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Endogenous transport price, R&D spillovers, and trade

Kazuhiro Takauchi and Tomomichi Mizuno

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 the 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 because of 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 the 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

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).

Many researchers have examined the relation between trade barriers and innovation activities. 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 because of a reduction in trade barriers (Scherer & Huh, 1992; Funk, 2003). There are also substantial differences among theoretical papers. In particular, such differences are remarkable among studies that employ an 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 al., 2018;

[1] Trade barriers also affect determinants of competition, such as market size and intensity of export market competition. Innovation incentives depend on these determinants 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 nontariff barriers is 7%.

Takauchi & Mizuno, 2020), 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 a firm's R&D investment, while in other cases it may inhibit it.

In this paper, we propose a model in which a reduction in transport cost causes both a rise and fall in a 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 interregional 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] Interregional transportation is a homogeneous 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 larger number of carriers lowers the transport price, so exports and imports rise but domestic supply falls.

[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.

Whether R&D investment increases or decreases depends on the rise and fall of the exporting firm's sales. On the one hand, a higher R&D spillover rate makes exporting firms' production costs fall and production activities easier. The expanded production raises transport demand, so carriers raise their prices as the spillover rate rises. Hence, when the spillover rate is low (high), the transport price is low (high). If the transport price is low, the trade barrier is low and the exporting firm is able to export with ease. Thus, when the number of carriers increases in the case where the spillover rate is low, because the increase in exports exceeds the reduction in domestic supply, the exporting firm's sales quantity can increase. This strengthens the R&D motive. In contrast, when the transport price is sufficiently high, the trade volume is small, and hence, each exporting firm is closer to a monopoly in its local market. Then, if the transport price falls, competition in the domestic market intensifies because of an increase in imports, so that domestic supply decreases sharply. That is, even if exports increase as a result of a reduction in the transport price, because the firm's domestic supply falls more than its increased exports, a rise in the number of carriers discourages R&D.

We also show that a larger 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

[4]We place the analysis of total surplus in the Supplementary Material section 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 total surplus.

decreases, aggregate output falls because the decline in the domestic supply exceeds the increase in the foreign rival's exports. In general, an increase in the number of firms promotes market competition, so it lowers prices and enhances consumer welfare. In contrast to this standard view, our result indicates that an increase in the number of carriers, and hence increasing competition in the transport industry, can reduce consumer surplus.[5] We believe that our analysis provides a new insight into R&D in the context of trade and competition.

To avoid criticism of the assumption 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, because 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.

A notable difference between this paper and the existing literature is that the transport price is endogenously determined by price competition among carriers. The existing trade studies that focus on the transport sector assume monopoly or quantity competition in the interregional transportation market (Asturias, 2020; Behrens et al., 2009; Behrens & Picard, 2011; Francois & Wooton, 2001; Ishikawa & Tarui, 2018;

[5]Dinda and Mukherjee (2014) show that when the government offers the optimal uniform subsidy/tax, a higher number of inefficient firms harms consumers, although in a different context.

Takauchi, 2015; Takauchi & Mizuno, 2019).[6] 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 a firm's agglomeration. While Behrens et al. (2009) focus on a carrier's market power, Behrens and Picard (2011) focus on the logistics problem associated with round trips. 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 noninnovative exporting firms. Contrary to these studies, Takauchi (2015) and Takauchi and Mizuno (2019) consider process innovation (i.e., cost-reducing R&D) of exporting firms under two-way trade.[7] Takauchi (2015) examines the effect of the cost efficiency of R&D on exporting firms' profits. Takauchi and Mizuno (2019) consider a hold-up problem resulting from carriers raising prices after observing an exporting firm's investment.

This paper is also related to the literature that focuses on the nexus of trade barriers and innovation (Ghosh & Lim, 2013; Haaland & Kind, 2008; Hwang et al., 2018; Long et al., 2011; Takauchi & Mizuno, 2020). Ghosh and Lim (2013), Haaland and Kind (2008), and Long et al. (2011) consider the effects of trade liberalization on firms'

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

[7]In their setting, exporting firms pay a freight charge to ship their products to their rival's domestic market, but freely supply to their local market. This market structure is similar to ours.

process innovation. By contrast, Hwang et al. (2018) and Takauchi and Mizuno (2020) consider firms' product innovation (i.e., R&D that promotes product differentiation). These studies report different results on the relationship between trade barriers and innovation incentives, but they all assume exogenous trade barriers.

This paper is organized as follows. Section 2 presents the baseline model and Section 3 derives the main results. In Section 4, we offer three extensions of our model: we first (i) extend the baseline model to the case in which exporting firms have monopsony power with respect to the transport service; second (ii), we endogenize the R&D spillover rate, which is an exogenous variable in the baseline model; finally (iii), we consider the case of differentiated products. 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 markets are 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 $a > 0$. 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 $c_i \equiv c - x_i - \delta x_j$;[8] that is, although firm i invests x_i to reduce the unit cost c, there is a knowledge spillover and firm i enjoys some part of its rival's developed knowledge, δx_j, without payment. $\delta \in [0, 1]$ 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, interregional 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 aggregate demand be $q_{HF} + q_{FH}$. Each firm employs the carrier 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,

[8] We can interpret c as including the initial investment level. When each firm invests x_0 before starting the game, we denote $c = c_0 - x_0 - \delta x_0$, where c_0 is the unit cost without any investment.

$(\lambda/2)q_k^2$, where $\lambda > 0$ denotes the transport efficiency.[9] 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 the 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, because firms can frequently adjust their outputs, the production decision occurs in the last stage. The Nash equilibrium is not unique in the second stage. Therefore, we employ the subgame perfect Nash equilibrium (SPNE) with payoff-dominance refinement as the equilibrium concept.[10] 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 $0 = a - c - q_{jj} - 2q_{ij} + x_i + \delta x_j - t$

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

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

$(i \neq j)$. 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 convex costs engage in homogeneous price competition, the Nash equilibrium is not unique. In our model, the pure strategy Nash equilibria of the 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

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

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 (i.e., the interval $[\underline{t}, \bar{t}]$), we employ the *payoff-dominance criterion*. For example, let t'_k and t''_k be two different equilibrium transport prices. If the profit of carrier k in t'_k is strictly larger than that in t''_k, then we say that t'_k *payoff-dominates* t''_k (Harsanyi & Selten, 1988, p. 81). In our model, the payoff-dominance criterion requires that each carrier $k \in \{1, \ldots, n\}$ chooses its profit-maximizing transport prices among the equilibria. As the carriers are symmetric, the transport price is

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

The "t_P" that satisfies the payoff-dominance criterion maximizes the joint profit of the carriers, so it is also known as the *collusive price* that maximizes the industry profit.[11] This price-setting by carriers is partially consistent with the actual characteristics of the transport industry. For example, some studies report that ocean shipping is an oligopoly market, and there is collusion (e.g., Hummels et al., 2009; Sjostrom, 2004; Sys, 2009; Sys et al., 2011). Among them, Sys (2009) empirically shows that the containerized shipping industry is tacitly collusive. Hence, the payoff-dominance criterion is partially consistent with the empirical evidence, and therefore, we use this criterion to capture a collusive aspect of the transport industry.

The prices $\underline{t}$, $\bar{t}$, and t_P, 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 $t_P < \bar{t}$;[12] that is, $t = t_P$, we require Assumption 1.

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

[11] To narrow the set of Nash equilibria, this collusive price criterion (or refinement) is often employed. For example, see Dastidar (2001), Gori et al. (2014), and Mizuno and Takauchi (2020).

[12] As long as the interior maximizer of each carrier's profit belongs to the Nash equilibria, i.e., $t_P < \bar{t}$, the collusive price criterion is identical to the payoff-dominance criterion. However, if the interior maximizer is strictly larger than the upper bound $\bar{t}$, we have no rationale of the use of the collusive price criterion.

We next define z to facilitate the analysis.

Definition 1. $z \equiv \lambda/n \in [3/2, \infty)$.[13]

In the first stage, each firm decides its R&D investment level, x_i. Substituting the outcomes of the second and third stages into the profit of firm i, we have

$$\Pi_i(\mathrm{x}) = \frac{[(a-c) + t_P + (2-\delta)x_i + (2\delta - 1)x_j]^2}{9} + \frac{[(a-c) - 2t_P + (2-\delta)x_i + (2\delta - 1)x_j]^2}{9} - x_i^2 \quad \text{for} \quad i \neq j.$$

Note that t_P is the second-stage transport price, which depends on $\mathrm{x} = (x_i, x_j)$ and it rises as the investment level increases. The first term on the right-hand side of $\Pi_i(\mathrm{x})$ is the profit of domestic supply and the second term is the profit of exports. The transport price, t_P, is the barrier to exports and imports, so a rise in the transport price can increase the first term and decrease the second term.

Solving the FOC for the profit maximization of firm i, $\partial \Pi_i(\mathrm{x})/\partial x_i = 0$,[14] and using the equilibrium level of R&D investment, x_i^*, we obtain the following.

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

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

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

[13] Although we need $z > (3/2)(1/(n-1))$ from Assumption 1 because the maximum of $1/(n-1)$ is 1, $\lambda > \lambda_0$ holds for all $z \geq 3/2$.

[14] The FOC is reported in Appendix C.

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.

Proposition 1. *(i) Stronger competition in the transport industry (i.e., a rise in n) and higher transport efficiency (i.e., a fall in λ) decrease transport prices and domestic supply but increase exports. (ii) Stronger competition in the transport industry and higher transport efficiency increase 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, that is, a decrease in z ($z \equiv \lambda/n$), have a similar effect. A higher n lowers transport prices by intensifying competition among carriers, which increases exports. A smaller λ flattens the slope of the carriers' cost curve, which induces a lower transport price, and thereby increases exports. Because a lower z increases imports and makes competition in the local market stronger, firm i's domestic supply falls.

Second, we examine the logic behind Lemma 2. A higher δ lowers exporting firms' production costs, facilitates production activities, and thus, increases outputs. That is, in our model, δ has exactly the same effect on both domestic supply and exports. As a higher δ leads to an increase 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, then both outputs and transport prices increase (decrease) as δ increases (decreases). However, an increase in transport prices raises trade barriers, which impedes exports. If δ rises when its level is low enough, then 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.[15]

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

[15] Additionally, $\partial x_i^*/\partial\delta$ can explain why the transport prices and the firm's outputs experience 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 $dq_{ij}/d\delta = \frac{n}{2(3n+2\lambda)}\left[x_i + (1+\delta)\frac{dx_i}{d\delta}\right]$.

(positive effect). If δ increases, because each firm enjoys its rival's 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 increases in 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 because the inflow of the rival firm's developed knowledge becomes large.

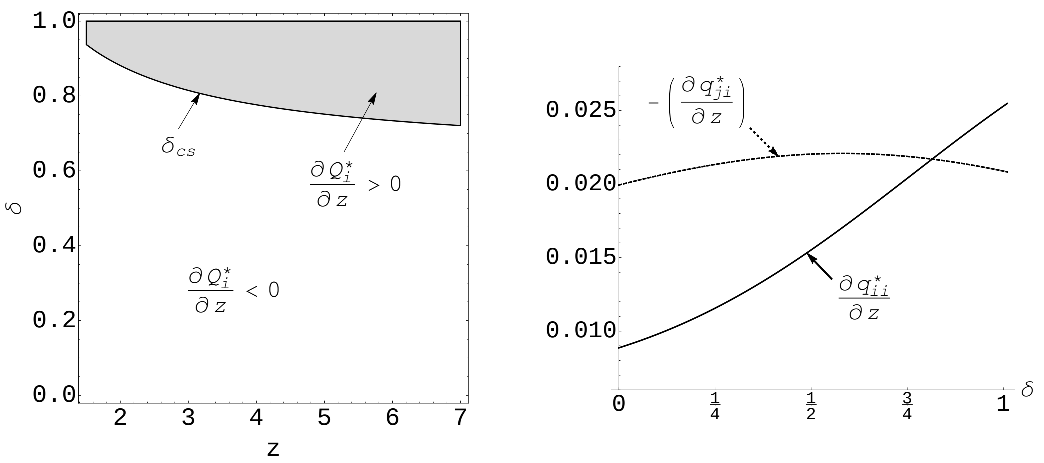
Finally, we consider part (ii) of Proposition 1. The R&D incentive depends on the sales quantity of the product. That is, if the sum of exports and domestic supply increases, firm i's incentive to undertake R&D strengthens. This, of course, raises R&D investments. As shown in Lemma 2, when δ is large, the transport price tends to be high. When the trade barrier is sufficiently high, then because firm i enjoys a situation close to a monopoly in its local market, the production of its domestic supply is considerably larger compared with its export production. Then, suppose that

z decreases and the transport price becomes lower. The high trade barrier falls, and imports (i.e., exports of firm i's rival) increase. This increases competition in firm i's local market and decreases firm i's relatively large quantity of domestic supply, so the reduction effect of domestic supply is strong. By contrast, the increase in exports is not large. This is because the level of the trade barrier is high and exports levels are small, so the increase in exports is small. Because the "reduction effect of domestic supply" can dominate the "increase effect of exports", a lower z discourages R&D. Oppositely, when δ is sufficiently small, because the "increase effect of exports" can dominate the "reduction effect of domestic supply", R&D incentives grow as z decreases.

Proposition 1 contributes to two strands of the literature. The first consists of studies on trade barriers and innovation. Proposition 1 clarifies a condition in which a transport price reduction because of a rise in the number of carriers impedes innovation in product markets. This result could be meaningful for practitioners who aim to promote further industrial development. The second strand consists of studies on competition and innovation. The effects of market competition and concentration on innovation has been actively debated (see, for example, Aghion et al., 2005; Dasgupta & Stiglitz, 1980; Ishida et al., 2011; Marshall & Parra, 2019; Vives, 2008). Although our model is limited to intra-industry trade of a homogeneous good, we examine the effects of competition in cross-border transportation services on the innovation of manufacturers. Hence, it can be claimed that we extend previous studies to examine the effects of competition among nonproducers on the innovation of producers, and therefore, complement the existing literature.

Do 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.[16] To examine this, we use (2) and obtain the following proposition.

Proposition 2. *Stronger competition in the transport industry and higher transport efficiency reduce 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).*



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

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

Note: (a) $\text{sign}\{\partial Q_i^*/\partial z\} = \text{sign}\{\partial CS_i^*/\partial z\}$. (b) As $\partial q_{ji}^*/\partial z$ has a negative value, we multiply it by -1.

Figure 1: Illustration of Proposition 2.

Proposition 2 is explained as follows. As shown in Proposition 1, a larger number of carriers makes competition in the transportation market stronger, and thus lowers the

[16]The relationship between total output Q_i and consumer surplus CS_i is positive and monotonic (i.e., $CS_i = (Q_i)^2/2$ and $Q_i > 0$), so it is sufficient to consider the change in Q_i for z.

transport price. Now, suppose that the R&D spillover parameter, δ, is large enough. When δ increases, because exporting firms' production costs fall and final goods production becomes active, the aggregate demand for transport services increases. When the aggregate demand for transportation is large, because carriers are symmetric, their individual demands are also large. That is, each carrier's individual demand expands as the aggregate demand for transportation becomes large. Hence, if δ is large, each carrier's individual demand is also large.

Then, let us consider the effect of an increase in the number of carriers (i.e., z decreases). When the size of aggregate demand is large, the effects of a new entry are strong. Although this undoubtedly increases the aggregate demand, it strengthens competition, the effects of which are stronger in the transport market. Hence, if an entry occurs, given the stronger competitive effects, each carrier loses a large size of its individual demand. That is, because carriers lose a large amount of their individual demands when δ is large, carriers have an incentive to lower their prices. The incentive to lower price becomes stronger as δ increases. Hence, if δ rises, the effect of a transport price reduction because of an increase in the number of carriers, $\partial t^*/\partial z$, intensifies.[17] The transport price is a barrier to imports, so the decrease in the domestic supply is large if the reduction effect of the transport price is large. Therefore, because the decrease in domestic supply exceeds the increase in imports, a rise in the number of carriers reduces total output (consumer surplus). Fig. 1 depicts this result.

We illustrate $\partial q_{ii}^*/\partial z$ and $-(\partial q_{ji}^*/\partial z)$ as functions of δ in panel (b) of Fig. 1. As

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

δ increases above a certain level, the "$\partial q^*_{ii}/\partial z$" curve exceeds the "$-(\partial q^*_{ji}/\partial z)$" curve. Hence, if δ is sufficiently high, $\partial Q^*_i/\partial z$ has a positive value.

Proposition 2 has an important policy implication. For example, today, the US competition authority adopts a *consumer welfare standard*. Under this standard, while practices that worsen consumer welfare are prohibited, those that enhance consumer welfare are permitted. (Viscusi et al., 2018, pp. 96–97.) In general, an increase in the number of firms lowers product price through promoting market competition. This is also the case in vertically related markets. When the upstream price (here, the transport price) decreases because of a rise in the number of upstream firms (here, the carriers), because the production costs of downstream firms fall and their outputs increase, the product price falls. Hence, consumer surplus increases. If the competition authority believes this conventional wisdom, it begins to appreciate that the promotion of competition in transport industries can similarly raise consumer surplus, and then has an incentive to implement policy that increases the number of carriers by relaxing the entry regulation into transport industries. By contrast, Proposition 2 asserts the possibility that consumer surplus decreases as the number of carriers increases. Our results identify a problematic issue with competition (antitrust) policy in a two-way trade situation, so it provides a new insight into trade and competition.

Although Proposition 2 may be counterintuitive, it is partially consistent with empirical evidence. This is because some empirical studies report an enhancement of competition through a market-entry raised price (e.g., Caves et al., 1991; Grabowski & Vernon, 1992; Thomadsen, 2007). Therefore, we believe that our result not only makes a theoretical contribution but is also supported empirically.

4 Extensions

This section presents three extensions of the baseline model: (i) duopsony in the transport market; (ii) endogenous spillover rate of R&D; and (iii) differentiated products.

(i) Duopsony in the transport market

In Section 3, we assumed that firms are price takers in relation to the transport services; 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."[18] 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 the transport supply, we consider the following timing of the game.

- *First stage:* 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

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

its freight traffic, q_k. Then, the shape of the inverse transport-supply function, $t = T(q_{HF} + q_{FH})$, 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) influence the inverse transport supply. Hence, in the duopsony case, the equilibrium transport price, t^{d*}, is lower compared with the case in which they are price takers, that is, $t^* > t^{d*}$.[19]

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

Proposition 3. *Suppose that exporting firms have monopsony power in the transportation market. Then, (i) stronger competition in the transport industry and higher transport efficiency decrease transport prices but increase exports. (a) If* $z < \tilde{z} \simeq 1.56576$ *or [*$\delta > \delta_{ds}^d$ *and* $z > \tilde{z}$*], then stronger competition in the transport industry and higher transport efficiency decrease domestic supply. (b) If* $\delta < \delta_{ds}^d$ *and* $z > \tilde{z}$*, then stronger*

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

competition in the transport industry and higher transport efficiency increase domestic supply (we define the threshold δ^d_{ds} in Appendix B).

(ii) Stronger competition in the transport industry and higher transport efficiency increase 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, because carriers decide their prices, if they raise their prices, they then inhibit the foreign firm's exports because this increases the trade barrier. Hence, competition in the domestic market weakens. 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 are equal. However, when δ becomes large, because the transport demand increases as a result of the expanding outputs through a reduction in production costs, the transport price increases, as in the price-taker case. If the transport price is high, then the effect of its change is also strong.[20] Then, the foreign rival's exports increase sharply because of a fall in z, so the domestic supply decreases.

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

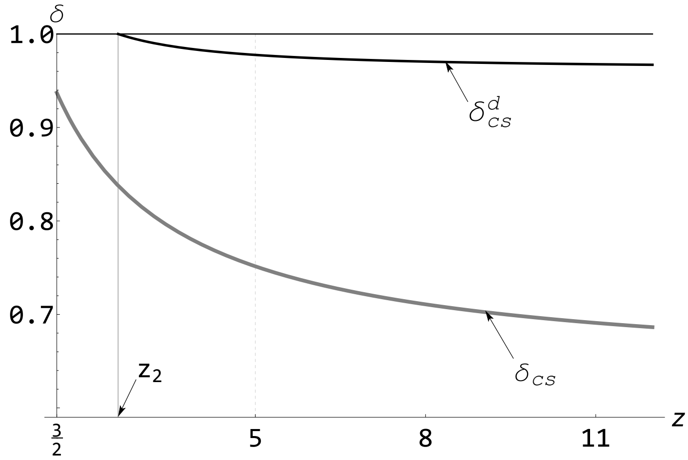
From (A3) in Appendix A, we establish the following proposition.

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

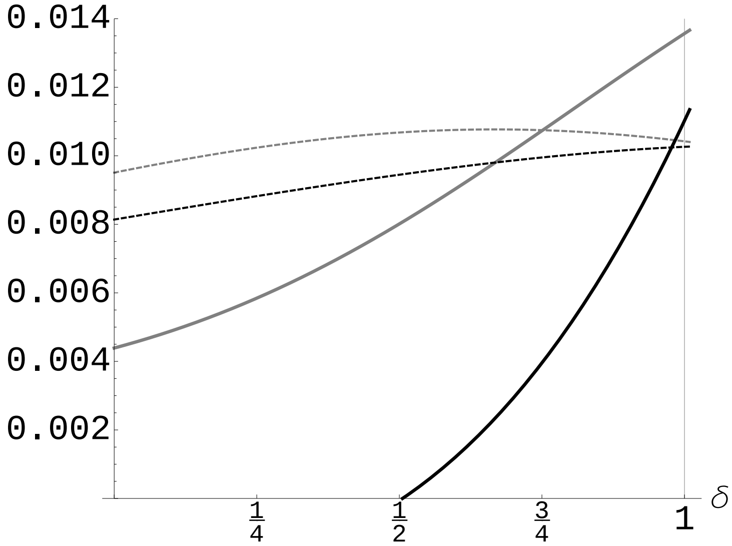
Proposition 4. *Suppose that exporting firms have monopsony power in the transportation market. (i) If $z < z_2 \simeq 2.58114$ or [$\delta < \delta^d_{cs}$ and $z > z_2$], then stronger competition in the transport industry and higher transport efficiency increase consumer surplus. (ii) If $\delta > \delta^d_{cs}$ and $z > z_2$, then stronger competition in the transport industry and higher transport efficiency reduce consumer surplus (we define the threshold $\delta^d_{cs} > 0$ in Appendix B).*

A rise in the spillover rate, δ, increases the size of the change in the transport price because of a change in z (i.e., the "$\partial t/\partial z$" effect), and also strengthens the degree of change in the domestic supply because of 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.[21] As mentioned 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 case, 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.

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



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.

(ii) Endogenous spillover rate of R&D

Here, we introduce a spillover function of investment levels and relax the assumption of an exogenous spillover rate. Then, we show that equilibrium spillover rates are symmetric between two firms.

We assume that firm i's spillover rate is $s(x_i, x_j)$, where $i, j = H, F$ and $i \neq j$.[22] We assume $s(x_i, x_j)$ such that for any (x_i, x_j), Π_i is a concave function in the investment stage. The unit cost of firm i is $c_i \equiv c - x_i - s(x_i, x_j)x_j$. The other settings are the same as in the previous section.

In the third stage, the FOCs for firm i lead to each firm's outputs: $q^s_{ii}(t, \mathrm{x})$ and $q^s_{ij}(t, \mathrm{x})$. In the second stage, substituting the outputs into the carriers' profit functions and using the payoff-dominance criterion, we obtain the transport price.

$$t^s_P \equiv \frac{(3n + 4\lambda)[2(a - c) + x_H + x_F + s(x_F, x_H)x_H + s(x_H, x_F)x_F]}{8(3n + 2\lambda)}.$$

In the first stage, substituting $q^s_{ii}(t, \mathrm{x})$, $q^s_{ij}(t, \mathrm{x})$, and t^s_P into Π_i, we obtain each firm's profit $\Pi^s_i(x_i, x_j)$. From the first derivative of $\Pi^s_i(x_i, x_j)$ with respect to x_i, for any x' and x'', we obtain the following equation.

$$\frac{\partial \Pi^s_i(x', x'')}{\partial x_i} = \frac{\partial \Pi^s_j(x', x'')}{\partial x_j}.$$

From this result, the FOCs are symmetric. As we assume the concavity of Π_i, there exists a symmetric equilibrium: $x^s_i = x^s_j$. Therefore, the equilibrium spillover rates are also symmetric.

[22] We allow that $s(x_i, x_j) \neq s(x_j, x_i)$ if $x_i \neq x_j$.

(iii) Differentiated products

To check the robustness of our results, we relax the assumption of consumer surplus. Here, we consider that each firm's or country's goods are differentiated. Because we use a Singh and Vives (1984)-type utility function, consumer surplus in region i is as follows:

$$CS_i^D = a(q_{ii} + q_{ji}) - \frac{q_{ii}^2 + q_{ji}^2}{2} - \gamma q_{ii} q_{ji} - p_{ii} q_{ii} - p_{ji} q_{ji}, \quad i, j = H, F; \; i \neq j,$$

where p_{ii} (p_{ji}) is firm i's (j's) product price in region i. The parameter $\gamma \in [0, 1]$ denotes the degree of product substitutability between H and F. If $\gamma = 1$ ($\gamma = 0$), the products are homogeneous (independent). Then, the profit of firm i is $\Pi_i = (p_{ii} - c_i)q_{ii} + (p_{ij} - c_i - t)q_{ij} - x_i^2$. The other settings are the same as in the previous section.

In the third stage, the FOCs for firm i yield $q_{ii}^D(t, \mathrm{x})$ and $q_{ij}^D(t, \mathrm{x})$. In the second stage, substituting the outputs into the carriers' profit functions and using the payoff-dominance criterion, we obtain the transport price.

$$t_P^D \equiv \frac{(2-\gamma)[n(4-\gamma^2) + 4\lambda][2(a-c) + (x_i + x_j)(1+\delta)]}{8[n(4-\gamma^2) + 2\lambda]}.$$

In the first stage, substituting $q_{ii}^D(t, \mathrm{x})$, $q_{ij}^D(t, \mathrm{x})$, and t_P^D into Π_i, we obtain each firm's profit $\Pi_i^D(\mathrm{x})$. Solving the FOCs, we obtain the following investment level.

$$x_i^{D*} = \frac{(a-c)\left[\begin{array}{l} 16z^2(4-\gamma\delta-\gamma) - 8z(2-\gamma)(\gamma^2\delta+\gamma^2+5\gamma\delta-\gamma+2\delta-18) \\ -(2-\gamma)^2(\gamma^3\delta+\gamma^3+10\gamma^2\delta+2\gamma^2+36\gamma\delta-28\gamma+8\delta-88) \end{array}\right]}{(\gamma-2)^2 E^D},$$

where $E^D \equiv 16z^2(\gamma\delta^2 + 2\gamma\delta - 7\gamma - 4\delta + 12) - 8z(\gamma-2)(\gamma^2\delta^2 + 2\gamma^2\delta - 15\gamma^2 + 5\gamma\delta^2 + 4\gamma\delta - \gamma + 2\delta^2 - 16\delta + 46) + (\gamma^3\delta^2 + 2\gamma^3\delta - 31\gamma^3 + 10\gamma^2\delta^2 + 12\gamma^2\delta - 62\gamma^2 + 36\gamma\delta^2 +$

$8\gamma\delta + 100\gamma + 8\delta^2 - 80\delta + 168) > 0$. Using x_i^{D*}, t_P^D, $q_{ii}^D(t, \mathrm{x})$, and $q_{ij}^D(t, \mathrm{x})$, we obtain equilibrium outcomes as follows.

$$t_P^{D*} = \frac{8(2-\gamma)^2(a-c)(\gamma^2 - 4z - 4)(\gamma^2 - 2z - 4)}{E^D},$$
$$q_{ii}^{D*} = \frac{8(2-\gamma)(a-c)[(\gamma-2)^2(\gamma^2 + 6\gamma + 8) + 8z^2 + (-6\gamma^2 - 4\gamma + 32)z]}{E^D},$$
$$q_{ij}^{D*} = \frac{16(2-\gamma)^2(a-c)(4 + 2z - \gamma^2)}{E^D}.$$

First, we discuss the result of Proposition 1 under differentiated products. From the first derivative of the equilibrium outcomes with respect to z, we obtain Remark 1.

Remark 1. *We assume a linear inverse demand function with differentiated products. (i) Stronger competition in the transport industry and higher transport efficiency decrease transport prices, which increases exports. (ii) Stronger competition in the transport industry and higher transport efficiency tend to decrease domestic supply if both products are not so differentiated. (iii) Stronger competition in the transport industry and higher transport efficiency increase the firm's investment if and only if* $\delta < [4z(1-\gamma) + (2-\gamma)^2(4+\gamma)]/[4z(1+\gamma) + \gamma(12 - 4\gamma - \gamma^2)]$.

As part (i) and part (iii) are the same as Proposition 1, the intuition is also the same. Therefore, these results are robust to product differentiation. In addition, part (ii) is different from Proposition 1; that is, the sign of $\partial q_{ii}^{D*}/\partial z$ is negative if γ is high. The intuition behind this result is as follows. The crowding-out effect of stronger competition in the transport industry on domestic supplies is small if products are highly differentiated. Hence, the stronger competition among carriers stimulates firms' investments, which yields large domestic outputs.

Next, we discuss the effects of product differentiation on Proposition 2. From the first derivative of Q_i^{D*} $(= q_{ii}^{D*} + q_{ji}^{D*})$ with respect to z, we obtain Remark 2.

Remark 2. *Stronger competition in the transport industry and higher transport efficiency tend to reduce consumer surplus if both products are not so differentiated or the spillover rate is high.*

This result is qualitatively the same as Proposition 2. Hence, we confirm that Proposition 2 is robust to product differentiation.

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 two-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 the 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 the 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 a rise in the number of carriers, and we therefore believe that our analysis provides a new insight into studies of trade and competition.

Moreover, our main result could be empirically testable. In our analysis, by defining "$z \equiv \lambda/n$", we used comparative statics of z. Thus, if λ is fixed at some appropriate value, it will be possible to estimate the relationship between the number of carriers n and the total output Q_i ($= q_{ii} + q_{ji}$ and $i \neq j$). In this way, we can test the result offered by Proposition 2. For example, a higher number of carriers reduces the total output, i.e., the consumer surplus, if the R&D spillover is large enough. According to the empirical analysis by Xu and Wang (1999), the spillover is relatively large in capital goods trade. Hence, by considering two-way trade of capital goods, it may be possible to observe the effects of a change in n on consumer surplus.

In this paper, we do not consider the possibility of improved production efficiency because of 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. 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 in order to equalize transport supply with its demand. However, the transport demand and total exports of two firms are 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 "$\prime$" 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. Substituting $t = (q_{HF} + q_{FH})\lambda/n$ 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 SPNE 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) Simple algebra yields $t_P - \underline{t} = \frac{3n[2(a-c)+(x_H+x_F)(1+\delta)]}{8(3n+2\lambda)} > 0$.

(ii) As $\bar{t} - t_P = \frac{3n[2(a-c)+(x_H+x_F)(1+\delta)][2\lambda(n-1)-3n]}{8(3n+2\lambda)[(3+2\lambda)n+2\lambda]}$, $t_P \leq \bar{t}$ 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, $\lim_{z\to\infty}\delta_x = \left(3-2\sqrt{2}\right) \simeq 0.171573$, 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

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

(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. As $CS_i^* = (Q_i^*)^2/2$, $\text{sign}\{\partial CS_i^*/\partial z\} = \text{sign}\{\partial Q_i^*/\partial z\}$. 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 $L_3 \equiv 1228z^6+1564z^5-1429z^4-4020z^3-2970z^2-864z-81$. As $L_3>0$ for $z>1.56433$, in this range, we find that

$$\left(\sqrt{3}\sqrt{(2z+1)^2L_3}\right)^2 - \left[(2z+3)^2(z^2-2z-1)\right]^2$$
$$= 4(3680z^8+8368z^7+1360z^6-15076z^5-22054z^4-14784z^3-5373z^2-1026z-81)$$
$$\geq 0 \quad \text{for} \quad z \geq \tilde{z} \simeq 1.56576.$$

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

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

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.

C. The exporting firm's FOC in the first stage of the game

From the profit of firm i in the first stage of the game, $\Pi_i(\mathrm{x})$, the FOC for profit maximization is

$$\begin{aligned} &\frac{\partial \Pi_i(\mathrm{x})}{\partial x_i} = 0 \\ &\Leftrightarrow -\frac{\left(\begin{array}{l} 2(a-c)\left[16(\delta-3)z^2+16(4\delta-9)z+55\delta-113\right] \\ +\left[(7+4z)(13+12z)+2(7+4z)(37+28z)\delta-(149+216z+80z^2)\delta^2\right]x_i \\ +\left[(7+4z)(37+28z)(\delta^2+1)-2(317+424z+144z^2)\delta\right]x_j \end{array}\right)}{32(2z+3)^2} = 0, \end{aligned}$$

where $i, j = H, F$ and $i \neq j$.

By solving the above FOCs with respect to each firm's investment level, we obtain the equilibrium level of R&D investment, x_i^*. (See (1).)

D. Calculating Remarks 1 and 2

Calculation of Remark 1: We start with the first part of Remark 1. The first derivative of t_P^{D*} with respect to z is

$$\frac{\partial t_P^{D*}}{\partial z}=\frac{16(a-c)(2-\gamma)^2}{(E^D)^2}$$
$$\times\left[\begin{array}{l} z^2[-16\gamma^2(\delta^2+2\delta+9)+64\gamma(\delta+1)^2+64(\delta^2-2\delta+5)] \\ +8z(\gamma-2)[\gamma^3(\delta^2+2\delta+17)-2\gamma^2(\delta^2+2\delta-15)-4\gamma(7\delta^2+6\delta+15)-8(\delta-3)^2] \\ -(\gamma-2)^2(\gamma+2)\{\gamma^3(\delta^2+2\delta+33)-2\gamma^2(\delta^2+2\delta-31) \\ \qquad\qquad\qquad\qquad -4\gamma(15\delta^2+14\delta+31)-8(\delta^2-14\delta+17)\} \end{array}\right].$$

The sign of $\partial t_P^{D*}/\partial z$ is the same as that of the expression in the large square brackets. The expression is a quadratic function of z and the coefficient of z^2 is positive. In addition, the discriminant of the quadratic function takes a negative value as follows.

$$-512(\gamma-2)^2(\gamma^3-2\gamma^2+4\gamma-8)(\delta+1)^2[\gamma^3+2\gamma^2-2\gamma(\delta^2+\delta+2)-4(1-\delta)]<0.$$

Hence, we find $\partial t_P^{D*}/\partial z>0$.

Next, we consider the sign of $\partial q_{ij}^{D*}/\partial z$. Differentiating q_{ij}^{D*} with respect to z leads to the following equation.

$$\frac{\partial q_{ij}^{D*}}{\partial z}=\frac{32(a-c)(2-\gamma)^2}{(E^D)^2}\left[\begin{array}{l} z^2[64(\delta-3)-16\gamma(\delta^2+2\delta-7)] \\ +16z(\gamma^2-4)[\gamma(\delta^2+2\delta-7)-4(\delta-3)] \\ -(\gamma-2)^2\{\gamma^3(3\delta^2+6\delta-29)+2\gamma^2(9\delta^2+10\delta-31) \\ \qquad\qquad +4\gamma(3\delta^2-10\delta+19)+8(\delta^2-6\delta+25)\} \end{array}\right].$$

The sign of $\partial q_{ij}^{D*}/\partial z$ is the same as that of the expression in the large square brackets. The expression is a quadratic function of z and the coefficient of z^2 is negative. We denote the discriminant of the quadratic function by Φ_1: $\Phi_1 \equiv -64(2-\gamma)^3(1+\delta)^2[4(3-\delta)-\gamma(7-2\delta-\delta^2)]$. Hence, $\Phi_1 < 0$ if $\gamma < 4(3-\delta)/(7-2\delta-\delta^2)$. As $4(3-\delta)/(7-2\delta-\delta^2) > 1$ and $0 \leq \gamma \leq 1$, we find $\Phi_1 < 0$, which means the discriminant is negative. Therefore, we obtain $\partial q_{ij}^{D*}/\partial z < 0$.

We consider the second part of the remark. The first derivative of $\partial q_{ii}^{D*}/\partial z$ is

$$\frac{\partial q_{ii}^{D*}}{\partial z} = \frac{16(a-c)(2-\gamma)^2}{(E^D)^2} \left[\begin{array}{l} -16z^2[\gamma^2(\delta^2+2\delta+9) - 2\gamma(\delta^2+2\delta+9) - 4\delta^2 + 4] \\ +8z(\gamma-2)z\{\gamma^3(\delta^2+2\delta+17) + 2\gamma^2(\delta+1)^2 \\ \qquad\qquad -4\gamma(5\delta^2+6\delta+17) - 8(\delta^2-2\delta-3)\} \\ -(\gamma-2)^2\{\gamma^4(\delta^2+2\delta+33) + 2\gamma^3(3\delta^2+6\delta+35) \\ \;-4\gamma^2(7\delta^2+6\delta+31) - 8\gamma(13\delta^2+10\delta+29) + 128(\delta+1)\} \end{array} \right].$$

The sign of $\partial q_{ii}^{D*}/\partial z$ only depends on the terms in the large square brackets. As it is difficult to analytically solve the inequality $\partial q_{ii}^{D*}/\partial z > 0$, we use numerical calculation. For $z \in \{2, 10, 50, 100\}$, drawing the areas $\partial q_{ii}^{D*}/\partial z > 0$, we obtain Figure 3. In this figure, the shadow areas denote the condition for $\partial q_{ii}^{D*}/\partial z > 0$. From this figure, we confirm that $\partial q_{ii}^{D*}/\partial z > 0$ if γ is large. In addition, as z increases, the region where $\partial q_{ii}^{D*}/\partial z > 0$ becomes wider. Therefore, we obtain the second part of the remark.

Finally, we consider the last part of the remark. Differentiating x_i^{D*} with respect to z, we have the following equation.

$$\frac{\partial x_i^{D*}}{\partial z} = \frac{128(a-c)(2-\gamma)^3(4+2z-\gamma^2)}{\left(E^D\right)^2} \left[\begin{array}{l} \delta[4z(\gamma+1) + \gamma(12-4\gamma-\gamma^2)] \\ -4z(1-\gamma) - (\gamma+4)(\gamma-2)^2 \end{array} \right].$$

The sign of $\partial x_i^{D*}/\partial z$ only depends on the terms in the large square brackets. The expression is a linear function of δ and the coefficient of δ is positive. Hence, the

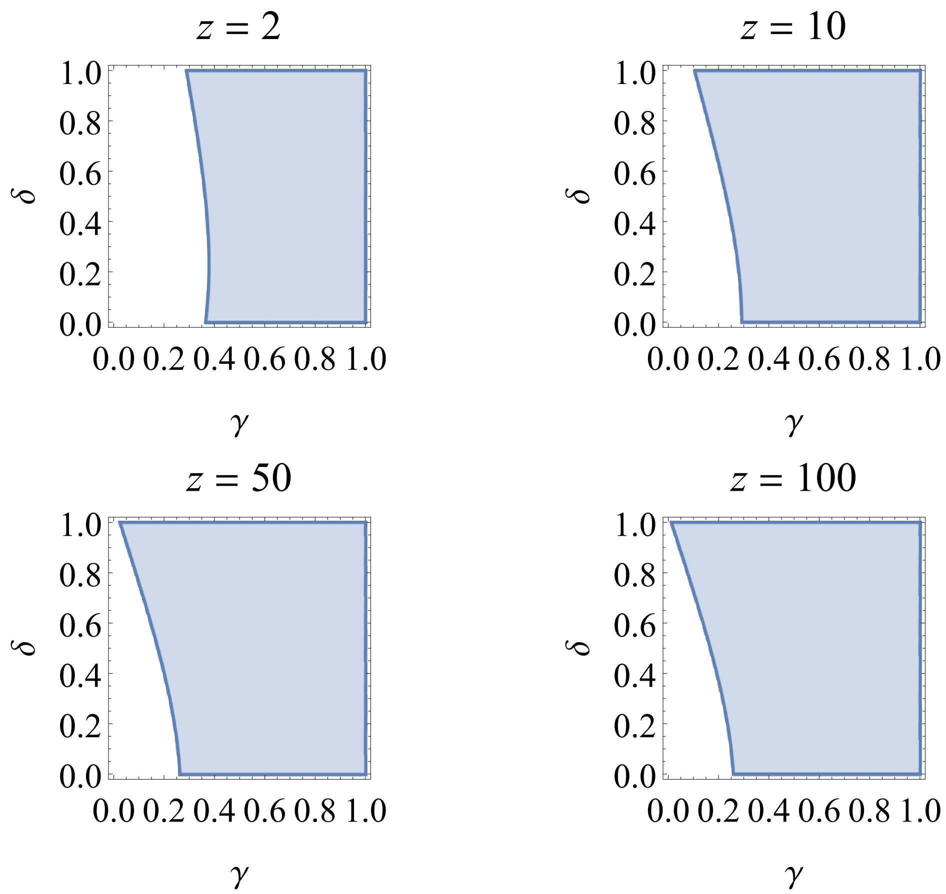


Figure 3: Regions of $\partial q_{ii}^{D*}/\partial z > 0$.

condition for $\partial x_i^{D*}/\partial z > 0$ is $\delta < [4z(1-\gamma)+(2-\gamma)^2(4+\gamma)]/[4z(1+\gamma)+\gamma(12-4\gamma-\gamma^2)]$. Therefore, we complete the calculation of Remark 1.

Calculation of Remark 2: Differentiating Q_i^{D*} with respect to z leads to the following.

$$\frac{\partial Q_i^{D*}}{\partial z} = \frac{16(a-c)(2-\gamma)^3}{(E^D)^2}\left[\begin{array}{l} 16z^2[\gamma(\delta^2+2\delta+9)+2(\delta^2+2\delta-7)] \\ -8(\gamma-2)z[\gamma^2(\delta^2+2\delta+17)+8\gamma(\delta+1)^2+4(\delta^2+2\delta-15)] \\ +(\gamma-2)^2\{\gamma^3(\delta^2+2\delta+33)+2\gamma^2(7\delta^2+14\delta+39) \\ \qquad +4\gamma(9\delta^2+18\delta-23)-8(\delta^2+2\delta+33)\} \end{array}\right].$$

The sign of $\partial Q_i^{D*}/\partial z$ is the same as that of the expression in the large square brackets. As these terms are complicated, we will use numerical calculations to determine the sign. Here, we consider the cases for $z \in \{2, 10, 50, 100\}$. Depicting the conditions of $\partial Q_i^{D*}/\partial z > 0$ we obtain Figure 4. In the shadow area, we have $\partial Q_i^{D*}/\partial z > 0$. Hence, stronger competition in the transport industry and higher transport efficiency tend to reduce consumer surplus if both products are not so differentiated or the spillover rate is high. This completes the calculation of Remark 2.

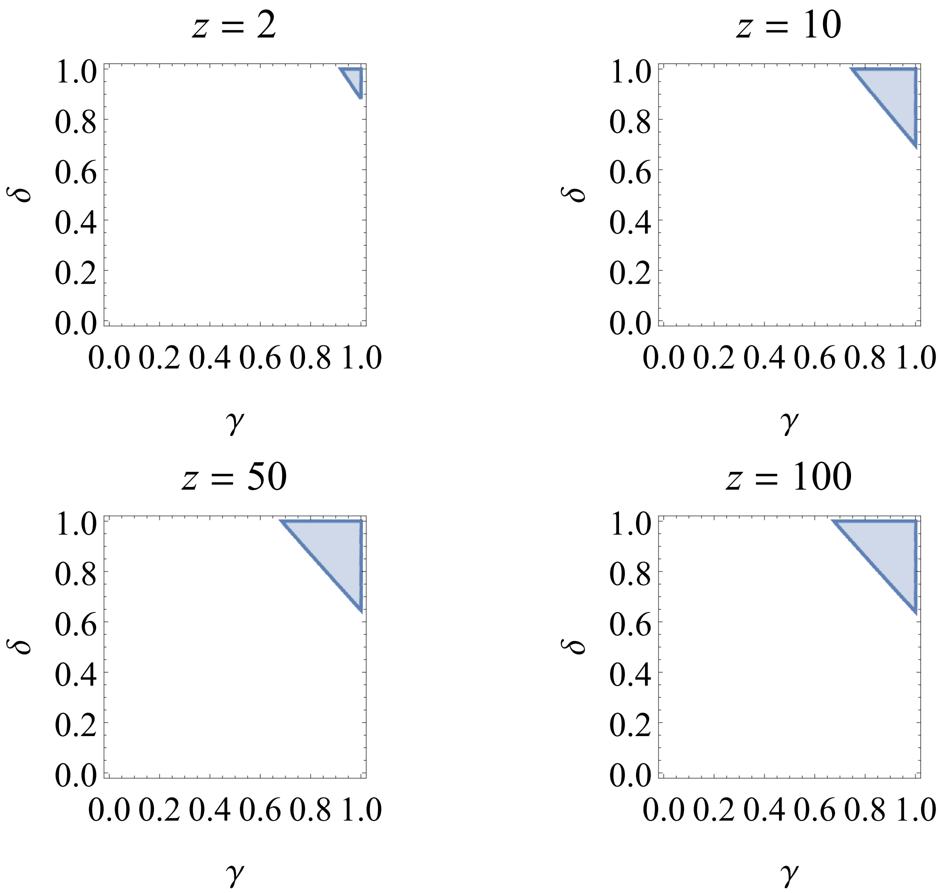


Figure 4: Regions of $\partial Q_i^{D*}/\partial z > 0$.

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