Unilateral Emission Standards, Quality of Vertically Differentiated Products, and the Global Environment

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Abstract

Employing an environmentally-differentiated products model with heterogeneous consumers in terms of environmental consciousness, this paper examines the effect of a unilateral change in a home emission standard on the qualities of products, aggregate emissions, and welfare of both home and foreign countries. When firms compete with each other in a Cournot fashion, as the home emission standard becomes stricter, aggregate emissions of both domestic and foreign countries decrease if a firm which produces a 'dirtier product' supplies the same product to both domestic and foreign markets. On the other hand, if the firm supplies different products in environmental features to different markets, a stricter emission standard by the home government increases aggregate emissions of the foreign country. Even in the Bertarnd duopoly case, the effects of a stricter emission standard on both countries could be different from each other.

JEL Classification: D43; F12; Q28.
Key words: emission standards; international duopoly; environmentally differentiated products.

1. Introduction

As countries develop, and accordingly, per capita incomes increase, the people in those countries become more environmentally conscious. Accordingly, the growing concerns on emissions and health problems arising from the consumption of products can be seen. In response to this situation, governments usually adopt various kinds of standards on emissions and other types of consumption-related environmental and health problems. For example, many countries have emission standards on exhausts of vehicles and motorcycles: some of them are very strict, whereas others are relatively lax.[1] Moreover, many countries also have the strict standards on food safety, such as that on food additives and the residuals of agrochemicals, although international standards exist.[2]

Faced with these standards, firms improve the qualities of their products, in particular, in environmental and health aspects. In the case of vehicles, some automakers have improved fuel efficiency drastically, whereas others have developed hybrid or electric vehicles. Since the strictness of standards in one country is different from those in other countries, firms have to comply with various types of regulations if they supply their products more than one country. In some cases, they produce various types of products in terms of environmental quality according to the number of markets they enter. In other cases, they supply the same type of product to more than one market, since it is costly to supply more than one type of product.[3]

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1 For example, the standards of EU can be seen in the following homepage. (http://europa.eu/legislation_summaries/environment/air_pollution/index_en.htm)
In the case of the United States, see http://www.epa.gov/otaq/standards/ (Environmental Protection Agency). Republic of Korea has determined that it will adopt the standard similar to that of EU.

2 For example, see http://www.mhlw.go.jp/english/topics/foodsafety/index.html (the Ministry of Health, Labor, and Welfare) for the case of Japan. The international standard is called as the CODEX standard. See http://www.codexalimentarius.net/web/standard_list.do?lang=en for details.

3 For example, it may be difficult for one automaker to supply both hybrid and electric vehicles at the same time, since it has to invest in R&D, plants, supply chains, and recycling systems.

Observing the behavior of these firms on how many types of products they supply, it is natural to consider that a change in an emission standard in one country influences the other countries' markets, and that the effect on the domestic market may be different from that on the foreign market.

Focusing on the emission from consumption, this paper investigates the effect of a unilateral change in an emission standard of one country on the qualities of products, aggregate emissions, and welfare of both domestic and foreign countries.

Over the past few decades, a considerable number of studies have been devoted to the study of the effect of environmental policies in an open economy, when pollution is emitted in the production process (See Conrad (1993), Kennedy (1994), Ulph (1996, 1999), Rauscher (1997), and Neary (2006) among them). On the other hand, relatively few studies have been made at the environmental policies and international trade when pollution is emitted during consumption, in particular, when consumers are heterogeneous. Motta and Thisse (1999) examine the effect of a minimum environmental-quality standard on firms' behavior and international trade strategies. They, however, did not take into consideration environmental damage when they compare welfare in different situations. Moreover, they did not consider the number of types of products chosen by firms.

Based on Moraga-González and Pandrón-Fumero (2002), we employ a differentiated products model with heterogeneous consumers in terms of environmental consciousness. Some consumers prefer an environmental friendly product to an environmentally unfriendly product even if the former is more expensive than the latter. To the contrary, others prefer the latter to the former one. Therefore, when two firms enter the market with these consumers, the products of them are differentiated in environmental features. Toshimitsu (2008a) employs this type of model, and analyzes the effect of the setting of emission standards by one country on its own welfare when two foreign firms enter the domestic market.[4] By contrast, we analyze not only the effect on the domestic market but also on the foreign market, and examine whether or not those effects on both countries are the same. Usually, it is considered that a unilateral emission standard improves the quality of imported products. Even if this effect works for the domestic environment, this does not necessarily lead to a decrease in aggregate emissions from the consumption in the foreign market. Thus, it is important to clarify the effect of a change in a unilateral emission standard on the environment.

In term of the purpose of this paper, there are three important features of our model. First, to extract the essence of our focus, we consider two types of basic duopoly models: Cournot duopoly, and Bertrand duopoly. One firm supplies a 'dirtier product', and the other supplies a 'cleaner product' to each market. Since the emission standard we focus on is the upper limit of emission levels per unit consumption, the dirtier product is directly influenced by a change in the level of an emission standard.

Second, the firm which produces dirtier products may produce more than one type of dirtier product in terms of environmental characteristics. It means that, when the firm supplies its products to two countries (home and foreign), (a) the firm produces two types of dirtier products, (b) each type of product is supplied to either home or foreign market, and (c) only one type is supplied to each market.

When the emission in the production process is focused on, the location choices by firms are crucial to understand the effect of environmental policies. For example, Markusen et al. (1993) examines the effect of environmental policies on the aggregate emissions when plant locations are endogenously determined.[5] By contrast, since we focus on emissions in the

4 Toshimitsu (2008b) also applies this model to investigate the effect of a tariff on the domestic environment and welfare.

5 Many other analyses are made at this issue. See Markusen (1997) and Ulph and Valentini (1997) among them.

consumption stage, the number of products supplied and the qualities of them are crucial.

The main results are as follows. Suppose that firms compete with each other in a Cournot fashion in both home and foreign markets. Then, as an emission standard set by the home country becomes stricter, aggregate emissions of both home and foreign countries decrease, if a firm which produces a 'dirtier product' supplies the same product to both markets. On the other hand, if the firm supplies different types of dirtier products to different markets, as a home emission standard becomes stricter, the aggregate emission of the foreign country increases. Even in the Bertarnd duopoly case, the effect of a stricter home emission standard on both countries could be different from each other. Moreover, we refer to endogenous determination of the number of types of products produced by the firm which produces dirtier products.

The structure of the paper is as follows. Section 2 sets up the model. Section 3 describes the equilibria both in Cournot and Bertrand duopoly cases. Section 4 examines the effect of a stricter emission standard on the qualities of products, aggregate emissions, and the welfare of both countries. Section 5 investigates endogenous determination of the number of types of products. Section 6 and 7 provide further discussion and concluding remarks, respectively.

2. The Model

2.1 Markets

We consider a vertically differentiated product model, in which 'vertically differentiated' implies 'environmentally differentiated'. There are two countries: the home country, which is denoted by h, and the foreign country, which is denoted by f. In each country, there exists a continuum of heterogeneous consumers who differ in their marginal valuations, θ, of the green features of a product. To simplify, we assume that the distribution of consumers of both countries are identical, and that the consumer-matching value is uniformly distributed in the market in each country, $\theta \in [0,1]$. A consumer for whom θ is close to unity (resp. zero) is conscious (resp. not conscious) of the environment. Let e denote the observable level of polluting emissions associated with the unit consumption of a product. Each consumer purchases either one or no unit of the product. The net surplus of consumer θ in country i who acquires the variant e at a price p_i is $u = \max\{v - e\theta - p_i, 0\}$, $e \in (0, \infty)$. v is the utility obtained from consuming a single unit of the product irrespective of the variant's unit emission level. A consumer who does not buy any product is assumed to have a net surplus of zero.

There are two firms outside of these two consuming countries, which supply environmentally differentiated products to both countries h and f.[6] Without loss of generality, we assume that firm D (resp. C) supplies a product with a unit emission level $e_{D,i}$ (resp. $e_{C,i}$) at price $p_{D,i}$ (resp. $p_{C,i}$) to the market of country i ($i = h, f$), and that $e_{D,i} > e_{C,i}$. Thus, two types of products are supplied to each country. In the following, we call the product produced by firm D as the dirtier product, and the product produced by firm C as the cleaner product.

We derive the demand functions for those differentiated products in country i. The marginal consumer who is indifferent between the net surplus given by purchasing the dirtier and the cleaner products is characterized by $\tilde{\theta}_i = (p_{C,i} - p_{D,i})/(e_{D,i} - e_{C,i})$. On the other hand, the index of the marginal consumer who is indifferent between the net surplus given by purchasing the cleaner product and nothing is $\hat{\theta}_i = (v - p_{C,i})/e_{C,i}$. Thus, consumer θ falling into $0 \le \theta \le \tilde{\theta}$ (resp. $\tilde{\theta} < \theta \le \hat{\theta}$) purchases a dirtier (resp. cleaner) product, and consumer θ falling into $\hat{\theta} < \theta \le 1$ purchases nothing. Throughout the paper, it is assumed

6 The reason why we assume that two firms are located outside of these two consuming countries is that we focus on pollution emission from consumption, and accordingly, the conflict between consumer's surplus and environmental damage. We, however, investigate producer's surplus in Section 5.

that the markets of both countries are not completely covered by all consumers.

Let $q_{D,i}$ (resp. $q_{C,i}$) represent the quantity demanded for the dirtier (resp, the cleaner) product in country i. Since the uniform distribution is assumed, the demand functions are given by:

$$q_{D,i} = \tilde{\theta}_i = \frac{p_{C,i} - p_{D,i}}{e_{D,i} - e_{C,i}} \tag{1.1}$$

$$q_{C,i} = \hat{\theta}_i - \tilde{\theta}_i = \frac{e_{D,i}\left(v - p_{C,i}\right) - e_{C,i}\left(v - p_{D,i}\right)}{e_{C,i}\left(e_{D,i} - e_{C,i}\right)} \tag{1.2}$$

Given (1.1) and (1.2), the corresponding inverse demand functions are given by:

$$p_{D,i} = v - e_{D,i} q_{D,i} - e_{C,i} q_{C,i} \tag{2.1}$$

$$p_{C,i} = v - e_{C,i}\left(q_{D,i} + q_{C,i}\right). \tag{2.2}$$

2.2 Firms

Before price or quantity competition in the markets, the firms need to invest in product lines, plants, and a supply network with associated environmental qualities of the products.[7] Following Moraga-González and Padrón-Fumero (2002, Assumption 2), we assume that the cost function of a unit emission level for each firm can be expressed by a homogeneous function of degree $\varepsilon \geq 1$:

$$F_D\left(e_D\right) = \alpha\, e_D^{-\varepsilon} \tag{3.1}$$

$$F_C\left(e_C\right) = e_C^{-\varepsilon}. \tag{3.2}$$

Note that $F_j' < 0$, $F_j'' > 0$, $j = C, D$. To avoid multiple equilibria in the decision game of the unit emission levels, we assume that cost functions are sufficiently asymmetric among the firms: $\alpha > 1$. This implies that firm C (resp. D) has an efficient (resp. inefficient)

[7] In reality, firms often have to invest in setting up recycling systems.

environmental technology. For simplicity, we assume that marginal costs of production are independent of unit emission levels and are equal to zero.

Firm D can choose different unit emission levels for different markets, i.e., $e_{D,h} \neq e_{D,f}$. In such a case, however, it has to pay the cost for another extra plant, product line, and a supply network. In the main analysis in Section 4, the number of types of products produced by firm D is exogenous. In the following, when we describe that 'firm D produces two types of products' or 'firm D supplies different types of products to different markets', it means that firm D supplies two types of dirtier products, and either of two types is supplied to each country/market. In Section 5, we investigate the case in which the number of types of products produced by firm D is endogenously determined.

Since we will focus on an emission standard policy on a dirtier product, hereafter, we mainly assume that firm C supplies the same type of product to both markets.[8] This implies that firm C does not pay an additional fixed cost. Thus, the profit functions of both firms are given by:

$$\pi_D = p_{D,h}q_{D,h} + p_{D,f}q_{D,f} - F_{D,h} - \sigma F_{D,f} \tag{4.1}$$

$$\pi_C = p_{C,h}q_{C,h} + p_{C,f}q_{C,f} - F_C \tag{4.2}$$

where σ is a dummy variable; $\sigma = 0$ if $e_{D,h} = e_{D,f}$, or $\sigma = 1$ if $e_{D,h} \neq e_{D,f}$.

2.3 Governments and Social Welfare

We assume that the home government unilaterally sets an emission standard, which is the highest emission per unit of consumption when a product is sold and consumed in the home market. Since $e_{D,h} > e_C$, the emission standard implies the highest emission per unit

8 In reality, as noted in Footnote 3, it is sometimes very costly to supply more than one type of cleaner products. We briefly discuss the case in which firm C supplies more than one type of product in Section 6.

consumption of a dirtier product, $\bar{e}_{D,h}$. This variable is a parameter in our model. We assume that there is no emission standard for the foreign market, or the foreign emission standard is not binding even if it exists ($e_{D,f} < \bar{e}_{D,f}$). On the contrary, $\bar{e}_{D,h}$ is always binding, and accordingly, $\bar{e}_{D,h} \le e_{D,f}$.

The aggregate emissions, which increase environmental damage, are expressed by

$$E_i = e_{D,i} q_{D,i} + e_{C,i} q_{C,i} \quad (i = h, f) \tag{5}$$

Then, the whole aggregate emission in the global economy is given by $E^G = E_h + E_f$. Furthermore, as mentioned above, there are three types of consumers: those purchasing the dirtier product, those purchasing the cleaner product, and those never purchasing any products in the market. Thus, the aggregate consumer surplus can be represented as:

$$CS_i = \int_0^{\tilde{\theta}_i} (v - e_{D,i}\theta) d\theta - p_{D,i} q_{D,i} + \int_{\tilde{\theta}_h}^{\hat{\theta}_h} (v - e_C \theta) d\theta - p_{C,i} q_{C,i} \,. \tag{6}$$

The social net surplus of each country is given by:[9]

$$W_i = CS_i - \gamma_i E_i \quad i = h, f \,, \tag{7}$$

where $\gamma_i \ge 0 (i = h, f)$ is the marginal social valuation of environmental damages of country i. Equation (7) implies that the each government takes into consideration its own environment only. If the government is very conscious of the global environment, the net social surplus can be written as:

$$W_i^G = CS_i - \gamma_i E^G \,. \tag{8}$$

In what follows, we consider a three-stage game: in the first stage, the home government changes an emission standard charged on a dirtier product. This change is exogenous in this paper. In the second stage, the firms determine the unit emission levels,

[9] We consider the profits of firms in Section 5. As noted in Footnote 6, our main focus is the conflict between consumer's surplus and environmental damage when considering social surplus.

given the home emission standard. In the third stage, they compete in price or in quantity in the markets. We derive a subgame perfect Nash equilibrium by backward induction.

3. Equilibria

3.1 Cournot Duopoly Case

As the derivation of the Cournot-Nash equilibrium in the final stage is straightforward, the procedure of the derivation is omitted. The equilibrium quantities in the third stage are given by:

$$q_{D,i}^{C} = \frac{1}{4e_{D,i} - e_C} v, \tag{9.1}$$

$$q_{C,i}^{C} = \frac{2e_{D,i} - e_C}{e_{C,i}\left(4e_{D,i} - e_C\right)} v, \tag{9.2}$$

where $i = h, f$. Superscript C denotes Cournot competition. Hence, the revenue functions in the second stage are expressed by:

$$R_D^C = \frac{\bar{e}_{D,h}}{\left(4\bar{e}_{D,h} - e_C\right)^2} v^2 + \frac{e_{D,f}}{\left(4e_{D,f} - e_C\right)^2} v^2 \tag{10.1}$$

$$R_C^C = \frac{\left(2\bar{e}_{D,h} - e_C\right)^2}{e_C\left(4\bar{e}_{D,h} - e_C\right)^2} v^2 + \frac{\left(2e_{D,f} - e_C\right)^2}{e_C\left(4e_{D,f} - e_C\right)^2} v^2 \tag{10.2}$$

Since $\bar{e}_{D,h}$ is binding, when firm D supplies the same type of product to both markets, $\bar{e}_{D,h} = e_{D,f}$. This implies that firm D does not solve the profit maximization problem in the second stage. On the other hand, when firm D chooses a unit emission level for the foreign market different from that for the home market, the first-order condition for the profit maximization for firm D in the second stage is obtained as follows:

$$-\frac{4e_{D,f} + e_C}{\left(4e_{D,f} - e_C\right)^3} v^2 - F'_{D,f} = 0. \tag{11.1}$$

On the other hand, firm C can choose the unit emission level of its own product by itself. From (4.2) and (10.2), the first-order condition is:

$$-\sum_i \frac{\left(2e_{D,i}-e_C\right)\left(8e_{D,i}^2-2e_{D,i}e_C+e_C^2\right)}{e_C^2\left(4e_{D,i}-e_C\right)^3}v^2-F_C'=0,\quad i=h,f,\quad e_{D,h}=\bar{e}_{D,h}. \tag{11.2}$$

It is assumed that the second-order conditions are satisfied. See Appendix 1 for the details. Based on (11.1) and (11.2), let us define the reaction functions of the unit emission levels in the Cournot duopoly case as follows:

$$e_{D,f}=\phi_D^C\left(e_C\right),\ \phi_D'^C<0. \tag{12.1}$$

$$e_C=\phi_C^C\left(\bar{e}_{D,h},e_{D,f}\right),\quad \partial\phi_C^C\big/\partial\bar{e}_{D,h}>0,\ \partial\phi_C^C\big/\partial e_{D,f}>0 \tag{12.2}$$

In view of (12.1), and (12.2), the unit emission levels of the products are strategic substitutes (resp. complements) with respect to firm D (resp. firm C) in the Cournot duopoly case (See Appendix 1). The intuition is as follows. An increase in the unit emission level of the cleaner (resp. the dirtier) product reduces (resp. increases) the difference in environmental qualities between products. As the difference becomes smaller (resp. larger), a competition among the firms is intensified (resp. mitigated). Thus, the marginal revenue of increasing the unit emission level for firm D (resp. firm C) decreases (resp. increases).

Based on (12.1) and (12.2), when firm D chooses the unit emission level for the product supplied to the foreign market, there is a unique and stable Nash equilibrium, i.e., $\left\{e_{D,f}^C,e_C^C\right\}$, given $\bar{e}_{D,h}$. See Appendix 2.

3.2 Bertrand Duopoly Case

Similar to the Cournot duopoly case, the equilibrium quantities for the Bertrand duopoly case in the third stage are given by:

$$q_{D,i}^B=\frac{1}{4e_{D,i}-e_C}v, \tag{13.1}$$

$$q_{C.i}^{B}=\frac{2e_{D,i}}{e_C\left(4e_{D,i}-e_C\right)}v, \tag{13.2}$$

where $i=h,f$. Superscript B denotes Bertrand competition. Hence, the revenue functions in the second stage are expressed by:

$$R_D^B=\frac{\bar{e}_{D,h}-e_C}{\left(4\bar{e}_{D,h}-e_C\right)^2}v^2+\frac{e_{D,f}-e_C}{\left(4e_{D,f}-e_C\right)^2}v^2 \tag{14.1}$$

$$R_C^B=\frac{4\bar{e}_{D,h}\left(\bar{e}_{D,h}-e_C\right)}{e_C\left(4\bar{e}_{D,h}-e_C\right)^2}v^2+\frac{4e_{D,f}\left(e_{D,f}-e_C\right)}{e_C\left(4e_{D,f}-e_C\right)^2}v^2. \tag{14.2}$$

When firm D chooses a unit emission level for the foreign market different from that for the home market, the first-order condition for the profit maximization of firm D in the second stage is obtained from (4.1) and (14.1) as follows:

$$-\frac{4e_{D,f}-7e_C}{\left(4e_{D,f}-e_C\right)^3}v^2-F'_{D,f}=0. \tag{15.1}$$

On the other hand, from (4.2) and (14.2), the first-order condition for firm C is given by:

$$-\sum_i\frac{4e_{D,i}\left(4e_{D,i}^2-3e_{D,i}e_C+2e_C^2\right)}{e_C^2\left(4e_{D,i}-e_C\right)^3}v^2-F'_C=0,\quad i=h,f,\quad e_{D,h}=\bar{e}_{D,h} \tag{15.2}$$

It is assumed that the second-order conditions are satisfied. See Appendix 3 for the details. Based on the properties of the revenue functions, let us define the reaction functions of the unit emission levels in the Bertrand duopoly case as follows:

$$e_{D,f}=\phi_D^B\left(e_C\right),\ \phi_D'^B>0, \tag{16.1}$$

$$e_C=\phi_C^B\left(\bar{e}_{D,h},e_{D,f}\right),\quad \partial\phi_C^B/\partial\bar{e}_{D,h}>0,\ \partial\phi_C^B/\partial e_{D,f}>0. \tag{16.2}$$

That is, the unit emission levels of the products are strategic complements for both firms (See Appendix 3). The intuition is as follows. In the Bertrand competition, as the difference in environmental qualities between products becomes larger, price competition between firms is mitigated, and the revenue of both firms becomes greater. Therefore, a decrease in the unit emission level of the dirtier (resp. the cleaner) product gives firm C (resp. firm D) an incentive to improve the environmental quality of its own product.

Based on (16.1) and (16.2), when firm D chooses the unit emission level for the product supplied to the foreign market, there is a unique and stable Nash equilibrium, i.e., $\{e_{D,f}^{B}, e_{C}^{B}\}$, given $\overline{e}_{D,h}$. See Appendix 2.

4. An Emission Standard, the Quality of Products, and the Environment

In this section, we investigate the effect of a change in the emission standard set by the home government on the environmental qualities of products supplied to both markets, aggregate emissions, and net social surpluses of both countries.

4.1 Cournot Duopoly Case

First, we consider the effect on the unit emission levels of products. When firm D supplies the same type of product to both markets, which means that the unit emission level for both markets is $\overline{e}_{D,h}$, firm D does not solve the profit maximization problem, whereas firm C does. For this case, we obtain the following condition.

Proposition 1: $0 < \dfrac{de_{C}^{C}}{d\overline{e}_{D,h}} < 1$ and $0 < \dfrac{de_{C}^{C}}{d\overline{e}_{D,h}} \cdot \dfrac{\overline{e}_{D,h}}{e_{C}^{C}} < 1$ hold.

See Appendix 4 for proof. Proposition 1 implies that a stricter home emission standard decreases the unit emission levels of both dirtier and cleaner products. Moreover, the amount of the decrease in the unit emission level of the cleaner product is smaller than that of the dirtier product.

On the other hand, when firm D produces a product with a unit emission level for the foreign market different from that for the home market, the following conditions are obtained.[10]

Proposition 2: $0 < \dfrac{de_C^C}{d\bar{e}_{D,h}} < 1$, $0 < \dfrac{de_C^C}{d\bar{e}_{D,h}} \cdot \dfrac{\bar{e}_{D,h}}{e_C^C} < 1$, and $\dfrac{de_{D,f}^C}{d\bar{e}_{D,h}} < 0$ hold.

See Appendix 5 for proof. Proposition 2 implies that when the home government makes its emission standard stricter, (a) the unit emission level of the cleaner product reduces, (b) the unit emission level of the dirtier product supplied to the foreign market increases.

It should be noted that when firm D supplies the same product to both markets, the effects of a stricter home emission standard is the same for both markets. On the other hand, when firm D supplies different types of products to different markets, the effects of a stricter emission standard are different between the home and foreign markets.

Now let us investigate the aggregate emissions. Substituting (9.1) and (9.2) into (5), the aggregate emission in country i is written as:

$$E_i^C = \frac{3e_{D,i} - e_{C,i}}{4e_{D,i} - e_{C,i}} \cdot v \tag{17}$$

and the effects of changes in the unit emission levels on the aggregate emission is given by:

$$\frac{\partial E_i^C}{\partial e_{D,i}} = \frac{e_{C,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v > 0, \quad \frac{\partial E_i^C}{\partial e_{C,i}} = -\frac{e_{D,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v < 0. \tag{18}$$

An increase in the unit emission level of the dirtier product increases the supply of the cleaner product. These effects dominate the effect of a decrease in the supply of the dirtier product. On the other hand, an increase in the unit emission level of the cleaner product (a)

[10] We do not explicitly analyze the case in which firm D produces a product with a different emission level for the foreign market, and $\bar{e}_{D,f}$ is binding. This case can be analyzed in a similar way, and the results are essentially the same.

decreases the supply of the cleaner product, (b) decreases the unit emission level of the dirtier product, and (c) increases the supply of the dirtier product. In total, the aggregate emission decreases.

From (18) and Proposition 1, when firm D supplies the same product to both markets, the effects of a strict emission standard on the aggregate emissions are obtained:

$$\frac{dE_i^C}{d\bar{e}_{D,h}} \geq 0, \qquad i = h, f. \tag{19}$$

On the other hand, from (18) and Proposition 2, when firm D supplies different types of products to different markets, the effects are given by:

$$\frac{dE_h^C}{d\bar{e}_{D,h}} \geq 0 \ , \quad \frac{dE_f^C}{d\bar{e}_{D,h}} \leq \ 0 \ . \tag{20}$$

Consequently, the following proposition is established.

Proposition 3: *Suppose that the firms compete with each other in a Cournot fashion. As the home emission standard become stricter, the home aggregate emission decreases. On the other hand, the effect on the foreign aggregate emission depends on whether or not firm* D *supplies different types of products to different markets: (a) when firm* D *supplies the same product to both markets, the foreign aggregate emission also decreases, (b) when firm* D *supplies different types of products to different markets (*$\bar{e}_{D,h} < e_{D,f}$*), the foreign aggregate emission increases.*

Now, we can derive the effects on the social net surplus. From the definition of the consumer surplus, it is easily verified that:

$$\frac{\partial CS_i^C}{\partial e_{D,i}} < 0, \ \frac{\partial CS_i^C}{\partial e_{C,i}} < 0, \qquad i = h, f. \tag{21}$$

Therefore, from Proposition 1, it is clear that $dCS_i^C \big/ d\bar{e}_{D,h} < 0 \, (i = h, f)$ holds when firm D supplies the same product to both markets. Even if firm D supplies different types of products to different markets, $dCS_i^C \big/ d\bar{e}_{D,h} < 0 \; (i = h, f)$ holds, since the effect of a change in e_C dominates that of a change in $e_{D,f}$. Therefore, when the social net surplus is defined as (7), from (19) and (20), the following proposition holds.

Proposition 4: *Suppose that the firms compete with each other in a Cournot fashion. As the home emission standard becomes stricter, the home social net surplus increases, which is defined as the consumer surplus minus environmental damage. As far as firm D supplies the same product to both markets, the foreign social net surplus also increases. On the other hand, when firm D supplies different types of products to different markets, the foreign social net surplus decreases if the marginal valuation of environmental damage (γ_f) is greater than a certain level.*

Two points should be noted. First, a strict home emission standard decreases the global emission when firm D supplies the same product to both markets, whereas it is ambiguous whether or not it decreases when firm D chooses a unit unit emission levels for the foreign market different from that for the home market. Thus, even if the emission is international public bad, a stricter unilateral emission standard improves the home net social surplus, which is defined as (8), as far as firm D supplies the same product to both markets.

The second point is the comparison of the optimal emission standard for the home government with the world optimum. When firm D supplies the same product to both markets, it is clear from Proposition 4 that the unilateral emission standard is likely to be laxer than the world optimum. On the other hand, when firm D chooses a different unit emission level for the foreign market, whether or not the unilateral standard is stricter than the world optimum depends on the two factors: the degree of the marginal environmental damage of the foreign government, and whether or not emissions cross the national border. For example, (a) if the foreign government attaches importance to the environmental damage, and (b) if emissions do not cross the border, the unilateral emission standard is likely to be stricter than the world optimum, since the home government does not take into consideration an increase in the environmental damage in the foreign country.

4.2 Bertrand Duopoly Case

First, we consider the effect on the unit emission levels of products. When firm D supplies the same type of product to both markets, we obtain the following conditions.

Proposition 5: $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} < 1$ and $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} \cdot \dfrac{\bar{e}_{D,h}}{e_C^B} < 1$ hold.

See Appendix 4 for proof. This result is the same as the Cournot case.

On the other hand, when firm D chooses a unit emission level for the foreign market different from that for the home market, we obtain the following conditions.

Proposition 6: $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} < 1$, $0 < \dfrac{de_C^B}{d\bar{e}_{D,h}} \cdot \dfrac{\bar{e}_{D,h}}{e_C^B} < 1$, $\dfrac{de_{D,f}^B}{d\bar{e}_{D,h}} > 0$,

$$0 < \frac{de_{D,f}^B \big/ d\bar{e}_{D,h}^B}{de_C^B \big/ d\bar{e}_{D,h}^B}, \text{ and } 0 < \frac{de_{D,f}^B \big/ d\bar{e}_{D,h}^B}{de_C^B \big/ d\bar{e}_{D,h}^B} \cdot \frac{e_C^B}{e_{D,f}^B} < 1 \text{ hold.}$$

See Appendix 5 for proof. Proposition 6 implies that when the home government makes its emission standard stricter, (a) the unit emission level of the cleaner product reduces, (b) the unit emission level of the dirtier product supplied to the foreign market also decreases.

Now let us investigate the aggregate emissions. Substituting (13.1) and (13.2) into (5), the aggregate emission in country i is written as:

$$E_i^B = \frac{3e_{D,i}}{4e_{D,i} - e_{C,i}} \cdot v, \qquad i = h, f \tag{22}$$

and the effects of changes in the unit emission levels on the aggregate emission is given by:

$$\frac{\partial E_i^B}{\partial e_{D,i}} = -\frac{3e_{C,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v < 0, \quad \frac{\partial E_i^B}{\partial e_{C,i}} = \frac{3e_{D,i}}{\left(4e_{D,i} - e_{C,i}\right)^2} v > 0, \qquad i = h, f\ . \tag{23}$$

Note that the directions of changes in the aggregate emission are opposite to those in the Cournot duopoly case. Intuitively, whether or not price competition becomes more serious is an important factor. Serious competition increases the supply of both products, and accordingly, the aggregate emission.

From (23) and Proposition 5, when firm D supplies the same product to both markets, the effects of a strict emission standard on the aggregate emissions are obtained:

$$\frac{dE_i^B}{d\bar{e}_{D,h}} < 0, \qquad i = h, f. \tag{24}$$

On the other hand, from (23) and Proposition 6, when firm D supplies different types of products to different markets, the effects are given by:

$$\frac{dE_h^B}{d\bar{e}_{D,h}} < 0, \qquad \frac{dE_f^B}{d\bar{e}_{D,h}} > 0. \tag{25}$$

Consequently, the following proposition is established.

Proposition 7: *Suppose that the firms compete with each other in a Bertrand fashion. As the home emission standard becomes stricter, the home aggregate emission increases. On the* *other hand, the effect on the foreign aggregate emission depends on whether or not firm* D *supplies different types of products to different markets: (a) when firm* D *supplies the same product to both markets, the foreign aggregate emission also increases, (b) when firm* D *supplies different types of products to different markets, the foreign aggregate emission decreases.*

From the definition of the consumer surplus, it is easily verified that:

$$\frac{\partial CS_i^B}{\partial e_{D,i}} < 0, \ \frac{\partial CS_i^B}{\partial e_{C,i}} < 0, \qquad i = h, f. \tag{26}$$

Therefore, it is clear from Proposition 5 that $dCS_i^B \big/ d\bar{e}_{D,h} < 0 \,(i = h, f)$ holds when firm D supplies the same product to both markets. Even if firm D produces two types of products, $dCS_i^B \big/ d\bar{e}_{D,h} < 0 \ (i = h, f)$ holds from Proposition 6. Thus, when the social net surplus is defined as (7), from (24) and (25) , the following proposition holds.

Proposition 8: *Suppose that the firms compete with each other in a Bertrand fashion. When firm* D *supplies different types of products to different markets, as the home emission standard becomes stricter, the foreign social net surplus increases. On the other hand, if the marginal valuation of environmental damage is smaller than a certain level, a stricter home emission standard increases the home social net surplus, which does not depend on whether firm* D *produces one or two types of dirtier products.*

Three points should be noted. First, the home aggregate emission increases as the home emission standard becomes stricter. This is because the number of consumers who buy either of two types of products increases. Then, from the environmental point of view, the home government should not set any emission standard in this case. There is, however, a possibility that the home government has an incentive to set an emission standard. When firm D supplies different types of products to different markets, the foreign aggregate emission decreases due to a stricter home emission standard. Therefore, when the social net surplus is defined as (8), which means that the home government care about the global emission, a stricter emission standard may decrease the environmental damage for the home country.

Second, similar to the Cournot duopoly case, the comparison of the optimal emission standard for the home government with the world optimum is interesting. For example, when firm D chooses a different unit emission level for the foreign market from that for the home market, it is clear from Proposition 8 that the unilateral emission standard is likely to be laxer than the world optimum.

Third, although the directions of changes are different between Cournot and Bertrand cases, the following fact holds for both cases: when firm D produces two types of dirtier products, the effects of a stricter home emission standard on the aggregate emissions of both countries are different from each other.

5. Endogenous Determination of the Number of Types of Dirtier Products

In the previous section, the number of types of products of firm D is assumed to be exogenous. It is, however, important to consider when firm D determines to produce two types of dirtier products. In this section, we focus on the difference in the social valuation of environmental damages, which is considered to be reflected in emission standards.

If there are no emission standards in both countries, firm D supplies the same type of product to both markets, since it has to pay an additional fixed cost to produce two types of products. If, however, the emission standard in one country is much higher than that in the other country, firm D may have an incentive to supply different types of products to different markets. In other words, firm D makes fit each type of product to each emission standard. Even if it has to pay an additional cost, the profit may be greater when it produces two types of products than when it supplies the same type of product to both markets due to less serious competition. Similar to the previous section, we assume that the foreign emission standard is not binding, whereas the home emission standard is binding. This implies that if firm D produces two types of products, the unit emission level of the product for the foreign market is higher than that for the home market ($\bar{e}_{D,h} < e_{D,f}$). Thus, we investigate whether or not a stricter emission standard changes firm D's decision making on the number of the types of products.

Let us begin with the case of Cournot duopoly. In this case, from (10.1), we obtain that $\partial R_D^C / \partial e_{D,f} < 0$. Since firm C supplies the same type of product to both markets, firm D has no incentive to pay an additional cost to produce another type of product. This fact immediately leads to the following proposition.

Proposition 9: *When firms compete with each other in a Cournot fashion. Then, firm D supplies the same type of products to both markets irrespective of the strictness of the home emission standard.*

This result is simple, but important. In the previous section, we demonstrated that whether or not firm D supplies the same type of product to both markets crucially affects the effect of a home emission standard on the aggregate emission and the social surplus of the foreign country. Proposition 9 states that, if the number of types of products supplied by firm D is endogenously determined, and if the mode of competition is the Cournot competition, the effect of a change in the home emission standard on the home country is the same as that on the foreign country.

Let us now turn to the case of Bertrand duopoly. When there is no home emission standard, $\partial R_D^B / \partial e_{D,f} < 0$ holds. Even if there is a home emission standard, if it is not very strict, $\partial R_D^B / \partial e_{D,f} < 0$ also holds (See Appendix 3). In this case, the same result as the case of Cournot duopoly holds (Proposition 9). However, the stricter is the home emission standard, the more likely it is that $\partial R_D^B / \partial e_{D,f} > 0$ holds as far as firm D supplies the same type of product to both markets.

Let us focus on firm D's incentive to deviate from the situation in which $e_{D,f} = \bar{e}_{D,h}$. Consider the case in which $\partial R_D^B / \partial e_{D,f} > 0$ holds, and let $e'_{D,f}$ denote a unit emission level which is greater than $\bar{e}_{D,h}$.

When $e_{D,f} = \bar{e}_{D,h}$, from (14.1),

$$\begin{aligned} \frac{d\pi_D^B}{d\bar{e}_{D,h}} &= \frac{\partial R_D^B}{\partial \bar{e}_{D,h}} + \frac{\partial R_D^B}{\partial e_C^B} \cdot \frac{de_C^B}{d\bar{e}_{D,h}} - F'_D \\ &= 2 \cdot \left(\frac{-4\bar{e}_{D,h} + 7e_C^B}{\left(4\bar{e}_{D,h} - e_C^B\right)^3} + \frac{-2\bar{e}_{D,h} - e_C^B}{\left(4\bar{e}_{D,h} - e_C^B\right)^3} \cdot \frac{de_C^B}{d\bar{e}_{D,h}} \right) - F'_D \end{aligned} \tag{27}$$

If $\bar{e}_{D,h} = e_C^B$, $\partial R_D^B / \partial \bar{e}_{D,h} + \partial R_D^B / \partial e_C^B = 0$ holds. Then, since $0 < de_C^B / d\bar{e}_{D,h} < 1$ from Proposition 5 and $F'_D < 0$, $d\pi_D^B / d\bar{e}_{D,h} > 0$ holds, if $\bar{e}_{D,h} = e_C^B$. In equilibrium, e_C^B never be equal to $\bar{e}_{D,h}$. However, the smaller the difference between the unit emission levels of both firms' products, the more likely it is that $d\pi_D^B / d\bar{e}_{D,h} > 0$ holds. This means that, the stricter is the home emission standard, the more likely it is that a small decrease in $\bar{e}_{D,h}$ decreases the profit of firm D.

On the other hand, since $\partial R_D^B / \partial e_C < 0$ and $0 < de_C / d\bar{e}_{D,h} < 1$, the profit of firm D when setting the unit emission level for the foreign market equal to $e'_{D,f}$ increases as the home emission standard becomes stricter. It holds for any level of $e'_{D,f}$. Thus, the following proposition holds.

Proposition 10: *When firms compete with each other in a Bertrand fashion. Then, the stricter is the home emission standard, the stronger incentive firm D has to deviate from the situation in which it supplies the same type of products to both markets.*

This result for the Bertrand case is sharp contrast to that for the Cournot case. According to Proposition 10, when the environmental consciousness of the home country is much greater than that of the foreign country, it is likely that the unit emission level regulated by the home emission standard is lower than that of the dirtier product for the foreign market. Thus, the effect of a change in the home emission standard on the home aggregate emission is likely to be different from that on the foreign aggregate emission.

6. Further Discussion

6.1 Producer's Surplus and Domestic Firms

Although we have assumed that firms are located outside of the two consuming countries heretofore, it is possible that they are located in these countries. Therefore, the profits of firms are worth examining.

First, let us examine the profit of firm C. Whether or not firm D supplies the same type of product to both markets, firm C chooses the unit emission level of its own product to maximize its own profit given the unit emission levels of the products of firm D. Therefore, the effect of a change in the home emission standard on the profit is represented as:

$$\frac{d\pi_C^j}{d\bar{e}_{D,h}} = \frac{\partial R_C^j}{\partial \bar{e}_{D,h}} > 0, \qquad j = B, C.$$

It is clear that, the stricter is the home emission standard, the smaller is the profit of firm C, when firm D supplies the same type of the product. Moreover, from Proposition 6, if firms compete with each other in a Bertrand fashion, even when firms supplies different types of products to different markets, the profit of firm C decreases as the home emission standard becomes stricter. In this case, from (21) and (26), the effect of a strict home emission standard on the consumer's surplus and that on the profit of firm C conflict with each other.

Second, let us examine the profit of firm D. From (27), we know that the effect of a change in the home emission standard on the profit is ambiguous. However, when the effect is evaluated at the unit emission level when there is no emission standard ($e_{D,0}^j$), it is obtained that:

$$\frac{d\pi_D^j}{d\bar{e}_{D,h}} = \frac{\partial R_D^j}{\partial e_C} \cdot \frac{de_C}{d\bar{e}_{D,h}}. \tag{28}$$

Recall that $\partial R_D^j / \partial e_C < 0$ holds when firms compete with each other in a Bertrand fashion. In this case, both the consumer's surplus and the profit of firm D increases when the home emission standard becomes stricter marginally from $e_{D,0}^j$. This implies that Proposition 8 may hold for a country in which firm D is located, even if the profits of firms are taken into consideration.

6.2 Firm C's Choice on the Number of Types of Cleaner Products

Heretofore, assuming that firm C supplies the same type of product to both markets, we have mainly focused on the types of dirtier products of firm D. It is, however, easily extended to the case in which firm C supplies different types of products to different markets.

First, consider the case in which both firms determine one unit emission level for each market. When the home government makes its emission standard stricter, each firm changes the unit emission level of its own product for the home market. Both firms, however, do not change the unit emission levels of products supplied to the foreign market. This is because the unit emission level of the dirtier product supplied to the foreign market is not influenced by a change in the home emission standard.

Second, consider the case in which firm C determines one unit emission level for each market whereas firm D supplies only one type of product, which is supplied to both markets. In this case, a change in the home emission standard has the same effect on the unit emission levels of dirtier products supplied to both markets. Accordingly, the unit emission levels of the cleaner products supplied to both markets also change in the same way. This result is the same as the case in which each firm supplies only one type of product.

Consequently, it can be concluded that whether or not firm D, whose products are directly affected by emission standards, supplies different types of products to different markets crucially affects the effect of the home emission standard on the foreign market.

7. Concluding Remarks

We have examined the effect of a unilateral change in an emission standard on the qualities of products, aggregate emissions, and welfare of both domestic and foreign countries. To this end, we employ a differentiated products model with heterogeneous consumers in terms of environmental consciousness. Moreover, we consider both Cournot and Bertrand duopoly cases.

The results we obtain are very clear: whether or not the effects of a stricter home emission standard on both the domestic and foreign countries are the same depends on the types of products produced by the firm which supplies dirtier products (firm D). In other words, when firm D supplies different products in terms of environmental features to different markets, the effects on both countries are different from each other. This means that a unilateral change in an emission standard could be either beneficial or harmful to other countries, and that the firms' behavior on how many types of products they supply is crucial.

Moreover, when considering the endogenous determination of the number of types of products produced by firm D, the result in the case of Bertrand duopoly is sharp contrast to that of Cournot duopoly. In the former case, the stricter is the home emission standard, the stronger incentive firm D has to produce two types of dirtier products. On the other hand, in the latter case, firm D keeps producing one type of dirtier product, even if the home emission standard become stricter.

To extract the essence of the issue we focus on, some interesting factors were excluded from the analysis, although the results obtained in this paper are not influenced by those factors. First, the environmental criteria for cleaner products, such as environmental labeling, could also be focused on. The effects of a strict awarding rule for a 'cleaner product' on both domestic and foreign markets could also be different from each other, and may be counterintuitive. Second, the strategic behavior of both governments was not taken into consideration. It is important to verify whether or not emission standards of countries are optimal in terms of the world welfare. In this respect, the situation in which a government sets its emission standard depending on emission standards of other countries should be examined. To elucidate these effects is also our future task.

Appendix 1

Given (10.1) and (10.2), the first-order properties are given by:

$$\frac{\partial R_D^C}{\partial e_{D,f}} < 0,\ \frac{\partial R_C^C}{\partial e_C} < 0,\ \frac{\partial R_D^C}{\partial e_C} > 0,\ \frac{\partial R_C^C}{\partial \overline{e}_{D,h}} > 0,\ \frac{\partial R_C^C}{\partial e_{D,f}} > 0\,. \tag{A.1}$$

Furthermore, the second-order properties are given by:

$$\frac{\partial^2 R_D^C}{\partial e_{D,f}^2} > 0,\quad \frac{\partial^2 R_C^C}{\partial e_C^2} > 0\,, \tag{A.2}$$

$$\frac{\partial^2 R_D^C}{\partial e_{D,f}\partial e_C} < 0,\ \frac{\partial^2 R_C^C}{\partial e_C \partial e_{D,f}} > 0,\ \frac{\partial^2 R_C^C}{\partial e_C \partial \overline{e}_{D,h}} > 0\,. \tag{A.3}$$

From (A.2), since it holds that the revenue functions are not concave, the cost functions should be sufficiently convex to ensure that the second-order conditions hold. (A.3) implies that the unit emission levels of the products are strategic substitutes (resp. complements) for firm D (resp. firm C) in the Cournot duopoly case.

Appendix 2

The determinant of the matrix can be generally expressed as:

$$\Delta^k = \frac{\partial^2 \pi_D^j}{\partial e_D^2}\frac{\partial^2 \pi_C^j}{\partial e_C^2} - \frac{\partial^2 \pi_D^j}{\partial e_{D,f}\partial e_C}\frac{\partial^2 \pi_C^j}{\partial e_C \partial e_{D,f}},\qquad j = C, B \tag{A.4}$$

Furthermore, from (11.1), (11.2), (15.1) and (15.2), the following equations hold:

$$e_{D,f}\,\frac{\partial^2 R_D^k}{\partial e_{D,f}^2} + e_C\,\frac{\partial^2 R_D^k}{\partial e_{D,f}\partial e_C} = -2F'_{D,f} \tag{A.5.1}$$

$$e_C\,\frac{\partial^2 R_C^k}{\partial e_C^2} + e_{D,f}\,\frac{\partial^2 R_C^k}{\partial e_C \partial e_{D,f}} + \overline{e}_{D,h}\,\frac{\partial^2 R_C^k}{\partial e_C \partial \overline{e}_{D,h}} = -2F'_C \tag{A.5.2}$$

Substituting (A.5.1) and (A.5.2) into (A.4), we obtain that

$$\Delta^j = \frac{e_{D,f}}{e_C}\frac{\partial^2 R_C^j}{\partial e_C \partial e_{D,f}}\left(-\frac{F'_{D,f}}{e_{D,f}}\right)(\eta_{D,f}-2)+\frac{e_C}{e_{D,f}}\frac{\partial^2 R_D^j}{\partial e_{D,f}\partial e_C}\left(-\frac{F'_C}{e_C}\right)(\eta_C-2)$$
$$+\left(-\frac{F'_{D,f}}{e_{D,f}}\right)(\eta_{D,f}-2)\left(-\frac{F'_C}{e_C}\right)(\eta_C-2) \tag{A.6}$$
$$+\frac{\bar{e}_{D,h}}{e_C}\frac{\partial^2 R_C^j}{\partial e_C \partial \bar{e}_{D,h}}\cdot\left\{\frac{e_C}{e_{D,f}}\frac{\partial^2 R_D^j}{\partial e_{D,f}\partial e_C}+\left(-\frac{F'_{D,f}}{e_{D,f}}\right)(\eta_{D,f}-2)\right\},$$

where $\eta_C \equiv e_C F''_C/(-F'_C)$, and $\eta_{D,f} \equiv e_{D,f}F''_{D,f}/(-F'_{D,f})$. From (3.1) and (3.2), both of them are equal to $\varepsilon+1(>2)$.

In the Bertrand duopoly case, since all cross partial derivatives are positive (See Appendix 3), the sign of the determinant is positive. Thus, the stability condition is satisfied. On the other hand, in the Cournot duopoly case, $\partial^2 R_D^C / \partial e_{D,f}\partial e_C < 0$. However, if $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ and $\partial^2 \pi_C / \partial e_C^2 < 0$ holds, it is clear from (A.4) that the sign of the determinant is positive. This fact is also verified from (A.6). If $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ holds, the absolute value of the third term in (A.6) is greater than that of the second term. Thus, the stability condition is satisfied.

Appendix 3

Given (14.1) and (14.2), the first-order properties are given by:

$$\frac{\partial R_D^B}{\partial e_{D,f}} \geq (<) 0 \Leftrightarrow \frac{7}{4}e_C \geq (<) e_{D,f} \quad , \frac{\partial R_C^B}{\partial e_C}<0,\ \frac{\partial R_D^B}{\partial e_C}<0,\ \frac{\partial R_C^B}{\partial \bar{e}_{D,h}}>0,\ \frac{\partial R_C^B}{\partial e_{D,f}}>0. \tag{A.7}$$

We assume the existence of an interior solution such that $7e_C/4 < e_{D,f}$ when firm D chooses a unit emission level for the foreign market different from that for the home market. Furthermore, the second-order properties are given by:

$$\frac{\partial^2 R_D^B}{\partial e_{D,f}^2} \geq (<) 0 \Leftrightarrow e_{D,f} \geq (<) \frac{5}{2}e_C, \quad \frac{\partial^2 R_C^B}{\partial e_C^2} > 0, \tag{A.8}$$

$$\frac{\partial^2 R_D^B}{\partial e_{D,f}\partial e_C} > 0,\ \frac{\partial^2 R_C^B}{\partial e_C \partial e_{D,f}} > 0,\ \frac{\partial^2 R_C^B}{\partial e_C \partial \overline{e}_{D,h}} > 0\,. \tag{A.9}$$

From (A.7), since it holds that the revenue functions are not necessarily concave, the cost functions should be sufficiently convex to ensure that the second-order conditions hold. (A.8) implies that the unit emission levels of the products are strategic complements for both firms in the Bertrand duopoly case.

Appendix 4

In this Appendix, the same results hold for both modes of competition, we abbreviate superscripts B and C. When $e_{D,f} = \overline{e}_{D,h}$,

$$\frac{de_C}{d\overline{e}_{D,h}} = -\frac{\dfrac{\partial^2 \pi_C}{\partial e_C \partial \overline{e}_{D,h}}}{\dfrac{\partial^2 \pi_C}{\partial e_C^2}} \tag{A.10}$$

From (A.3), when the second order conditions are satisfied, (A.10) is positive. In this case, (A.5.2) can be rewritten as:

$$e_C \frac{\partial^2 R_C}{\partial e_C^2} + \overline{e}_{D,h} \frac{\partial^2 R_C}{\partial e_C \partial \overline{e}_{D,h}} = -2F_C'\,. \tag{A.5.2)'$$

Thus,

$$\frac{de_C}{d\overline{e}_{D,h}} = \frac{\dfrac{\partial^2 R_C}{\partial e_C \partial \overline{e}_{D,h}}}{\dfrac{\overline{e}_{D,h}}{e_C}\dfrac{\partial^2 R_C}{\partial e_C \partial \overline{e}_{D,h}} - \dfrac{F_C'}{e_C}\cdot\left(\eta_C - 2\right)} \tag{A.11}$$

Since $\eta_C > 2$ and $\overline{e}_{D,h} > e_C$, Propositions 1 and 5 hold.

Appendix 5

We basically abbreviate superscripts B and C in this Appendix. The effect of a change in the home emission standard on the unit emission levels are obtained as follows:

$$\frac{de_{D,f}}{d\bar{e}_{D,h}} = \frac{\dfrac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}} \dfrac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C}}{\dfrac{\partial^2 \pi_D}{\partial e_{D,f}^2} \dfrac{\partial^2 \pi_C}{\partial e_C^2} - \dfrac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C} \dfrac{\partial^2 \pi_C}{\partial e_C \partial e_{D,f}}} \tag{A.12.1}$$

$$\frac{de_C}{d\bar{e}_{D,h}} = \frac{-\dfrac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}} \dfrac{\partial^2 \pi_D}{\partial e_{D,f}^2}}{\dfrac{\partial^2 \pi_D}{\partial e_{D,f}^2} \dfrac{\partial^2 \pi_C}{\partial e_C^2} - \dfrac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C} \dfrac{\partial^2 \pi_C}{\partial e_C \partial e_{D,f}}} \tag{A.12.2}$$

From (A.3) and (A.9), (A.12.1) is negative (resp. positive) in the Cournot (resp. Bertrand) duopoly case. (A.12.2) is positive regardless of the mode of competition. Thus,

The numerator of (A.12.2) is

$$-\frac{\partial^2 \pi_C}{\partial e_C \partial \bar{e}_{D,h}} \frac{\partial^2 \pi_D}{\partial e_{D,f}^2} = \left(\frac{e_C}{e_{D,f}} \frac{\partial^2 R_D}{\partial e_{D,f} \partial e_C} + \frac{2F'_{D,f}}{e_{D,f}} + F''_{D,f} \right) \frac{\partial^2 R_C}{\partial e_C \partial \bar{e}_{D,h}} .$$

If $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ holds, from (A.6), Proposition 2 holds.

From (A.12.1) and (A.12.2), it holds that

$$\frac{de_{D,f}}{d\bar{e}_{D,h}} \bigg/ \frac{de_C}{d\bar{e}_{D,h}} = -\frac{\partial^2 \pi_D}{\partial e_{D,f} \partial e_C} \bigg/ \frac{\partial^2 \pi_D}{\partial e_{D,f}^2} \tag{A.13}$$

In the case of Bertrand competition, if $\partial^2 \pi_D / \partial e_{D,f}^2 < 0$ holds, (A.13) is positive. Taking (A.5.1) and $\eta_{D.f} > 2$ into consideration, Proposition 6 holds.

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