (2015) and Takauchi and Mizuno (2019a), who employ a similar market structure. In their setting, exporting firms must pay a freight charge to ship their products to their rival's domestic market, but freely supply to their local market. Takauchi (2015) examines the effect of the cost efficiency of R&D on exporting firms' profits. Takauchi and Mizuno (2019a) consider a hold-up problem resulting from carriers raising prices after observing an exporting firm's investment. By contrast, we incorporate price competition among carriers into a reciprocal market model and examine the effects of the number of carriers on consumer welfare.

This paper is also related to two strands of literature. One strand focuses on

[5] Dinda and Mukherjee (2014) show that when the government offers the optimal uniform subsidy/tax, a higher number of inefficient firms harms consumers, though in a different context. Additionally, some empirical analyses find that an entry or increased competition can raise prices. See Grabowski and Vernon (1992) and Thomadsen (2007).

the nexus of trade barriers and innovation (Ghosh & Lim, 2013; Haaland & Kind, 2008; Hwang et al., 2018; Long et al., 2011; Takauchi & Mizuno, 2019b), and the other focuses on the explicit treatment of the transport sector in international trade (Asturias, 2020; Behrens et al., 2009; Behrens & Picard, 2011; Francois & Wooton, 2001; Ishikawa & Tarui, 2018).[6] Ghosh and Lim (2013), Haaland and Kind (2008), and Long et al. (2011) consider the effects of trade liberalization on firms' process innovation (i.e., cost-reducing R&D). By contrast, Hwang et al. (2018) and Takauchi and Mizuno (2019b) consider firms' product innovation. These studies report different results on the relationship between trade barriers and innovation incentives, but they all assume exogenous trade barriers.

Francois and Wooton (2001) focus on an imperfectly competitive transport sector and examine the effect of tariff reductions in a competitive framework. Asturias (2020) incorporates carriers who choose their technology into a competitive trade model. Behrens et al. (2009) and Behrens and Picard (2011) examine the effects of endogenous freight rates on the firm's agglomeration. While Behrens et al. (2009) focus on the carrier's market power, Behrens and Picard (2011) focus on the logistics problem associated with roundtrips. Ishikawa and Tarui (2018) 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 assume non-innovative exporting firms and quantity competition among carriers.

[6] Moreover, Abe et al. (2014) consider a trade model in which international transportation generates pollution.

This paper is organized as follows. Section 2 presents the baseline model and Section 3 derives the main results. In Section 4, we extend the baseline model to the case in which exporting firms have monopsony power with respect to the transport service. Section 5 offers our conclusions. We provide all proofs in the appendix.

2 Model

We consider two regions, the H (Home) and F (Foreign) regions, whose product market is segmented from each other. Each region has an exporting firm, *firm* i ($i = H, F$), that engages in cost-reducing R&D activity and supplies its product to the local and other markets. The inverse demand in region i is $p_i = a - Q_i$, where p_i is the product price, $Q_i = q_{ii} + q_{ji}$ is total output, q_{ii} is firm i's domestic supply, q_{ji} is firm j's exports, $i, j = H, F$, $i \neq j$, and $a > 0$. The region i's consumers surplus is $CS_i = Q_i^2/2$.

As firms have no means of carrying out long haul transportation, they pay a per-unit transport price, t, and use a transportation service to export their products. The profit of firm i is

$$\Pi_i \equiv (p_i - c_i)q_{ii} + (p_j - c_i - t)q_{ij} - x_i^2 \quad \text{for} \quad i \neq j,$$

where x_i is firm i's investment level and x_i^2 is the R&D cost. Firm i's production cost after investment is $c_i \equiv c - x_i - \delta x_j$; that is, although firm i invests x_i to reduce the unit cost c, there is a knowledge spillover and the firm i enjoys some part of its rival's developed knowledge, δx_j, without any payments. $\delta \in [0, 1]$ is the spillover rate of R&D and $a > c > 0$.

In the transport industry, there are n (≥ 2) identical cargo transporters, which we refer to as *carriers*. For simplicity, we assume that carriers exist in regions besides the Home and Foreign regions. In our model, inter-regional transportation is a homogeneous service and carriers compete in a Bertrand fashion. Let the transport price offered by carrier k ($\in \{1, \ldots, n\}$) be t_k, carrier k's individual transport demand be q_k, and the aggregate demand be $q_{HF} + q_{FH}$. Each firm employs the carriers offering the lowest price, so the individual transport demand of carrier k is $q_k = [q_{HF}(t^l) + q_{FH}(t^l)]/m$ if the carrier offers the lowest price, $t_k = t^l$. Here, m denotes the number of carriers offering the lowest price. If carrier k offers a slightly higher price than t^l, then $q_k = 0$. To obtain explicit solutions, we assume that carrier k has a quadratic operation cost, $(\lambda/2)q_k^2$, where $\lambda > 0$ denotes the transport efficiency.[7] The profit of carrier k is

$$\pi_k \equiv t_k q_k - \frac{\lambda}{2} q_k^2.$$

The timing of the game is as follows. In the first stage, each firm independently and simultaneously decides its investment level. In the second stage, the transport price is determined through price competition among carriers. In the third stage, each firm independently and simultaneously decides its level of its domestic supply and exports. The timing structure corresponds to the difficulty of a change in each decision. R&D generally takes much more time, so its investment decision is in the first stage of the game. In contrast, since firms can frequently adjust their outputs, the production

[7] The quadratic cost is popular in this type of price competition. For example, see Dastidar (1995 pp. 27), Dastidar (2001 pp. 85), Delbono and Lambertini (2016a, 2016b), Gori et al. (2014), and Mizuno and Takauchi (2020).

decision occurs in the last stage. Since in the second stage the Nash equilibrium is not unique, we employ subgame perfect Nash equilibrium (SPNE) with payoff-dominance refinement as the equilibrium concept.[8] We solve the game using backward induction.

3 Results

In the third stage of the game, the first-order conditions (FOCs) to maximize the profit of firm i are $0 = a - c - 2q_{ii} - q_{ji} + x_i + \delta x_j$ and $0 = a - c - q_{jj} - 2q_{ij} + x_i + \delta x_j - t$ $(i \neq j)$. These FOCs yield the following third-stage outputs of $q_{ii}(t, \mathrm{x}) = \frac{1}{3}[a - c + t + (2 - \delta)x_i + (2\delta - 1)x_j]$ and $q_{ij}(t, \mathrm{x}) = \frac{1}{3}[a - c - 2t + (2 - \delta)x_i + (2\delta - 1)x_j]$, where $i, j = H, F$, $i \neq j$, and $\mathrm{x} = (x_i, x_j)$.

In the second stage, the transport price t is determined by price competition among carriers. As Dastidar (1995) demonstrates, if oligopolists with a convex cost engage in a homogeneous price competition, the Nash equilibrium is not unique. In our model, the pure strategy Nash equilibria of transport price has a certain range of $[\,\underline{t},\ \bar{t}\,]$ derived from the following two conditions: The first condition is given by

$$\pi_k(t, \mathrm{x}, n) \equiv t\left(\frac{q_{HF}(t, \mathrm{x}) + q_{FH}(t, \mathrm{x})}{n}\right) - \frac{\lambda}{2}\left(\frac{q_{HF}(t, \mathrm{x}) + q_{FH}(t, \mathrm{x})}{n}\right)^2 \geq 0,$$

which implies that "carriers do not raise their prices." The second condition is given by

$$\pi_k(t, \mathrm{x}, n) \geq \pi_k(t, \mathrm{x}, 1) \equiv t\big(q_{HF}(t, \mathrm{x}) + q_{FH}(t, \mathrm{x})\big) - \frac{\lambda}{2}\big(q_{HF}(t, \mathrm{x}) + q_{FH}(t, \mathrm{x})\big)^2,$$

[8] For example, Cabon-Dhersin and Drouhin (2014) and Mizuno and Takauchi (2020) employ this concept.

which implies that "carriers do not lower their prices." The first condition yields the lower bound $\underline{t}$, and the second yields the upper bound $\bar{t}$:

$$\underline{t} = \frac{[2(a-c)+(x_H+x_F)(1+\delta)]\lambda}{2(3n+2\lambda)}; \quad \bar{t} = \frac{(n+1)[2(a-c)+(x_H+x_F)(1+\delta)]\lambda}{2[(3+2\lambda)n+2\lambda]}.$$

To narrow the equilibria, we employ the *payoff-dominance criterion* that maximizes each carrier's profit. Since carriers are symmetric, the transport price is

$$t_P = \operatorname*{argmax}_t \ \pi_k(t, \mathrm{x}, n) \ = \frac{[2(a-c)+(x_H+x_F)(1+\delta)](3n+4\lambda)}{8(3n+2\lambda)}.$$

The prices $\underline{t}$, $\bar{t}$, and t_P,[9] yield Lemma 1.

Lemma 1. *(i)* $t_P > \underline{t}$. *(ii)* $t_P \leq \bar{t}$ *if and only if* $\lambda \geq \lambda_0 \equiv 3n/[2(n-1)]$.

To ensure $t_P < \bar{t}$; that is, $t = t_P$,[10] we require Assumption 1.

Assumption 1. $\lambda > \lambda_0 \equiv 3n/[2(n-1)]$.

We next define z to facilitate the analysis.

Definition 1. $z \equiv \lambda/n \in [3/2, \infty)$.[11]

[9] The price t_P is also known as *collusive-price* because it maximizes joint profit of carriers. To narrow the set of Nash equilibria, this collusive-price refinement is often employed. For example, see Dastidar (2001), Gori et al. (2014), and Mizuno and Takauchi (2020). The collusive-price refinement is identical to the payoff-dominance refinement if the Nash equilibria contain the interior maximizing point of each carrier's profit (i.e., the upper bound of the equilibria is strictly larger than the interior maximizer of each carrier's profit).

[10] "$t = t_P$" is partially consistent with the characteristics of the transport industry. For example, as indicated by Hummels et al. (2009), ocean shipping is an oligopoly market. Moreover, some studies report collusion in this industry (e.g., Sjostrom, 2004; Sys, 2009; Sys et al., 2011). Among them, Sys (2009) empirically demonstrates that the containerized shipping industry is tacitly collusive.

[11] Although we need $z > (3/2)(1/(n-1))$ from Assumption 1 because the maximum of $1/(n-1)$ is

Substituting the outcomes of the third and second stages into the profit of firm i and solving the FOC, we obtain the following.

$$x_i^* = \frac{(a-c)[48z^2+144z+113-(4z+5)(4z+11)\delta]}{E}, \tag{1}$$

$$q_{ii}^* = \frac{8(a-c)(2z+3)(4z+5)}{E}; \quad q_{ij}^* = \frac{16(a-c)(2z+3)}{E}, \quad i \neq j, \tag{2}$$

$$t^* = \frac{8(a-c)(2z+3)(4z+3)}{E}, \tag{3}$$

where

$$E \equiv (4z+5)(4z+11)\delta^2 - 2(16z^2+40z+29)\delta + 5(4z+5)(4z+7) > 0.$$

The variable $*$ is the SPNE outcome.

The profits of carrier k and firm i are $\pi_k^* = \left(\frac{2z+3}{n}\right)(q_{ij}^*)^2$ and $\Pi_i^* = (q_{ii}^*)^2 + (q_{ij}^*)^2 - (x_i^*)^2$, respectively.

To ensure a positive unit production cost after investment, we require Assumption 2.

Assumption 2. *$c/(a-c) > (1+\delta)[48z^2+144z+113-(4z+5)(4z+11)\delta]/E$.*

From (1)–(3), we establish Lemma 2.

Lemma 2. *I. If $\delta >$ (=,<) $\delta_t \equiv \frac{16z^2+40z+29}{(4z+5)(4z+11)}$, $\partial t^*/\partial\delta$, $\partial q_{ii}^*/\partial\delta$, and $\partial q_{ij}^*/\partial\delta <$ (=,>) 0. II. (i) Suppose $z < z_1 \simeq 5.90928$; then, $\partial x_i^*/\partial\delta < 0$. (ii) Suppose $z > z_1$; then, if $\delta < \delta_x$, $\partial x_i^*/\partial\delta > 0$. Otherwise, $\partial x_i^*/\partial\delta \leq 0$. (The threshold δ_x is defined in Appendix B.)*

Similarly, (1)–(3) yield the following result.

1, $\lambda > \lambda_0$ holds for all $z \geq 3/2$.

Proposition 1. *(i) Keener competition in the transport industry (i.e., a rise in n) and higher transport efficiency (i.e., a fall in λ) decreases transport prices and domestic supply, but these increase exports. (ii) Keener competition in the transport industry and higher transport efficiency increases the firm's investment if and only if $\delta < 5/(8z+7)$.*

We first consider part (i) of Proposition 1. A higher n and a smaller λ (i.e., a decrease in z) have a similar effect. A higher n lowers transport prices by intensifying competition among carriers and it therefore increases exports. A smaller λ flattens the slope of the carriers' cost curve, which induces a lower transport price, and thereby promotes exports. Because both a higher n and a lower λ expand imports and makes competition in the local market tougher, firm i's domestic supply falls.

Second, we examine the logic behind Lemma 2. A higher δ lowers production costs, facilitates production activities, and thus increases both domestic supply and exports. That is, in our model, δ has exactly the same effect on both domestic supply and exports. Since a higher δ leads to an expansion in transport demand, it encourages carriers to set higher prices. (A lower δ yields the inverse result.) Hence, if a higher (lower) δ increases (decreases) transport demand, both outputs and transport prices increase (decrease) as δ goes up (down) because it also raises (lowers) transport price. On the one hand, an increase in transport prices raises the trade barrier, which impedes exports. If δ rises when its level is low enough, because the transport price is low and the positive effects of a reduction in production costs exceeds the export impeding effect of rising transport prices, the firm's exports increase. Conversely, when both δ and transport prices are high, a rise in δ reduces exports because the export impeding effect becomes large. Transport demand then falls and carriers lower their prices as δ rises.[12]

A rise in δ has positive and negative effects on the R&D motive. A higher δ encourages investment because it reduces the unit production cost and facilitates production (positive effect). If δ increases, because each firm enjoys its rivals developed knowledge without cost, the R&D motive weakens (negative effect). Investment usually decreases as δ rises because the negative effect is dominant. This is a well-known result illustrated by d'Aspremont and Jacquemin (1988).

Different from the standard result, in our model, the positive effect can be dominant. When λ is large, that is, z is large, transportation is inefficient and its price is high. A high transport price impedes cross-hauling and strengthens the monopolization of the local firm in its market. Suppose that the R&D spillover arises, that is, δ slightly increases from 0 in this case; the unit production cost then falls and outputs increase, but it also raises transport prices and the domestic supply increases more rapidly than exports. This strengthens the degree of the local firm's relative monopoly in its market. Because such enlargement in the domestic supply promotes investment and the positive effect becomes dominant, R&D investment increases as δ rises. However, if δ goes above a certain level, the negative effect is dominant since an inflow of the rival firm's developed knowledge becomes large.

[12] Additionally, $\partial x_i^*/\partial\delta$ can explain why the transport prices and the firm's outputs have the same change for δ. From the third-stage outputs and $t = t_P$, noting that $x_i = x_j$ in equilibrium, the total differentiation of $q_{ii} = q_{ii}(\mathrm{x}, t, \delta)$, $q_{ij} = q_{ij}(\mathrm{x}, t, \delta)$, and $t = t(\mathrm{x}, \delta)$ yields $dt/d\delta = \frac{3n+4\lambda}{4(3n+2\lambda)}\left[x_i + (1+\delta)\frac{dx_i}{d\delta}\right]$, $dq_{ii}/d\delta = \frac{5n+4\lambda}{4(3n+2\lambda)}\left[x_i + (1+\delta)\frac{dx_i}{d\delta}\right]$, and $dq_{ij}/d\delta = \frac{n}{2(3n+2\lambda)}\left[x_i + (1+\delta)\frac{dx_i}{d\delta}\right]$.

We next consider part (ii) of Proposition 1, which indicates that to raise investment by lowering transport prices, δ should be sufficiently small. The intuition is as follows. As we show in Lemma 2, when δ is sufficiently small, the transport price is also low and the degree of export restriction is weak. Although a higher n and a smaller λ commonly reduce transport prices and increase exports, they decrease the domestic supply. If δ is sufficiently small, because the transport price reduction leads to an increase in exports in excess of the decrease in the domestic supply, a higher n and a smaller λ can encourage investment. In contrast, if δ is large, a higher n and a smaller λ can never encourage investment because the degree of the reduction in domestic supply becomes larger.

Does an increase in the number of carriers and improved transport efficiency make consumers better off? We next focus on the effects of z on consumer surplus. To examine this, we use (2) and obtain the following proposition.

Proposition 2. *Keener competition in the transport industry and higher transport efficiency reduces consumer surplus if and only if the R&D spillover rate is sufficiently high; that is, $\partial Q_i^*/\partial z > 0$ if and only if $\delta > \delta_{cs}$. (The threshold δ_{cs} is defined in Appendix B.)*

[Fig. 1 around here]

Panel (a) of Fig. 1 depicts Proposition 2. As long as the R&D spillover is not too high, the trade promotion due to the transport price reduction increases total output, $Q_i = q_{ii} + q_{ji}$, and lowers the product price and consumer surplus therefore increases.

However, Proposition 2 indicates that this promotion of inter-regional trade is not always desirable for consumers. A key to this result is the role of $\partial t^*/\partial z$.

A higher δ lowers the production costs of firms and increases aggregate transport demand. When the aggregate transport demand is high, each carrier's individual demand is also high because carriers are symmetric. Then, suppose that the number of carriers n increases; that is, z ($\equiv \lambda/n$) decreases. Tougher competition among them reduces each carrier's demand, and the size of the demand that the carrier loses increases as the aggregate transport demand increases. Although each carrier lowers its price if there is a reduction in its demand, carriers sharply lower their prices compared to the case of low aggregate transport demand because the size of the lost demand increases as the aggregate transport demand increases. Hence, a higher δ strengthens $\partial t^*/\partial z$.[13]

Although a higher δ facilitates production, it can raise transport prices (Lemma 2). A higher δ has both export promotion and restriction effects and a higher δ therefore strengthens $\partial q^*_{ji}/\partial z$ in some cases, but it weakens $\partial q^*_{ji}/\partial z$ in the other cases. On the one hand, as we show in Proposition 1, a higher n (or lower z) reduces domestic supply because transport prices (i.e., the rival firm's trade barrier) fall. If δ is high, the degree of reduction in domestic supply for an increase in n is also large because the degree of the reduction in transport prices for an increase in n is large. That is, when δ rises, the "$\partial t^*/\partial z$" effect becomes stronger, which strengthens the "$\partial q^*_{ii}/\partial z$" effect.

We illustrate $\partial q^*_{ii}/\partial z$ and $-(\partial q^*_{ji}/\partial z)$ as functions of δ in Panel (b) of Fig. 1. (Since $\partial q^*_{ji}/\partial z$ has a negative value, we multiply it by -1.) As δ increases above a certain

[13] $\forall z \geq 3/2$, $(\partial/\partial\delta)(\partial t^*/\partial z) > 0$ holds.

level, $\partial q_{ii}^*/\partial z$ (the increasing curve) exceeds $-(\partial q_{ji}^*/\partial z)$ (the inverted U-shaped curve). Hence, if δ is sufficiently high, $\partial Q_i^*/\partial z$ has a positive value. When δ is high, a higher n (lower z) reduces total output.

4 An Extension

Duopsony in the transport market

In Section 3, we assumed that firms are price takers in relation to the transport service, that is, firms have monopoly power in the downstream product market, whereas they do not have monopsony power in the upstream transport market. Although this assumption is frequently employed in the study of vertically related markets, there is also a criticism that "while downstream firms recognize their monopoly power and strategically behave as sellers in the downstream market, they do not strategically behave as buyers and are price takers in the upstream market."[14] To avoid such criticism, we further examine the situation in which firms have *monopsony power* in the transport service market.

To examine the situation in which the export decision of each firm directly affects to the transport supply, we consider the following timing of the game.

- *First stage:* The firm i ($i = H, F$) chooses its investment level, x_i.
- *Second stage:* Given the transport price t, each carrier k ($k = 1, ..., n$) chooses its freight traffic, q_k. Then, the shape of the inverse transport supply function,

[14] For this criticism see, for example, Ishikawa and Spencer (1999). They offer some arguments to justify the assumption such that downstream firms are price takers in the upstream market.

$t = T(q_{HF} + q_{FH})$, is fixed.

- *Third stage:* Given the inverse transport supply function, firm i decides its exports, q_{ij}, and domestic supply q_{ii} $(i, j = H, F$ and $i \neq j)$.

- *Fourth stage:* The transport market is cleared by the equilibrium price, t.

The game is solved using backward induction. In Appendix A, we report the detailed procedure used to obtain the SPNE of this game and the necessary equilibrium outcomes.

When firms have monopsony power regarding the transport service, they can lower the transport price by decreasing their export volume because their exports (i.e., volume of traffic) influences to the inverse transport supply. Hence, in the duopsony case, the equilibrium transport price, t^{d*}, is lower compared to the case in which they are price takers, that is, $t^* > t^{d*}$.[15]

The following proposition addresses the impact of z on the outputs, the transport price, and the investment, which are derived from (A1) and (A2) in Appendix A.

Proposition 3. *Suppose that exporting firms have monpsony power in the transportation market. Then, (i) keener competition in the transport industry and higher transport efficiency decrease transport prices, but these factors increase exports. If $\delta > \delta^d_{ds}$, then keener competition in the transport industry and higher transport efficiency decrease domestic supply. Otherwise, these factors increase domestic supply. (We define the threshold δ^d_{ds} in Appendix B.) (ii) Keener competition in the transport in-*

[15] We summarize this result as "Lemma S1" in Supplementary Material.

dustry and higher transport efficiency increases the firms' investment if and only if $\delta < \frac{2(38z^3+55z^2+30z+9)}{92z^3+154z^2+84z+9} \in (0, 1)$*.*

Part (i) of Proposition 3 has partially different results from part (i) of Proposition 1. In the price-taker case, since carriers decide their prices, if they raise their prices, then they inhibit the foreign firm's exports because this increases the trade barrier. Hence, competition in the domestic market softens. Then, the local firm always increases its domestic supply. By contrast, in the duopsony case, because carriers do not directly decide their prices, the change in both exports and domestic supply as z changes can be the same. However, when δ becomes large, because the transport demand increases due to the expanding outputs through a reduction in production costs, the transport price increases, as with the price-taker case. If the transport price is at a high level, then the effect of its change is also strong.[16] Then, the foreign rival's exports increase sharply due to a fall in z, so the domestic supply decreases.

The logic behind part (ii) of Proposition 3 is same as for part (ii) of Proposition 1. When δ is large enough, the degree of the decrease in the transport price as z decreases is large. Because this strengthens the effect of the domestic supply reduction due to a rise in the rival's exports, a fall in z weakens the motive for R&D investment.

From (A3) in Appendix A, we establish the following proposition.

Proposition 4. *Suppose that exporting firms have monpsony power in the transportation market. (i) If* $z < z_2 \simeq 2.58114$ *or [*$\delta < \delta^d_{cs}$ *and* $z > z_2$*], then keener competition in the transport industry and higher transport efficiency increase consumer surplus.*

[16] $\forall z \geq 3/2$, $(\partial/\partial\delta)(\partial t^{d*}/\partial z) > 0$.

(ii) If $\delta > \delta^d_{cs}$ and $z > z_2$, then keener competition in the transport industry and higher transport efficiency reduce consumer surplus. (We define the threshold $\delta^d_{cs} > 0$ in Appendix B.)

[Fig. 2 around here]

A rise in the spillover rate, δ, strengthens the degree of a change in the transport price due to a change in z (i.e., the "$\partial t/\partial z$" effect), and also strengthens the degree of change in the domestic supply due to a change in z (i.e., the "$\partial q_{ii}/\partial z$" effect). Hence, when δ is sufficiently high, the "$\partial q_{ii}/\partial z$" effect is dominant, and thus, the area such that $\partial Q/\partial z > 0$ appears (see Fig. 1). On the one hand, in the duopsony case, the equilibrium transport price is lower than that in the price-taker case (i.e., $t^* > t^{d*}$). Because the decline in the transport price makes the "$\partial t/\partial z$" effect weaker, the "$\partial t/\partial z$" effect in the duopsony case becomes weaker than that in the price-taker case.[17] As shown in the logic behind Proposition 2, if the "$\partial t/\partial z$" effect becomes weaker, the "$\partial q_{ii}/\partial z$" effect also becomes weaker. Hence, in the duopsony case, the "$\partial q_{ii}/\partial z$" effect is weaker than that in the price-taker case. Therefore, in the duopsony, the value of the spillover rate that makes the "$\partial q_{ii}/\partial z$" effect dominant (i.e., the threshold δ^d_{cs}) is higher than that in the price-taker case. Panels (a) and (b) in Fig. 2 illustrate this relationship.

[17] Using Mathematica plotting, we find that $\partial t^*/\partial z > \partial t^{d*}/\partial z > 0$.

5 Conclusion

This paper considers the effects of an increase in the number of carriers on a firm's R&D investment and consumer surplus. In a simple two-region (or country) R&D rivalry model with a transport sector, we show that R&D investment rises as the number of carriers increases if the R&D spillover is small, and decreases as the number of carriers increases if the spillover is large enough. We also show that although a higher number of carriers lowers the transport price, it can reduce consumer surplus in each region. We further extend the case in which firms have no market power (i.e., are price-takers) to the case in which firms have monopsony power over the transportation service. However, firms can lower the transport price by reducing their export volumes, and hence the equilibrium transport price in the duopsony case is lower than that in the price-taker case, a higher number of carriers also reduces consumer surplus if the R&D spillover is sufficiently large. Hence, competition in the transport sector can harm consumers. Our model highlights the results of competition promotion, and we therefore believe that our analysis provides a new insight into studies of competition and welfare.

In this paper, we do not consider the possibility of improved production efficiency due to foreign direct investment (FDI). While the level of transport costs possibly affects a firm's FDI decision, this aspect is beyond the scope of our analysis. In the case of international trade with transportation services, it may be fruitful for future research to examine exporting firms' FDI strategies.

Appendix

A. The SPNE outcomes in a duopsony of exporting firms

We present the calculation to derive the equilibrium outcomes in the game in which firms have monopsony power in the transport market.

In the fourth stage of the game, the equilibrium transport price is decided so as to equalize transport supply with its demand. However, the transport demand, total exports of two firms, is chosen in the third stage. Thus, to solve the game correctly, we assume an inverse transport-supply function, $t = T(q_{HF} + q_{FH})$, and consider this in the third stage.

• **The third stage.** From the profit of firm i and $t = T(q_{HF} + q_{FH})$, the FOCs for profit maximization of firms are $\partial \Pi_i / \partial q_{ii} = 0 \Leftrightarrow a - c - 2q_{ii} - q_{ji} + x_i + \delta x_j = 0$ and $\partial \Pi_i / \partial q_{ij} = 0 \Leftrightarrow a - c - 2q_{ij} - q_{jj} + x_i + \delta x_j - t - T'(q_{HF} + q_{FH}) q_{ij} = 0$ $(i \neq j)$. Let "$'$" be the first derivative and $T' = T'(\,\cdot\,)$. The FOCs yield the third-stage outputs: $q_{ii}(t, \mathrm{x}; T') = [a - c + (2 - \delta)x_i + (2\delta - 1)x_j + t + (a - c + x_i + \delta x_j)T']/(3 + 2T')$ and $q_{ij}(t, \mathrm{x}; T') = [a - c + (2 - \delta)x_i + (2\delta - 1)x_j - 2t]/(3 + 2T')$.

• **The second stage.** The carrier k's maximization problem, $\max_{q_k} \pi_k$, yields $q_k = t/\lambda$. Because the transport demand is $q_{HF} + q_{FH}$, the market clearing condition is $q_{HF} + q_{FH} = \sum_{k=1}^{n} q_k = nt/\lambda$. From this, the inverse transport supply in this subgame is $t = T(q_{HF} + q_{FH}) = (q_{HF} + q_{FH})\lambda/n$, and hence, $T' = \lambda/n$ holds. Plugging $t = (q_{HF} + q_{FH})\lambda/n$ and $T' = \lambda/n$ into the third-stage outputs and solving these for outputs again, we obtain the second-stage outputs:

$$q_{ii}(\mathrm{x}) = \frac{(a-c)(3n+2\lambda)(n+3\lambda)+u_i x_i + u_j x_j}{3(n+2\lambda)(3n+2\lambda)},$$
$$q_{ij}(\mathrm{x}) = \frac{n[(a-c)(3n+2\lambda)+v_i x_i + v_j x_j]}{3(n+2\lambda)(3n+2\lambda)},$$

where $u_i \equiv 2(3n^2+8n\lambda+3\lambda^2)-n(3n+5\lambda)\delta$, $u_j \equiv 2(3n^2+8n\lambda+3\lambda^2)\delta - n(3n+5\lambda)$, $v_i \equiv 2(3n+5\lambda)-(3n+8\lambda)\delta$, and $v_j \equiv 2(3n+5\lambda)\delta-(3n+8\lambda)$.

The above $q_{ij}(\mathrm{x})$ yields the second-stage transport price: $t(\mathrm{x}) = \frac{(2(a-c)+(1+\delta)(x_H+x_F))\lambda}{3(n+2\lambda)}$.

• **The first stage.** In this stage, each firm decides its investment level, x_i. The objective function of firm i, $\Pi_i(\mathrm{x})$, is derived from $q_{ii}(\mathrm{x})$, $q_{ij}(\mathrm{x})$, and $t(\mathrm{x})$. Solving the FOCs, $\partial\Pi_i(\mathrm{x})/\partial x_i = 0$ $(i = H, F)$, with respect to x_i, we obtain the following SPNE investment level:

$$x_i^{d*} = \frac{(a-c)[2(9z^3+32z^2+25z+6)-(23z^2+25z+6)\delta]}{K}, \tag{A1}$$

where

$$K \equiv 54z^3+116z^2+76z+15-(2z+3)(9z^2+7z+2)\delta+(23z^2+25z+6)\delta^2 > 0.$$

We need the following assumption to ensure a positive (unit) production cost.

Assumption 3. $c/(a-c) > (1+\delta)[2(9z^3+32z^2+25z+6)-(23z^2+25z+6)\delta]/K$.

The SNPE outputs and transport price are

$$\left.\begin{aligned} q_{ii}^{d*} &= \frac{3(a-c)(2z+1)(2z+3)(3z+1)}{K};\ q_{ij}^{d*} = \frac{3(a-c)(2z+1)(2z+3)}{K}, \\ t^{d*} &= \frac{6(a-c)z(2z+1)(2z+3)}{K}. \end{aligned}\right\} \tag{A2}$$

The profit of carrier k and firm i are $\pi_k^{d*} = \frac{1}{n}t^{d*}q_{ij}^{d*}$ and $\Pi_i^{d*} = (q_{ii}^{d*})^2+(q_{ij}^{d*})^2-(x_i^{d*})^2$.

The equilibrium outputs yield the total output in region i:

$$Q_i^{d*} = q_{ii}^{d*} + q_{ji}^{d*} = \frac{3(a-c)(2z+1)(2z+3)(3z+2)}{K}, \quad j \neq i. \tag{A3}$$

B. Proofs

Proof of Lemma 1. (i) A simple algebra yields $t_P - \underline{t} = \frac{3n[2(a-c)+(x_H+x_F)(1+\delta)]}{8(3n+2\lambda)} > 0$.

(ii) Since $\bar{t} - t_P = \frac{3n[2(a-c)+(x_H+x_F)(1+\delta)][2\lambda(n-1)-3n]}{8(3n+2\lambda)[(3+2\lambda)n+2\lambda]}$, $t_P \leq \bar{t}$ iff $\lambda \geq \frac{3n}{2(n-1)}$. Q.E.D.

Proof of Lemma 2. I. Differentiating (2) and (3) with respect to δ yields $\partial t^*/\partial\delta = \frac{16(a-c)(2z+3)(4z+3)}{E^2}L_1$, $\partial q_{ii}^*/\partial\delta = \frac{16(a-c)(2z+3)(4z+5)}{E^2}L_1$, and $\partial q_{ij}^*/\partial\delta = \frac{32(a-c)(2z+3)}{E^2}L_1$, where $L_1 \equiv 16z^2 + 40z + 29 - (4z+5)(4z+11)\delta$. These yield part I.

II. Differentiating (1) with respect to δ yields $\partial x_i^*/\partial\delta = \frac{(a-c)}{E^2}L_2$, where $L_2 \equiv 256z^4 - 512z^3 - 4640z^2 - 7008z - 3071 - 2\delta(4z+5)(4z+11)(48z^2+144z+113) + \delta^2(4z+5)^2(4z+11)^2$. Solving $L_2 \geq 0$ for δ, we obtain $\delta \leq \delta_x \equiv \frac{48z^2+144z+113-4\sqrt{2}\sqrt{(2z+3)^2(4z+5)(4z+11)}}{(4z+5)(4z+11)}$; δ_x is increasing for z, $\lim_{z\to\infty}\delta_x = (3-2\sqrt{2}) \simeq 0.171573$, and $\delta_x = 0$ for $z = z_1 \simeq 5.90928$. Q.E.D.

Proof of Proposition 1. (i) Differentiating (2) and (3) with respect to z yields

$$\frac{\partial t^*}{\partial z} = \frac{16(a-c)[9(23\delta^2-18\delta+55)+16(7\delta^2-2\delta+15)z^2+8(37\delta^2-22\delta+85)z]}{E^2} > 0,$$
$$\frac{\partial q_{ii}^*}{\partial z} = \frac{16(a-c)[125\delta^2-38\delta+125+16(5\delta^2+2\delta+5)z^2+8(25\delta^2+2\delta+25)z]}{E^2} > 0,$$
$$\frac{\partial q_{ij}^*}{\partial z} = -\frac{32(a-c)[41\delta^2-62\delta+185+16(\delta^2-2\delta+5)z(3+z)]}{E^2} < 0.$$

(ii) Differentiating (1) with respect to z yields $\partial x_i^*/\partial z = \frac{128(a-c)(2z+3)}{E^2}[\delta(8z+7)-5]$, which implies (ii). Q.E.D.

Proof of Proposition 2. Since $CS_i^* = (Q_i^*)^2/2$, $\text{sign}\{\partial CS_i^*/\partial z\} = \text{sign}\{\partial Q_i^*/\partial z\}$. The differentiation of total output yields $\partial Q_i^*/\partial z = \frac{16(a-c)}{E^2}[(48z^2+104z+43)(\delta^2+2\delta) - 5(4z+7)^2]$. Thus, $\partial Q_i^*/\partial z \geq 0$ for $\delta \geq \delta_{cs} \equiv -1 + \frac{4\sqrt{2}\sqrt{(2z+3)^2(48z^2+104z+43)}}{48z^2+104z+43}$ (>0); δ_{cs} is decreasing for z and $\delta_{cs} = 1$ for $z = (\sqrt{30}-1)/4 \simeq 1.11931$. Q.E.D.

Proof of Proposition 3. (i) Differentiating (A2) with respect to z, we have

$$\frac{\partial t^{d*}}{\partial z} = \frac{6(a-c)}{K^2}\left[\begin{array}{l} 4(23\delta^2 - 5\delta + 8)z^4 + 4(50\delta^2 - 23\delta + 71)z^3 \\ +(203\delta^2 - 149\delta + 440)z^2 + 3(2\delta^2 - 2\delta + 5)(16z+3) \end{array}\right] > 0,$$

$$\frac{\partial q_{ij}^{d*}}{\partial z} = -\frac{9(a-c)}{K^2}\left[\begin{array}{l} 9(\delta^2 - \delta + 4) + 24(3-\delta)(z+4)z^3 \\ +2(14\delta^2 - 65\delta + 185)z^2 + 6(5\delta^2 - 11\delta + 32)z \end{array}\right] < 0,$$

$$\frac{\partial q_{ii}^{d*}}{\partial z} = \frac{9(a-c)}{K^2}\left[\begin{array}{l} 9 + 48z + 70z^2 - 4z^3 - 40z^4 + \delta(2z+3)^2(z^2-2z-1) \\ +\delta^2(92z^4 + 200z^3 + 175z^2 + 66z + 9) \end{array}\right].$$

From the above equations, we have $\partial q_{ii}^{d*}/\partial z \leq (>)\ 0$ if $\delta \leq (>)\ \delta_{ds}^d$, where $\delta_{ds}^d \equiv \frac{\sqrt{3}\sqrt{(2z+1)^2 L_3} - (2z+3)^2(z^2-2z-1)}{184z^4+400z^3+350z^2+132z+18}$ and $L_3 \equiv 1228z^6 + 1564z^5 - 1429z^4 - 4020z^3 - 2970z^2 - 864z - 81$. Since $L_3 > 0$ for $z > 1.56433$, in this range, we find that

$$\left(\sqrt{3}\sqrt{(2z+1)^2 L_3}\right)^2 - [(2z+3)^2(z^2-2z-1)]^2$$

$$= 4(3680z^8 + 8368z^7 + 1360z^6 - 15076z^5 - 22054z^4 - 14784z^3 - 5373z^2 - 1026z - 81)$$

$$\geq 0 \quad \text{for} \quad z \geq z_2 \simeq 1.56576.$$

Furthermore, $\delta_{ds}^d < 1$, and $\delta_{ds}^d \to \frac{\sqrt{921}-1}{46} \simeq 0.638$ as $z \to \infty$. Hence, part (i) holds.

(ii) Differentiating (A1) with respect to z yields $\partial x_i^{d*}/\partial z = \frac{9(a-c)(2z+1)}{K^2}[\delta(92z^3 + 154z^2 + 84z + 9) - 76z^3 - 110z^2 - 60z - 18]$, which implies part (ii). Q.E.D.

Proof of Proposition 4. Differentiating (A3) with respect to z yields

$$\frac{\partial Q_i^{d*}}{\partial z} = \frac{9(a-c)}{K^2}\left[\begin{array}{l} z(92z^3+200z^2+147z+36)\delta^2+z(7z+4)(2z+3)^2\delta \\ -(4z+3)(28z^3+52z^2+36z+9) \end{array}\right].$$

Thus, $\partial Q_i^{d*}/\partial z \geq 0$ if $\delta \geq \delta_{cs}^d$, where $\delta_{cs}^d \equiv \frac{\sqrt{3}\sqrt{z(2z+1)^2M_1} - z(7z+4)(2z+3)^2}{2z(92z^3+200z^2+147z+36)}$ and $M_1 \equiv 3500z^5 + 13388z^4 + 21243z^3 + 17496z^2 + 7452z + 1296$. From the equation of δ_{cs}^d,

$$\begin{aligned}&\left(\sqrt{3}\sqrt{z(2z+1)^2M_1}\right)^2 - [z(2z+3)^2(7z+4)]^2 \\ &\quad = 4z(4z+3)(28z^3+52z^2+36z+9)(92z^3+200z^2+147z+36) > 0,\end{aligned}$$

so $\delta_{cs}^d > 0$. We find that $\delta_{cs}^d \to \frac{5\sqrt{105}-7}{46} \simeq 0.961625$ as $z \to \infty$, and $\delta_{cs}^d - 1 \leq 0$ for $z \geq z_2 \simeq 2.58114$. Q.E.D.

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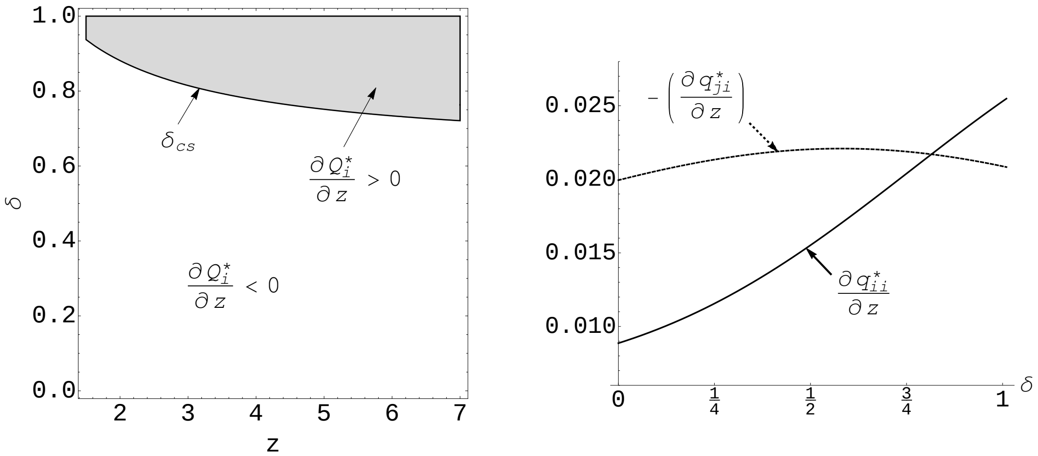
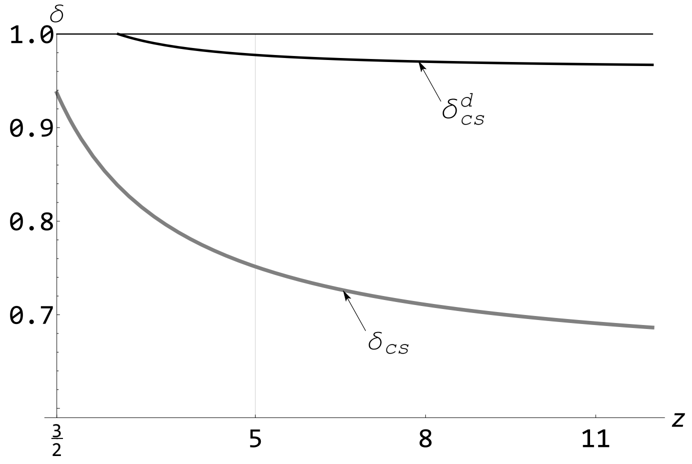


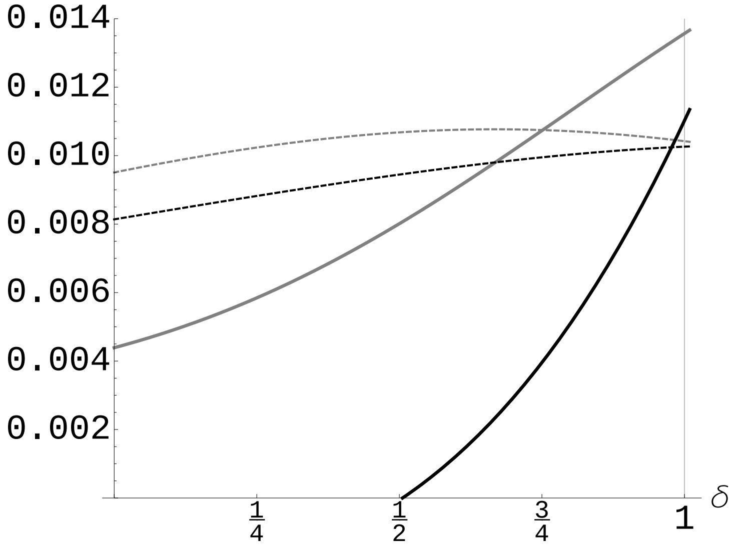
Panel (a): The area "$\partial Q_i^*/\partial z > 0$."

Panel (b): $\partial q_{ii}^*/\partial z$ and $-(\partial q_{ji}^*/\partial z)$ ($z = 3$; $a - c = 1$).

Figure 1: Illustration of Proposition 2.



Panel (a): Two thresholds: δ_{cs}^{d} (black curve) and δ_{cs} (gray curve).



Panel (b): $\partial q_{ii}^{*}/\partial z$ (gray curve), $-(\partial q_{ji}^{*}/\partial z)$ (dashed gray curve), $\partial q_{ii}^{d*}/\partial z$ (black curve), and $-(\partial q_{ji}^{d*}/\partial z)$ (dashed black curve).
Note: These four curves are illustrated where $z = 5$; $a - c = 1$.

Figure 2: Comparison of two cases: price-taker and duopsony.

Endogenous transport price, R&D spillovers, and trade Supplementary Material (Not for Publication)

In this supplement, we first provide the two additional results in Section 4 of the paper, and provide the welfare analysis.

1. Two additional results in Section 4.

Lemma S1. $t^* > t^{d*}\ \forall z \equiv \lambda/n \geq 3/2$.

Proof. The difference between t^* and t^{d*} is

$$t^* - t^{d*} = \frac{2(a-c)(2z+3)}{EK}\left[\varphi(\delta)\right],$$

where $\varphi(\delta) \equiv 180 + 627z + 838z^2 + 824z^3 + 384z^4 - 2(36 + 111z + 152z^2 + 148z^3 + 48z^4)\delta + (72 + 231z + 154z^2 - 64z^3 - 96z^4)\delta^2$. Note that

$$E \equiv (4z+5)(4z+11)\delta^2 - 2(16z^2+40z+29)\delta + 5(4z+5)(4z+7) > 0 \quad \text{and}$$
$$K \equiv 54z^3 + 116z^2 + 76z + 15 - (2z+3)(9z^2+7z+2)\delta + (23z^2+25z+6)\delta^2 > 0.$$

Thus, $\text{sign}\{t^* - t^{d*}\} = \text{sign}\{\varphi(\delta)\}$.

Let $A \equiv 72 + 231z + 154z^2 - 64z^3 - 96z^4$ in $\varphi(\delta)$. Then, from numerical calculation, $A > (=, <)\ 0$ for $z < (=, >)\ z_A \simeq 1.55637$. To show that $\varphi(\delta) > 0\ \forall z \geq 3/2$, we need to consider the sign of $\varphi(\delta)$ in the following three cases: (i) $A = 0$, (ii) $A > 0$, and (iii) $A < 0$.

Case (i) $A = 0$. When $z = z_A$, $\varphi(\delta)|_{z=z_A}$ is monotonically decreasing with respect to δ. Since $\varphi(\delta = 1)|_{z=z_A} = 5712.19 > 0$, $t^* > t^{d*}$.

Case (ii) $A > 0$. In this case, $\varphi(\delta)$ is downward convex. Solving $\varphi(\delta) = 0$ for δ, we obtain

$$\delta^+, \delta^- = \frac{(36 + 111z + 152z^2 + 148z^3 + 48z^4) \pm 2\sqrt{3}\sqrt{(2z+1)\Gamma}}{72 + 231z + 154z^2 - 64z^3 - 96z^4}$$

and $\Gamma \equiv 1632z^7 + 4096z^6 + 2558z^5 - 3201z^4 - 7992z^3 - 8235z^2 - 4617z - 972$. From numerical calculation, $\Gamma \leq 0$ for $z \leq \check{z} \simeq 1.37274$, so $\Gamma > 0$ for all $z \geq 3/2$.

δ^+ and δ^- yield

$$\delta^+ - 1 = \frac{2\{(72z^4 + 106z^3 - z^2 - 60z - 18) + \sqrt{3}\sqrt{(2z+1)\Gamma}\}}{A},$$
$$\delta^- - 1 = \frac{2\{(72z^4 + 106z^3 - z^2 - 60z - 18) - \sqrt{3}\sqrt{(2z+1)\Gamma}\}}{A}.$$

$72z^4 + 106z^3 - z^2 - 60z - 18 > 0$ for all $z \geq 3/2$, so $\delta^+ - 1 > 0$. Further,

$$\begin{aligned}&\left(72z^4 + 106z^3 - z^2 - 60z - 18\right)^2 - \left(\sqrt{3}\sqrt{(2z+1)\Gamma}\right)^2 \\ &\qquad = \left(45 + 159z + 172z^2 + 116z^3 + 48z^4\right) A > 0. \qquad \text{(S1)}\end{aligned}$$

Thus, (S1) yields $\delta^- - 1 > 0$, which implies that $t^* > t^{d*}$ for all $3/2 \leq z < z_A$.

Case (iii) $A < 0$. Since its numerator is positive, $\delta^+ < 0$. By contrast, from the numerator of δ^-, we obtain

$$\begin{aligned}&\left(48z^4 + 148z^3 + 152z^2 + 111z + 36\right)^2 - \left(\sqrt{3}\sqrt{(2z+1)\Gamma}\right)^2 \\ &\qquad = \left(384z^4 + 824z^3 + 838z^2 + 627z + 180\right) A < 0.\end{aligned}$$

Hence, $\delta^- > 0$. On the one hand, from (S1), the numerator of $\delta^- - 1$ is negative, and its denominator, A, is also negative; thus, $\delta^- - 1 > 0$. Therefore, $t^* > t^{d*}$ for all $z > z_A$. Q.E.D.

Lemma S2. $\partial \Pi_i^{d*}/\partial z > 0 \ \forall z \equiv \lambda/n \geq 3/2$.

Proof. Differentiating Π_i^{d*} with respect to z, we obtain

$$\frac{\partial \Pi_i^{d*}}{\partial z} = \frac{27(a-c)^2(2z+1)^2}{K^3}\left[\xi(\delta)\right],$$

where $\xi(\delta) \equiv 144z^5 + 1216z^4 + 2138z^3 + 1440z^2 + 378z + 27 - 3(2z+1)(3z^2 + 13z + 6)(28z^2 + 30z + 9)\delta + (552z^5 + 2672z^4 + 4222z^3 + 2961z^2 + 837z + 54)\delta^2$. $\xi(\delta)$ is downward convex. The discriminant of "$\xi(\delta) = 0$" is $(2z+3)^2(-15984z^8 - 258096z^7 - 785156z^6 - 990908z^5 - 561419z^4 - 82110z^3 + 50841z^2 + 21600z + 2268)$ and has a negative value for any $z > 0.332382$, so $\xi(\delta) = 0$ does not have real roots and $\xi(\delta) > 0 \; \forall z \geq 3/2$. This implies $\partial \Pi_i^{d*}/\partial z > 0$. Q.E.D.

2. Welfare analysis

- **Price-taker case**

z and δ have the following effects on the profits of the firms and carriers.

Lemma S3. *I.* $\partial \Pi_i^*/\partial z > 0$ *and* $\partial \Pi_i^*/\partial \delta > 0$. *II. (i)* $\partial \pi_k^*/\partial n < 0$, $\partial \pi_k^*/\partial \lambda < 0$, *and* $\partial\big(\sum_{k=1}^{n} \pi_k^*\big)/\partial z < 0$. *(ii) If* $\delta >$ *(=,<)* $\delta_t \equiv \frac{16\lambda^2+40\lambda n+29n^2}{(4\lambda+5n)(4\lambda+11n)}$, *then* $\partial \pi_k^*/\partial \delta <$ *(=,>)* 0.

Proof. I. From Π_i^*, we obtain $\partial \Pi_i^*/\partial z = [512(a-c)^2(2z+3)^2/E^3][3(47\delta^2 - 56\delta + 25) + 16(7\delta^2 - 4\delta + 5)z^2 + 16(17\delta^2 - 13\delta + 10)z] > 0$ and

$$\begin{aligned}\frac{\partial \Pi_i^*}{\partial \delta} =& \frac{2(a-c)^2(4z+5)}{E^3} \\ &\times \left[\begin{array}{l} 29696z^5{+}221952z^4{+}678272z^3{+}1054112z^2{+}829172z{+}263171 \\ +\,\delta^3(4z{+}5)^2(4z{+}11)^3{-}3\delta^2(4z{+}5)(4z{+}11)^2(48z^2{+}144z{+}113) \\ -\,\delta(4z+7)(4z+11)(832z^3+3024z^2+3756z+1563) \end{array}\right] > 0.\end{aligned}$$

II. (i) From π_k^* and $\sum_{k=1}^{n} \pi_k^* = n\pi_k^*$, we obtain

$$\begin{aligned}\frac{\partial \pi_k^*}{\partial n} &= -\tfrac{256(a-c)^2(2z+3)^2[3(55\delta^2-58\delta+175)+16(7\delta^2-2\delta+15)z^2+8(31\delta^2-28\delta+85)z]}{n^2E^3} < 0, \\ \frac{\partial \pi_k^*}{\partial \lambda} &= -\tfrac{512(a-c)^2(2z+3)^2[3(9\delta^2-22\delta+65)+16(\delta^2-2\delta+5)z^2+16(2\delta^2-7\delta+15)z]}{n^2E^3} < 0. \\ \frac{\partial\left(\sum_{k=1}^{n} \pi_k^*\right)}{\partial z} &= n^2\left(\frac{\partial \pi_k^*}{\partial \lambda}\right) < 0.\end{aligned}$$

(ii) From π_k^*, $\partial \pi_k^*/\partial \delta = \frac{1024(a-c)^2(2z+3)^3}{nE^3}[16z^2 + 40z + 29 - (4z+5)(4z+11)\delta]$, which implies part (ii). Q.E.D.

This result is intuitive. Since a larger n and a smaller λ promote less efficient supply activity, that is, exports, they reduce the firm's profit. In contrast, a higher δ decreases production costs, and thus increases the firm's profit. The carrier's profit depends on the transport price, so $\partial\pi_k^*/\partial n$ and $\partial\pi_k^*/\partial\delta$ correspond to the changes in the transport price. A smaller λ implies an efficiency improvement in transportation, and it thus increases the carrier's profit. A larger n; that is, a fall in z, toughens the competition among carriers and reduces each existing carrier's profit. However, the aggregate number of carriers increases and the total amount of their profits increases.

Subsequently, we examine the effects of a change in the number of carriers on each region's social surplus and that of the entire world. The social surplus in region i ($i = H, F$) is the sum of consumer surplus and the profit of firm i, which is given by

$$SW_i^* = \frac{(a-c)^2}{E^2}\left[\begin{array}{l} 3840z^4 + 22016z^3 + 48160z^2 + 47712z + 18047 \\ +\,2(4z+5)(4z+11)(48z^2+144z+113)\delta - (4z+5)^2(4z+11)^2\delta^2 \end{array}\right]. \tag{S2}$$

World welfare, WW, consists of the two countries' social surplus and the total profits of all carriers, that is, $WW^* \equiv \sum_{i=H,F} SW_i^* + \sum_{k=1}^{n}\pi_k^*$. π_k^* and (S2) yield

$$WW^* = \frac{2(a-c)^2}{E^2}\left[\begin{array}{l} 3840z^4 + 23040z^3 + 52768z^2 + 54624z + 21503 \\ +\,(4z+5)(4z+11)(48z^2+144z+113)\delta - (16z^2+64z+55)^2\delta^2 \end{array}\right]. \tag{S3}$$

From (S2) and (S3), we establish the following proposition.

Proposition S1. *Suppose that all carriers belong to all regions except the two regions, H and F. Then, keener competition in the transport industry and higher transport efficiency (i) always reduce each region's social surplus (i.e., $\partial SW_i^*/\partial z > 0$); (ii) reduce the world's welfare if and only if the R&D spillover rate is sufficiently high; that is, $\partial WW^*/\partial z > 0$ if and only if $\delta > \delta_{ww}$.*

Proof. (i) Differentiating (S2) with respect to z yields $\partial SW_i^*/\partial z = \frac{128(a-c)^2(2z+3)}{E^3}N$, where $N \equiv (1088z^3+4272z^2+5292z+1993)\delta^2 - 2(4z+7)(16z^2+88z+101)\delta + 5(64z^3+112z^2-84z-163)$. $N > 0$ if $z > 1.37301$; Therefore, $\partial SW_i^*/\partial z > 0 \;\; \forall z \geq 3/2$.

(ii) Differentiating (S3) with respect to z yields

$$\frac{\partial WW^*}{\partial z} = \frac{256(a-c)^2(2z+3)}{E^3}\left[\begin{array}{l}(1024z^3+4048z^2+4992z+1831)\delta^2 \\ -2(144z^2+552z+509)\delta - 5(176z^2+528z+397)\end{array}\right].$$

Thus, $\partial WW^*/\partial z \geq 0$ if and only if $\delta \geq \delta_{ww} \equiv \frac{509+552z+144z^2+4\sqrt{(3+2z)^2(27039+70232z+55984z^2+14080z^3)}}{1831+4992z+4048z^2+1024z^3}$. Since δ_{ww} is monotonically decreasing for z, $\lim_{z\to\infty}\delta_{ww} = 0$, and $\delta_{ww}\big|_{z=3/2} = \frac{1661+24\sqrt{305871}}{21883} \simeq 0.682463$, $\delta_{ww} \in \left(0, \frac{1661+24\sqrt{305871}}{21883}\right] \ \forall z \geq 3/2$. Q.E.D.

We first consider part (i). From the definition of social surplus, the symmetric outcomes ($x_i = x_j$, $q_{ii} = q_{jj}$, $q_{ij} = q_{ji}$, and $p_i = p_j$), and $p_i' = -1$, we can decompose the effects of a change in z (e.g., a change in n or λ) on welfare as follows:

$$\begin{aligned}\frac{\partial SW_i}{\partial z} = & \underbrace{[p_i - (c-(1+\delta)x_i)]\frac{\partial q_{ii}}{\partial z}}_{\text{(i) Domestic supply effect } (+)} + \underbrace{[(1+\delta)Q_i - 2x_i]\frac{\partial x_i}{\partial z}}_{\text{(ii) Investment effect } (+)/(-)} \\ & + \underbrace{[p_j - (c-(1+\delta)x_i) - t]\frac{\partial q_{ij}}{\partial z}}_{\text{(iii) Export effect } (-)} + \underbrace{\left(-q_{ij}\frac{\partial t}{\partial z}\right)}_{\text{(iv) Transport price effect } (-)}.\end{aligned} \tag{S4}$$

There are four effects (terms (i)–(iv)) in (S4) (for more detail, see "The four effects in (S4)"). The domestic supply effect, term (i), is positive because a decrease in z (i.e., an increase in n and a decrease in λ) raises the rival firm's exports and strengthens the competition in the domestic market. The investment effect, term (ii), depends on the change in investment $\partial x_i^*/\partial z$ and the effect can therefore be positive when the R&D spillover is low; otherwise, it is negative. Both the export and transport price effects, which correspond to terms (iii) and (iv), respectively, are negative. Since a decrease in z promotes exports, the export effect is negative. A fall in transport prices curtails the inefficiency of cross-hauling; this effect is therefore also negative.

In our model, the domestic supply effect (term (i)) dominates any other effects because the domestic supply production is more efficient than that for export activities. The difference in supply efficiencies makes the domestic supply larger than that of exports, and the domestic supply therefore sharply decreases when the competition in the local market increases due to the promotion of the rival firm's exports. A fall in z; that is, a rise in n, reduces welfare.

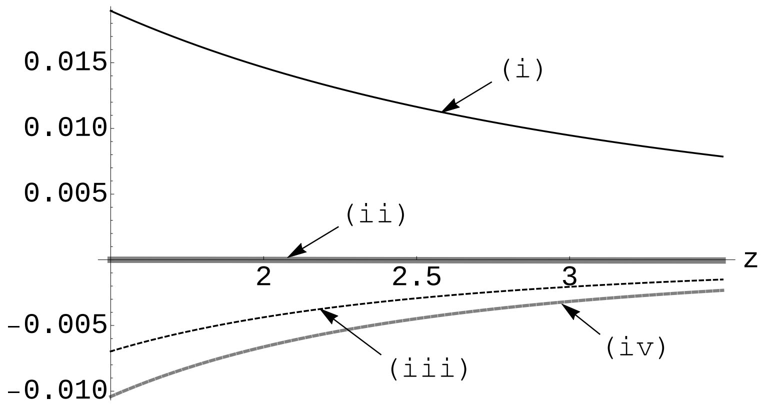


Figure 3: Graph of "(each term)/$(a-c)^2$." ($\delta = 1/4$)

We illustrate this result in Fig. 3. If the spillover rate of R&D is low, then the investment effect can be negative. Thus, all terms can be negative except for (i) if the spillover rate is low. Fig. 3 depicts each term when $\delta = 1/4$. Even in this case, we can immediately see that (i) (the curve (i) in Fig. 3) is extremely large compared to the other terms.

In contrast, world welfare includes the transport sector's profit, which may therefore improve due to competition among carriers. As Lemma S3 shows, the transport sector's profit, $\sum_{k=1}^{n} \pi_k^*$, increases as z decreases. To understand part (ii), it is enough to incorporate this negative effect into the argument of part (i). As we illustrated in the logic behind Proposition 2, a higher (lower) spillover rate strengthens (weakens) the effect of a change in the domestic supply due to a change in z (i.e., $\partial q_{ii}^*/\partial z$). Hence, when the spillover rate is small, the effect of term (i) in (S4) is not sufficiently strong. Then, because the effect of "$\partial(\sum_{k=1}^{n} \pi_k^*)/\partial z$" and other negative effects (terms (iii) and (iv) in (S4)) can be dominant, a fall in z improves the world welfare.

• **Duopsony case**

The social surplus in region i, $SW_i^{d*} = \frac{1}{2}(Q_i^{d*})^2 + \Pi_i^{d*}$, is

$$SW_i^{d*} = \frac{(a-c)^2}{2K^2}\left[\begin{array}{l} 3240z^6+14688z^5+25720z^4+23200z^3+11683z^2+3162z+360 \\ +8(23z^2+25z+6)(9z^3+32z^2+25z+6)\delta - 2(23z^2+25z+6)^2\delta^2 \end{array}\right]. \tag{S5}$$

From (S5), we establish the following proposition.

Proposition S2. *Suppose that all carriers belong to regions other the two regions H and F. Then, keener competition in the transport industry and higher transport efficiency reduce each region's social surplus if and only if the R&D spillover rate is sufficiently high. That is,* $\partial SW_i^{d*}/\partial z > 0$ *if and only if* $\delta > \delta_{sw}^d$.

Proof. Differentiating SW_i^{d*} with respect to z yields

$$\begin{aligned} \frac{\partial SW_i^{d*}}{\partial z} &= \frac{27(a-c)^2(2z+1)}{K^3} \\ &\times \left[\begin{array}{l} \left(1656z^6+8292z^5+15150z^4+13471z^3+5985z^2+1161z+54\right)\delta^2 \\ -\left(840z^6+5492z^5+10586z^4+9687z^3+4833z^2+1323z+162\right)\delta \\ -384z^6-632z^5-776z^4-1498z^3-1638z^2-783z-135 \end{array}\right]. \end{aligned}$$

Solving $\partial SW_i^{d*}/\partial z \geq 0$ for δ, we obtain $\delta \geq \delta_{sw}^d$, where

$$\delta_{sw}^d \equiv \frac{M_2 + (2z+1)(2z+3)\sqrt{M_3}}{2(1656z^6+8292z^5+15150z^4+13471z^3+5985z^2+1161z+54)},$$

$M_2 \equiv 840z^6+5492z^5+10586z^4+9687z^3+4833z^2+1323z+162$, and $M_3 \equiv 203076z^8 + 822036z^7+1677397z^6+2360146z^5+2340511z^4+1501530z^3+560061z^2+103248z+6156$. We find that $\delta_{sw}^d \to \frac{35+\sqrt{5641}}{138} \simeq 0.797874$ as $z \to \infty$, and $\delta_{sw}^d - 1 \leq 0$ for $z \geq \hat{z} \simeq 0.569$. Hence, $\delta_{sw}^d \in (0,1)\ \ \forall z \geq 3/2$. Q.E.D.

The logic behind Proposition S2 is intuitive. A fall in z reduces the transport price and promotes less efficient supply activity (i.e., exports), and it therefore decreases the firms' profits, as is the case for price takers. However, as Proposition 4 shows, the area in which the total output (or consumers surplus) rises due to a decline in z expands, and we can thus find an area in which the social surplus increases due to a decline in z. Different from the price-taker case, in a duopsony, even if the region contains no carrier, an increase in the number of carriers can enhance the social surplus of that region.

• **The four effects in (S4)**

(i) Domestic supply effect (term (i)) is

$$[p_i-(c-(1+\delta)x_i)]\frac{\partial q_{ii}}{\partial z} = \tfrac{128(a-c)^2(2z+3)(4z+5)}{E^3}\left[\begin{array}{l} 125\delta^2-38\delta+125+16(5\delta^2+2\delta+5)z^2 \\ +8(25\delta^2+2\delta+25)z \end{array}\right] > 0.$$

(ii) Investment effect (term (ii)) is

$$[(1+\delta)Q_i-2x_i]\frac{\partial x_i}{\partial z} = \tfrac{256(a-c)^2(2z+3)[\delta(8z+7)-5]}{E^3}[139\delta-29+16(3\delta-1)z^2+8(21\delta-5)z] \gtreqless 0.$$

(iii) Export effect (term (iii)) is

$$[p_j-(c-(1+\delta)x_i)-t]\frac{\partial q_{ij}}{\partial z} = -\tfrac{512(a-c)^2(2z+3)}{E^3}\left[\begin{array}{l} 41\delta^2-62\delta+185+16(\delta^2-2\delta+5)z^2 \\ +48(\delta^2-2\delta+5)z \end{array}\right] < 0.$$

(iv) Transport price effect (term (iv)) is

$$-q_{ij}\frac{\partial t}{\partial z} = -\tfrac{256(a-c)^2(2z+3)}{E^3}\left[\begin{array}{l} 9(23\delta^2-18\delta+55)+16(7\delta^2-2\delta+15)z^2 \\ +8(37\delta^2-22\delta+85)z \end{array}\right] < 0.$$