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Environmental Policy in a Green Market

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Abstract. This paper studies the impact of some frequently-used environmental policies in a duopolistic market where purchasers are willing to pay more for less polluting goods. When consumers differ in their environmental awareness, a cleaner and a dirtier variant coexist in equilibrium. The higher the average willingness-to-pay for the good, the lower are variants' unit emissions but the higher are industrial aggregate effluents. A maximum unit emission standard reduces unit emissions of both variants, but boosts firms' sales and consequently increases industrial aggregate emissions. As a result, social welfare may be reduced. We also explore the effects of technological subsidies and product charges, including differentiation of charges.

Key words: environmentalists, environmentally differentiated duopoly, green consumption, green market, product charges, subsidies, unit emission standards

JEL classification: L52, Q28

1. Introduction

This paper carries out the positive analysis of some frequently-used environmental policies in a market where (i) products vary in their environmental characteristics, and (ii) purchasers are willing to pay more for less polluting goods. We refer to these consumers as *environmentalists* and to the market as a *green market* in what follows. When environmentalists are heterogeneous in regard to how much they are willing to pay for environmentally-friendlier variants, firms find it optimal to differentiate their goods to achieve greater profits. In the presence of firms' strategic behavior, government regulation does not only affect products' environmental features but also consumers' allocation in the market. This latter effect may cause that typical environmental measures increase industrial aggregate emissions, even if variants' unit emissions decrease.

The literature has devoted no attention to study the consequences of environmental policy *on aggregate emissions and social welfare* in markets with imperfect competition and heterogeneous products in regard to their environmental characteristics.[1] The papers most closely related to the present work are Arora and Gangopadhyay (1995)[2] and Motta and Thisse (1999). The former studies the impact of minimum quality standards, output taxes and tradable emission permits on the firms' quality choices. The latter examines the effects of the introduction of a minimum environmental-quality standard on firms' quality choices and their international trade strategies. The present work departs from these papers *first* in that we model products' unit emissions as something environmentalists dislike, i.e., as a bad, and *second* in that our major concern is on the impact of regulation on industrial aggregate effluents and social welfare. Further work includes Cremer and Thisse (1999), who analyze the effects of ad-valorem taxation on the average environmental quality consumed in a natural oligopoly. In a regional setting, Kuhn (1998) studies the impact of domestic production standards on firms technological and location decisions. Finally, Crampes and Ibanez (1996) and Kuhn (1999) study the role of eco-labels in environments where there is asymmetric information in regard to the environmental quality of the goods.

We capture the main features of a market with green consumption by building a duopoly model of environmental product differentiation. Goods only differ in their associated level of unit emissions, which is an endogenous variable.[3] Purchasers, either buyers or firms, differ in their willingness-to-play for the goods but they all prefer less-polluting variants. On the supply side, there are two ex-ante symmetric duopolists. They engage in a two-stage game, first choosing the variant to offer, and then their prices. Producers' investments in technology, product design or, more specifically, abatement devices aimed at reducing the unit emissions of their variants are costly. This cost is higher the lower are the unit emissions of the variant chosen.

In the unique subgame perfect equilibrium, two different variants of the product emerge. These are referred to as the *cleaner* and the *dirtier* variant. Interestingly, the higher the average willingness-to-pay for the good, the lower are unit emissions, but the higher are industrial aggregate emissions. In this imperfectly competitive market, the externality associated to pollution may be considered too high by the government. Frequently-used environmental policies are the introduction of unit emission standards, technology subsidies and product charges.[4] We study the effects of these three policies on unit emissions, on industrial aggregate effluents, and on social welfare.

We first show that a unit emission standard increases industrial aggregate emissions. After this government's intervention both firms offer less-polluting variants, but their reduction in unit emissions results in lower product differentiation. This brings about a tougher market competition stage which reduces prices substantially. The fact that environmentally-friendlier variants are offered at lower prices soar sales sufficiently to offset the positive impact associated to the fall in the unit emissions of both variants, and thus industrial aggregate effluents increase. In spite of the fact that the emission standard increases consumer surplus and firms' profits, it may be undesirable from a social welfare standpoint.

This counter-productive *quantitative* effect does not emerge when firms are offered, instead, a subsidy that lowers technological costs, and, consequently, the unit emissions of both variants. The reason is that product differentiation does not vary, i.e., the policy does not alter the degree of competitiveness in the market. Technological subsidization turns out to be welfare improving. Uniform product charges are shown to have the opposite effects to technology subsidies. Finally we investigate the effects of differentiated product charges. On the one hand, we show that by raising the tax rate of the cleaner variant, both variants' unit effluents as well as industrial aggregate emissions increase. Further, consumer surplus and gross profits fall. Therefore, this measure reduces welfare unambiguously. On the other hand, we show that by increasing the tax rate of the dirtier variant, both variants' unit effluents increase but aggregate pollution decreases. Thus, even though consumer surplus and gross firms' profits are reduced, this policy may be desirable on welfare grounds because it decreases industrial aggregate emissions.

The remainder of the paper is organized as follows. Section 2 describes the model and characterizes the unregulated equilibrium. In Section 4 we explore the effects of unit emissions standards. In Section 5 we analyze uniform and non-uniform product charges while the effects of technological subsidies are studied in Section 6. Section 7 presents concluding remarks.

2. The Model

We present a duopoly model of environmentally differentiated products.[5] The demand side of the market is constituted of a unit continuum of *purchasers* (either consumers or firms) who differ in their marginal valuation θ for the green features of the product. Let e denote the observable per unit level of polluting emissions (environmental wastes or effluents) of the product. The buyer-specific matching value θ is assumed to be uniformly distributed on $[0, \bar{\theta}]$. Purchasers buy either one unit of the product or nothing.[6] If they acquire a variant of the good whose level of emissions is e at price p, they obtain a (indirect) utility $W(\theta, e) = V - \theta e - p$. No consumption is assumed to give zero surplus.[7]

According to this specification, a purchaser that acquires the variant e obtains a gross surplus $V - \theta e$. One possible interpretation is that demand comes from consumers who care seriously about the environment, i.e., *environmentalists*. Then, V would stand for the utility obtained from consuming a single unit of the good regardless of the level of unit emissions of the variant acquired. Environmentalist θ, in addition, derives a desutility θe from purchasing a variant whose level of unit emissions is e.[8] Since θ varies across individuals, environmentalists differ in their environmental awareness. The parameter $\bar{\theta}$ thus measures the maximum *environmental consciousness*.[9] Note that if purchasers were given a free choice between any pair of different variants, they would agree and choose the one with the lowest level of unit emissions. This characteristic implies that our model falls into the category of vertical product differentiation models.

Assume that two firms operate in this market. To produce the variant e, firms must incur the fixed (setup) cost $C(e)$, with $C'(e) < 0$, which implies that producing variants with lower levels of unit emissions is more costly. Further, it is assumed that once a firm has incurred the technological cost needed to ensure the provision of the variant e, production takes place at a unit marginal cost c that is independent of the level of unit effluents chosen by the firm. We normalize c to zero.

Competition between the duopolists takes place in two stages: In the first stage, firms simultaneously decide which variant e to produce. In the second stage, when technological costs have already been invested, firms compete in prices. This two-stage modelling collects the idea that firms can rapidly change their prices while a change in the production technology must take place in the long run. In our context, it is reasonable to assume that environmental (abatement) technology decisions are long-run variables while prices are short-run variables. We will look for the subgame perfect equilibrium of this game and proceed by backwards induction.

The following assumptions, which will be discussed below, are used throughout the analysis.

Assumption 1: *V is sufficiently small so that not all purchasers acquire the good in equilibrium.*

This assumption, which is formalized below, implies that the market is not fully covered in equilibrium, i.e., some purchasers do not acquire any variant at the equilibrium prices.

Assumption 2: *C(e) is assumed to be a homogenous function of degree* $\alpha < -1$

This assumption implies that the technology for the production of the variant e exhibits decreasing returns.

In what follows, we shall analyze the impact of three amply employed environmental policies: First, the imposition of a maximum unit emission standard; second, technology subsidization; and third, taxation by means of product charges. To evaluate and discuss the effects of these distinct environmental measures on welfare grounds, we consider the following (weighted) social welfare function

$$SW = CS + \Pi_T + GR - \gamma E_T \tag{2.1}$$

where (i) *CS* and Π_T denote consumers surplus and aggregate profits respectively, (ii) *GR* denotes either government' revenues obtained from product charges, or government's expenditures to implement the technology subsidization program, and (iii) γE_T denotes the social valuation of environmental damage caused by aggregate pollution E_T. The parameter $\gamma \geq 0$ is the marginal social damage of environmental wastes. The specification adopted here assumes that the shadow cost of public funding is equal to one, i.e., firms' profits are entirely redistributed among the buyers.

Discussion of Assumptions

Some of our assumptions need some clarification. Assumption 1 implies that the market is not fully covered in equilibrium. This modelling choice is in line with the papers mentioned above (see footnote 5) and often justified by casual empirical evidence. If this assumption was not satisfied, the interest of our analysis would be limited because both firms' reaction functions would be independent of the corresponding rivals' choices in the second stage of the game (see footnote 17 below for further implications). There is an alternative formulation that restores the interest of the analysis. This is the modelling alternative adopted in the quality choice models of Crampes and Hollander (1995) and Cremer and Thisse (1999). We could consider a fully covered market situation together with unit-emissions-dependent variable costs. Our main results would not change qualitatively employing this alternative modelling strategy. Indeed we have proved in a model in that spirit that for quadratic variable costs a unit emission standard would result in lower unit emissions of both variants, but in higher sales of the more polluting variant. This latter implication may increase industrial aggregate emissions.[10]

Assumption 2 restricts the analysis to the class of homogeneous cost functions of degree $\alpha < -1$. We require homogeneity for technical convenience. Euler's theorem helps us a great deal when proving our results. To ensure firms' profits maximization throughout the paper, the second order conditions must be satisfied. Given the convex nature of the revenue functions, one needs the cost function to be sufficiently convex, which is ensured by the condition $\alpha < -1$. General results on the existence of equilibrium are difficult to obtain in vertically differentiated models (see the discussion in Lehmann-Grube (1997, p. 374)). The main problems arise when studying stability conditions of a proposed equilibrium. One has to prove that there do not exist incentives to leapfrog rivals' technology choices. Most of the models tackle this issue by assuming quadratic cost functions (Motta 1993). We will also do this but only to prove that the set of models for which an equilibrium exists is not empty. The rest of our results hold true for any homogeneous cost function which is sufficiently convex.

The positive analysis of the various environmental policies follows. We start by characterizing the equilibrium under no regulation. This will serve us as a benchmark for welfare comparisons.

3. The Private Equilibrium

Next we compute the equilibrium under no regulation (benchmark case). Throughout, the firm that chooses a higher (lower) level of unit effluents will be referred to as the *dirtier* (*cleaner*) firm. Without any loss of generality, we consider firm 1 (firm 2) as the dirtier (cleaner) firm, offering a product with unit emissions e_1 (e_2) at price p_1 (p_2). Reasonably, $e_1 > e_2$ and $p_1 < p_2$.[11]

To derive the demand function for each variant, we assume that both variants are sold in the market. We later check that this is indeed true in equilibrium. If this is so, there is one purchaser indifferent between acquiring either of the variants. This buyer is characterized by the taste parameter $\tilde{\theta}$ satisfying $V - \tilde{\theta}e_2 - p_2 = V - \tilde{\theta}e_1 - p1$. Therefore, $\tilde{\theta} = (p_2 - p_1/(e_1 - e_2)$. Assumption 1 implies that there is a purchaser indifferent between buying the cleaner good and nothing. This buyer is identified by the parameter $\hat{\theta} = (V - p_2)/e_2$. It is easy to see that the demand for the dirtier variant stems from the group of consumers whose parameter θ is such that $0 \leq \theta \leq \tilde{\theta}$. Demand for the cleaner variant comes from those customers θ such that $\tilde{\theta} \leq \theta \leq \hat{\theta}$. The rest of purchasers buy nothing.[12] Using the distribution function of θ, the demands for the cleaner and the dirtier variants are easily derived:

$$q_1(\cdot) = \frac{p_2 - p_1}{\bar{\theta}(e_1 - e_2)}, q_2(\cdot) = \frac{V - p_2}{\bar{\theta}e_2} - \frac{p_2 - p_1}{\bar{\theta}(e_1 - e_2)} \tag{3.1}$$

In the second stage, firms simultaneously choose prices to maximize their profits $\Pi_i = p_i q_i - C(e_i), i = 1, 2$. Note that given any two levels of emissions satisfying $e_1 > e_2$, the second stage profit functions are strictly concave with respect to the prices. Therefore, necessary conditions also suffice for profit maximization. By solving the system of first order conditions, we obtain both duopolists' equilibrium prices

$$p_1^*(e_1, e_2) = \frac{V(e_1 - e_2)}{4e_1 - e_2}, p_2^*(e_1, e_2) = \frac{2V(e_1 - e_2)}{4e_1 - e_2}. \tag{3.2}$$

Note that, as expected, $p_2^*(e_1, e_2) > p_1^*(e_1, e_2)$, i.e., the variant with higher unit emissions is offered at a lower price. Observe also that given the prices in (3.2), the inequality $0 \leq \tilde{\theta} < \hat{\theta} < \bar{\theta}$ holds. Assumption 1 amounts to assume that $V/\bar{\theta} < e_2(4e_1 - e_2)/(2e_1 + e_2)$, which guarantees that the market is not fully served.

It is now convenient to define the variable $\lambda = e_1/e_2, \lambda > 1$. This new variable measures the *degree of product differentiation*.[13] We shall refer to λ as the *emissions gap* between the variants. Suppose for the moment that an equilibrium exists (we analyze its existence below in Proposition 3). Then, using the variable λ we can rewrite equilibrium prices as follows:

$$p_1^*(\lambda) = \frac{V(\lambda - 1)}{4\lambda - 1}, p_2^*(\lambda) = \frac{2V(\lambda - 1)}{4\lambda - 1} \tag{3.3}$$

Note that as the emissions gap between the variants diminishes, firms face a tougher price competition stage and equilibrium prices consequently fall ($\partial p_i/\partial\lambda > 0, i = 1, 2$).

Aggregate emissions associated to each variant are given by the product of unit emissions and total sales, i.e., $E_i = q_i e_i, i = 1, 2$. Using (3.3), equilibrium market shares can be written as:

$$q_1(\lambda, e_2) = \frac{V}{\bar{\theta}(4\lambda - 1)e_2}, q_2(\lambda, e_2) = \frac{2\lambda V}{\bar{\theta}(4\lambda - 1)e_2} \tag{3.4}$$

Therefore, aggregate emissions associated to each variant are

$$E_1 = \frac{\lambda V}{\bar{\theta}(4\lambda - 1)}, E_2 = \frac{2\lambda V}{\bar{\theta}(4\lambda - 1)} \tag{3.5}$$

respectively. Observe that the variant with lower unit emissions gives rise to greater aggregate effluents because it sells more. Further, note that aggregate pollution crucially depends on the emissions gap. Indeed, by differentiating, it is obtained that $\partial E_i/\partial\lambda < 0, i = 1, 2$. This means that industrial aggregate emissions increase as the emissions gap decreases. The intuition is that if firms differentiate their products to a lower extent, they face a stronger price competition stage, which consequently lowers equilibrium prices (see (3.3)). As a result, both firms' outputs increase, which soars aggregate emissions. To summarize:

Lemma 1. *Aggregate emissions associated to variant i, i.e., $E_i = q_i e_i, i = 1, 2$ increase as the equilibrium emissions gap between the variants decreases.*

As explained below the equilibrium emissions gap does not depend on V and $\bar{\theta}$ (see equation (3.12)). This enables us to already extract some comparative statics results. First, note that aggregate emissions associated to either of the variants increase as the parameter V rises (see (3.5)). This is simply due to the fact that the size of the active market is larger because environmentalists' willingness-to-pay for the goods is also higher. Second, observe that aggregate emissions decrease as parameter $\bar{\theta}$ increases. This is also reasonable because the higher the average consumers' environmental consciousness, the lower is their average willingness-to-pay for the products. As a result, equilibrium sales are lower and, consequently, aggregate emissions associated to either of the variants are also lower. We summarize next:

Proposition 1. *Equilibrium aggregate emissions associated to either of the variants (a) increase as the valuation of the product V increases, and (b) decrease as the maximum environmental awareness $\bar{\theta}$ increases.*

We next analyze firms' first stage decisions, i.e., the choice of per unit effluents. Anticipating that second stage equilibrium prices will be given by (3.2), the dirtier firm chooses e_1 to maximize

$$\Pi_1(e_1, e_2) = \frac{V^2(e_1 - e_2)}{\bar{\theta}(4e_1 - e_2)^2} - C(e_1), \tag{3.6}$$

and the cleaner firm selects e_2 to maximize

$$\Pi_2(e_1, e_2) = \frac{4V^2 e_1(e_1 - e_2)}{\bar{\theta}(4e_1 - e_2)^2 e_2} - C(e_2). \tag{3.7}$$

Note that both firms would obtain zero revenues if they offered identical variants. To increase revenues (and hence profits), duopolists have an incentive to relax price competition by differentiating their products. This is what actually happens in equilibrium. The first order conditions of both firms' decision problems are:

$$\frac{V^2(4e_1 - 7e_2)}{\bar{\theta}(4e_1 - e_2)^3} - C'(e_1) = 0 \tag{3.8}$$

$$\frac{4V^2 e_1(4e_1^2 - 3e_1e_2 + 2e_2^2)}{\bar{\theta}(-4e_1 + e_2)^3 e_2^2} - C'(e_2) = 0 \tag{3.9}$$

Using λ, we can rewrite conditions (3.8) and (3.9) as:

$$\frac{V^2\lambda^2(4\lambda - 7)}{\bar{\theta}(4\lambda - 1)^3} = -e_1^2 C'(e_1) \tag{3.10}$$

$$\frac{4V^2\lambda(4\lambda^2 - 3\lambda + 2)}{\bar{\theta}(4\lambda - 1)^3} = -e_2^2 C'(e_2) \tag{3.11}$$

Since $C(\cdot)$ is a homogeneous function of degree α, we can divide equations (3.10) and (3.11) to obtain:

$$\frac{(4\lambda - 7)\lambda}{(4\lambda^2 - 3\lambda + 2)} = 4\lambda^{\alpha+1} \tag{3.12}$$

A candidate equilibrium emissions gap is given by the solution to (3.12). Notice that the LHS of this equation is increasing and concave in λ, and approaches 1 as λ goes to infinity. The RHS of (3.12) is a non-decreasing function of λ bounded above 1 for all $\alpha \geq -1$; and a decreasing function of λ converging to zero for all $\alpha < -1$. Therefore, an equilibrium candidate exists for all $\alpha < -1$. This equilibrium candidate is unique. Let $\lambda(\alpha)$ be the solution to equation (3.12). It is easy to see that $\lambda(\alpha) > 1.75$, which ensures that unit effluents are positive. Moreover, $\lambda'(\alpha) > 0$, i.e., the lower the degree of homogeneity of the cost function, the lower is the equilibrium emissions gap. This finding, together with Lemma 1, allows us to state that:

Proposition 2. *Aggregate emissions associated to variant* $i\,(E_i, i = 1, 2)$ *increase as the degree of homogeneity* α *of the cost function* $C(\cdot)$ *falls.*

Note that α measures the degree of convexity of the cost function. The lower parameter α, the more convex is $C(\cdot)$. A lower α implies that firms must incur higher fixed costs in order to differentiate their products. As a consequence, duopolists differentiate their goods to a lower extent in equilibrium, which intensifies price competition and soars the sales of both variants.

In the Appendix we demonstrate that under Assumption 2 the unique solution to the system of equations (3.10), (3.11) and (3.12) satisfies the second order conditions, and that both firms make positive profits. Such a solution constitutes a subgame perfect equilibrium in pure strategies if and only if no firm has an incentive to leapfrog its rival's technological choice. Unfortunately, it is not possible to prove in general that none of the firms has an incentive to exercise leapfrogging (as in Lehmann-Grube 1997). However, for the cost function $C(e) = k/e^2, k > 0$, this is easily shown. The following proposition states the existence of the equilibrium:

Proposition 3. *Under Assumption 2 there is a unique (up to a permutation of firms) subgame perfect equilibrium in pure strategies. The equilibrium emissions gap* λ *is given by equation (3.12), while the equilibrium unit emissions* e_1 *and* e_2 *are given by equations (3.10) and (3.11), respectively. The set of costs functions C(e) for which an equilibrium exists is not empty.*

From equations (3.10) and (3.11), we can obtain additional comparative statics results. Using Euler's theorem and the fact that $\alpha < -1$, it is easily seen that the RHS of equation (3.10) is decreasing in e_1. Analogously, the RHS of expression (3.11) also decreases with e_2. These two facts enable us to state that:

Proposition 4. *Equilibrium unit emissions of both variants* ($e_i, i = 1, 2$) *(a) decrease as the valuation of the product (V) increases, and (b) increase as the maximum environmental awareness* ($\bar{\theta}$) *increases.*

The interest of this result is that it suggests that lower unit emissions are associated to products whose consumption yields substantial gains to the consumers. After all, lower unit emissions are here associated to greater technological investments, which are only possible when buyers' willingness-to-pay $V - \theta e$ is sufficiently large.

Finally, consumers' surplus, aggregate profits, and industrial aggregate emissions can be written as follows:

$$CS = \frac{V^2\lambda(4\lambda + 5)}{2\bar{\theta}(4\lambda - 1)^2 e_2}, \tag{3.13}$$

$$\Pi_T = \frac{V^2(4\lambda + 1)(\lambda - 1)}{\bar{\theta}(4\lambda - 1)^2 e_2} - C(e_1) - C(e_2), \tag{3.14}$$

$$E_T = \frac{3V\lambda}{4\lambda - 1}. \tag{3.15}$$

We shall use these expressions to evaluate the impact of various environmental policies on social welfare. We begin with the imposition of a maximum unit emission standard.

4. Unit Emission Standards

The literature has proposed several restrictions in the form of environmental standards to control pollution. The government can impose either design or technological standards, or restrictions either on the quantity produced or on the level of effluents (see e.g. Besanko (1987)). In the real world, standards in the form of input content or unit emissions are often used as a form of environmental regulation because they neither involve the high administrative costs associated to quantity restrictions, nor the observability problems associated with controlling aggregate effluents (see Hanley et al. 1997). Here we focus on technological standards in the form of *unit emission standards*.

Let $\bar{e}$ denote the unit emission standard and consider the no-regulation benchmark case analyzed previously (equations (3.10), (3.11) and (3.12)). Since an emission standard set above the level of unit emissions of firm 1's variant (e_1) would not have any effect on the previous unregulated equilibrium, we only consider standards set below e_1.[14] In the regulated equilibrium, the firm producing the variant with higher unit emissions meets the requirement and the cleaner firm chooses unit emissions by best-responding to its rival's choice (the standard). Thus,

$$e_1 = \bar{e} \tag{4.1}$$

and e_2 must satisfy[15]

$$\frac{-4V^2\bar{e}(4\bar{e}^2 - 3\bar{e}e_2 + 2e_2^2)}{\bar{\theta}(4\bar{e} - e_2)^3 e_2^2} - C'(e_2) = 0 \tag{4.2}$$

It is useful to analyze the sign of the derivative

$$\frac{de_2}{d\bar{e}} = \frac{\frac{8V^2(5\bar{e}+e_2)}{\bar{\theta}(4\bar{e}-e_2)^4}}{\frac{8V^2\bar{e}(16\bar{e}^3-16\bar{e}^2e_2+6\bar{e}e_2^2-3e_2^3)}{\bar{\theta}e_2^3(4\bar{e}-e_2)^4} - C''(e_2)}. \tag{4.3}$$

Note that the denominator of this expression is nothing else than the second order condition of firm 2's maximization problem, whose sign is negative as demonstrated in the Appendix (see equation (7.2)). Since the numerator is clearly positive, we conclude that:

Lemma 2. *After imposing a unit emission standard which is met by firm 1, firm 2 best-responses by reducing its unit effluents as well.*

The direct implication of this result is that the imposition of a unit emission standard is a proper policy to reduce both variants' unit effluents.[16] The intuition stems from the fact that firms differentiate their products to avoid a tougher price competition stage (see (3.3)). Thus, anticipating that firm 1 will reduce its unit emissions to meet the standard, the best strategy for firm 2 is to reduce its unit emissions as well.

By using variable λ, we can describe the (new) equilibrium by the following equations:

$$e_2 = \frac{\bar{e}}{\lambda} \tag{4.4}$$

$$\frac{-4V^2\lambda^3(4\lambda^2 - 3\lambda + 2)}{\bar{\theta}(4\lambda - 1)^3\bar{e}^2} - \frac{C'(\bar{e})}{\lambda^{\alpha-1}} = 0. \tag{4.5}$$

Equation (4.5) gives an implicit relationship between the equilibrium product differentiation λ and the unit emissions standard imposed $\bar{e}$. By employing the implicit function and the Euler's theorems, we can write

$$\frac{d\lambda}{d\bar{e}} = \frac{\bar{e}(\alpha + 1)C'(\bar{e})\bar{\theta}(4\lambda - 1)^4}{4V^2\lambda^{\alpha+1}(\alpha(16\lambda^3 - 16\lambda^2 + 11\lambda - 2) + 16\lambda^3 - 16\lambda^2 + \lambda - 4)}. \tag{4.6}$$

Since $\alpha < -1$, the numerator of this expression is positive. Thus, $d\lambda/d\bar{e}$ has positive sign whenever $\Gamma(\lambda, \alpha) = \alpha(16\lambda^3 - 16\lambda^2 + 11\lambda - 2) + 16\lambda^3 - 16\lambda^2 + \lambda - 4 < 0$. We can use the equilibrium equation (3.12) to obtain the relationship between α and λ:

$$\alpha = \frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda}.$$

Using this expression, we have that $d\lambda/d\bar{e}$ has positive sign whenever

$$\Gamma(\lambda) = \frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda}(16\lambda^3 - 16\lambda^2 + 11\lambda - 2) + 16\lambda^3 - 16\lambda^2 + \lambda - 4 < 0. \tag{4.7}$$

It is easily checked that this expression is negative. Therefore:

Lemma 3. *Emissions gap λ decreases after imposing a unit emission standard.*

The intuition goes as follows. As a result of the mandated standard, firm 1 diminishes its unit effluents, which reduces product differentiation and fosters price competition. To alleviate the effects of the tougher market interaction, the cleaner firm decreases its unit emissions as well. However, due to the fact that technology exhibits decreasing returns, firm 2's effort to reduce unit effluents is lower than firm 1's effort. As a result, after-policy equilibrium product differentiation falls.

Taking into consideration the impact of this policy on product differentiation, and hence on prices, firms' sales, and purchasers' allocation in the market, we can state one of our main results:[17]

Proposition 5. *Industrial aggregate emissions increase after imposing a maximum unit emission standard.*

The proof follows immediately from Lemmas 1 and 3. The key issue here is that the decrease in the emissions gap fosters price competition and, therefore, firms' equilibrium prices fall. The fact that environmentally cleaner variants are offered at lower prices soars firms' sales sufficiently so as to increase aggregate pollution, in spite of the fall in unit emissions. This result has important implications when evaluating the desirability (from a social welfare viewpoint) of unit emission standards to control pollution in differentiated markets as we shall see below.

THE EFFECTS OF UNIT EMISSION STANDARDS ON SOCIAL WELFARE

To study the impact of unit emission standards on social welfare, note that the relevant expression for social welfare is $SW = CS + \Pi_T - \gamma E_T$, with $\gamma \geq 0$. Proposition 5 implies that a unit emission standard can only be desirable on welfare grounds if it increases consumers surplus and/or aggregate firms' profits. Taking the expression for consumer surplus in (3.13), we can compute

$$\frac{dCS}{d\bar{e}} = \frac{V^2(28\lambda + 5)}{2\bar{\theta}e_2(4\lambda - 1)^3}\frac{d\lambda}{d\bar{e}} - \frac{V^2\lambda(4\lambda + 5)}{2\bar{\theta}e_2^2(4\lambda - 1)^2}\frac{de_2}{d\bar{e}}.$$

Note that $d\lambda/d\bar{e} > 0$ and $de_2/d\bar{e} > 0$ (Lemmas 2 and 3). Therefore $dCS/d\bar{e} < 0$, which means that consumer surplus increases after imposing a unit emissions standard. Consumers clearly benefit from the policy not only because it results in lower unit emissions but also because both variants are offered at lower prices.

Firms' aggregate profits (see (3.14)) can be written as

$$\Pi_T = \frac{V^2(4\lambda^2 - 3\lambda - 1)\lambda}{\bar{\theta}(4\lambda - 1)^2\bar{e}} - C(\bar{e}) - C(\frac{\bar{e}}{\lambda}).$$

Taking derivatives with respect to the unit emissions standard one obtains:

$$\frac{d\Pi_T}{d\bar{e}} = \left[\frac{V^2(16\lambda^3 - 12\lambda^2 + 10\lambda + 1)}{\bar{\theta}\bar{e}(4\lambda - 1)^3} + C'\left(\frac{\bar{e}}{\lambda}\right)\frac{\bar{e}}{\lambda^2}\right]\frac{d\lambda}{d\bar{e}} - \frac{V^2\lambda(4\lambda^2 - 3\lambda - 1)}{\bar{\theta}\bar{e}^2(4\lambda - 1)^2} - C'\left(\frac{\bar{e}}{\lambda}\right)\frac{1}{\lambda} - C'(\bar{e})$$

We can employ equation (4.2) to substitute

$$C'(\bar{e}/\lambda) = \frac{-4V^2\lambda^3(4\lambda^2 - 3\lambda + 2)}{\bar{\theta}\bar{e}^2(4\lambda - 1)^3}$$

in the above expression:

$$\frac{d\Pi_T}{d\bar{e}} = \frac{V^2(2\lambda + 1)^3}{\bar{\theta}\bar{e}(4\lambda - 1)}\frac{d\lambda}{d\bar{e}} + \frac{V^2\lambda(4\lambda^2 - 3\lambda - 1)}{\bar{\theta}\bar{e}^2(4\lambda - 1)^3} - C'(\bar{e}) \tag{4.8}$$

Since $d\lambda/d\bar{e} > 0$, the first term of (4.8) is positive. The second term is also positive. Since $C'(\bar{e}) < 0$, we conclude that $d\Pi_T/d\bar{e} > 0$. Therefore, equilibrium industry profits decrease after the introduction of a unit emission standard.

Some more algebra shows that the increase in consumer surplus more than compensates for the decrease in industry equilibrium profits. As a result total market surplus increases after the introduction of a unit emission standard. Define $\bar{\gamma}$ as the solution to $\gamma = (dCS/d\bar{e} + d\Pi_T/d\bar{e})/(dE_T/d\bar{e})$. Then:

Proposition 6. *A unit emission standard (i) increases consumer surplus, (ii) decreases firms profits, and (iii) decreases social welfare for all* $\gamma > \bar{\gamma}$.

This result shows that maximum emission standards may be undesirable on welfare grounds when the social concern for aggregate pollution is sufficiently large. In spite of the fact that a unit emission standard lowers both variants' unit emissions, it may be detrimental from a social viewpoint because it induces a price war sufficiently strong that boosts firms' sales and thus industrial aggregate emissions.

5. Product Charges

Special charges are often levied on polluting products to influence firms' behavior, aiming at either reducing the quantity produced, or at decreasing the amount of unit effluents. By imposing a charge directly on the product or input that causes environmental damage, the regulation avoids the information problems associated with first-best schemes such as emission or ambient charges. This is the case of Sweden and Norway, where product charges are applied to batteries, fertilizers and pesticides. Tobacco, fossil-fuels and cars, are other examples of goods facing special charges in European countries. Moreover, current government agendas include eco-taxes for energy production and product packaging (e.g., Italy levies a tax on plastic bags).[18]

Consider that an ad-valorem charge t_i is imposed on firm i, $i = 1, 2$. Firm i's profit is then given by:

$$\pi_i = (1 - t_i)p_i q_i - C(e_i), i = 1, 2 \tag{5.1}$$

We define $\tau_i = 1/(1 - t_i)$ as the tax burden of firm i. Note first that $\tau_i \geq 1$ defines a tax ($0 \leq t_i \leq 1$) while $\tau_i \leq 1$ defines a subsidy ($t_i \leq 0$). Besides, observe that by setting $\tau_1 = \tau_2 = 1$, we obtain the unregulated equilibrium analyzed above. As before we prove our results using derivatives; therefore, we concentrate the analysis on small charges. Multiplying (5.1) by τ_i, we obtain:

$$\tau_i \pi_i = p_i q_i - \tau_i C(e_i), i = 1, 2. \tag{5.2}$$

The following observations are useful in helping explain the intuition behind our results. A firm's optimal strategy facing the tax t_i and the cost function $C(e_i)$ is equal to its optimal strategy when it is not taxed at all and the cost function is $\tau_i C(e_i)$. Note also that, for any pair (e_1, e_2), equilibrium prices under emission charges are the same as those under no regulation, i.e., the prices in (3.3).

Given equilibrium prices, firms' choices of unit emissions are given by the equations:

$$\frac{V^2(4\lambda - 7)\lambda}{\bar{\theta}(4\lambda - 1)^3 e_2 \tau_1} = -C'(e_1)e_1 \tag{5.3}$$

$$\frac{4V^2\lambda(4\lambda^2 - 3\lambda + 2)}{\bar{\theta}(4\lambda - 1)^3 e_2 \tau_2} = -C'(e_2)e_2 \tag{5.4}$$

By dividing these two equations, we obtain that

$$\mu = \frac{4\lambda - 7}{4\lambda^{\alpha}(4\lambda^2 - 3\lambda + 2)}, \tag{5.5}$$

where the parameter $\mu = \tau_1/\tau_2$ measures the difference in charges of the variants. Interestingly, if $\tau_1 = \tau_2$, then $\mu = 1$ and equations (3.12) and (5.5) coincide. This implies that equilibrium emissions gap does not change whenever both firms charges are identical. We can differentiate (5.5) to obtain

$$\frac{d\lambda}{d\mu} = \frac{-4(4\lambda^2 - 3\lambda + 2)\lambda^{\alpha}}{4[1 - \lambda^{\alpha}\mu(8\lambda - 3 + (4\lambda^2 - 3\lambda + 2)\frac{\alpha}{\lambda})]} \tag{5.6}$$

Using (5.5) to substitute λ^{α} in this expression we obtain:

$$\frac{d\lambda}{d\mu} = \frac{1}{\mu(\frac{4}{4\lambda - 7} - \frac{\alpha}{\lambda} - \frac{8\lambda - 3}{4\lambda^2 - 3\lambda + 2})} \tag{5.7}$$

Evaluating this derivative in a neighborhood of the unregulated equilibrium, i.e., where $\mu = 1$ and (α, λ) satisfy equation (3.12), it is obtained that $d\lambda/d\mu > 0$. Therefore:

Lemma 4. *(a) If the charge on firm 1 raises, equilibrium emissions gap increases. (b) If the charge on firm 2 increases, equilibrium emissions gap decreases. (c) If both firms' charges increase proportionally, equilibrium emissions gap remains constant.*

5.1. UNIFORM COMMODITY TAXATION

Consider first that both firms charges are identical, i.e., $\tau_1 = \tau_2 = \tau$. A uniform tax rate can be in place due to possible legal constraints impeding charge rate differentiation among firms selling different variants of the same product. An illustrative example of this policy is the green point charge in Spain, where all types of market containers face a common charge associated to the product value.

Using (5.3) and (5.4), it is readily seen that

$$\frac{de_i}{d\tau} = \frac{-e_i}{\tau(\alpha + 1)} > 0; i = 1, 2; \tag{5.8}$$

Equation (5.8) and Lemmas 1 and 4 allow us to state that:

Proposition 7. *A uniform ad-valorem product charge (i) increases both variants' unit emissions and (ii) does not affect industrial aggregate emissions.*

The economic explanation is that even though unit emissions increase as a result of uniform taxation, firms end up selling fewer units. These two effects work in opposite directions and it turns out that they offset each other. As a result, aggregate effluents do not change with the intervention. In a model of environmental-quality choice, Arora and Gangopadhyay (1995) obtain a result similar to (i) in Proposition 7.

The Impact of Uniform Product Charges on Social Welfare

Recall the relevant measure of social welfare in (2.1). Notice that as τ raises, λ does not change while e_2 increases. It thus follows that consumer surplus in (3.13) decreases. On the other hand, gross industry profits, $\Pi_T + GR_T$, are given by

$$\Pi_T^{gross} = \frac{V^2(4\lambda + 1)(\lambda - 1)}{\bar{\theta} e_2 (4\lambda - 1)^2} - C(e_1) - C(e_2). \tag{5.9}$$

From (5.8) it follows that the first summand of this expression falls with τ. Since $C'(\cdot) < 0$, costs also decrease with τ; therefore, finding the sign of $d\Pi_T^{gross}/d\tau$ requires to see which of these effects dominates. Using the Euler's theorem and equations (5.3) and (5.4) we can rewrite gross industry profits as

$$\Pi_T^{gross} = \frac{V^2(4\lambda + 1)(\lambda - 1)}{\bar{\theta} e_2 (4\lambda - 1)^2} + \frac{V^2\lambda(4\lambda - 7)}{\alpha\bar{\theta}\tau e_2(4\lambda - 1)^3} + \frac{4V^2\lambda(4\lambda^2 - 3\lambda + 2)}{\alpha\bar{\theta}\tau e_2(4\lambda - 1)^3}.$$

Rearranging terms we obtain:

$$\Pi_T^{gross} = \frac{V^2}{\bar{\theta} e_2 (4\lambda - 1)^3} \left[(4\lambda - 1)(4\lambda + 1)(\lambda - 1) + \frac{\lambda(4\lambda - 7) + 4\lambda(4\lambda^2 - 3\lambda + 2)}{\alpha\tau} \right].$$

In the Appendix we show that an increase in τ increases gross industry profits because cost savings offset the fall in gross revenues. Taking into consideration the impact on consumer surplus and that on gross profits together one can state that (see Appendix):

Proposition 8. *A uniform product charge decreases consumers' surplus, raises gross industry profits, does not alter aggregate emissions, and reduces social welfare.*

It is worth to observe that this policy might be welfare enhancing if the shadow cost of public funding were sufficiently high.

5.2. NON-UNIFORM PRODUCT CHARGES

Given that a uniform charge does not affect aggregate emissions in our model, we next investigate the effects of tax differentiation in this market. This is the case, for example, of fuels in most European countries, where unleaded fuel often faces lower tax rates.

We analyze the incidence of non-uniform product charges in a neighborhood of the benchmark case. The impact of a charge levied on variant 1 on the unit emissions of variant 2 is given by:

$$\frac{de_2}{d\tau_1} = \frac{\partial e_2}{\partial \lambda}\frac{\partial \lambda}{\partial \tau_1}$$

In the Appendix we show that $\partial e_2/\partial\lambda > 0$, and from Lemma 4 it follows that $\partial\lambda/\partial\tau_1 > 0$. Therefore $de_2/d\tau_1 > 0$. Since $e_1 = \lambda e_2$ and $\partial\lambda/\partial\tau_1 > 0$, it follows that $de_1/d\tau_1 > 0$.

Similarly we can compute the impact of a charge levied on variant 2 on the unit emissions of variant 1:

$$\frac{de_1}{d\tau_2} = \frac{\partial e_1}{\partial \lambda}\frac{\partial \lambda}{\partial \tau_2}$$

The Appendix also shows that $\partial e_1/\partial\lambda < 0$ and from Lemma 4 it follows that $\partial\lambda/\partial\tau_2 < 0$. Therefore $de_1/d\tau_2 > 0$. Since $e_2 = e_1/\lambda$ and $\partial\lambda/\partial\tau_2 < 0$, it follows that $de_2/d\tau_2 > 0$. Taking into account the impact of τ_1 and τ_2 on λ and how the latter affects aggregate emissions we can state that:

Proposition 9. *Starting from the benchmark case of no-regulation:*
(1) A charge on variant 1 (i) raises both variants' unit emissions, and (ii) reduces industrial aggregate effluents.
(2) A charge on variant 2 (i) increases both variants' unit emissions, and (ii) raises industrial aggregate effluents.

Interestingly, this Proposition illustrates that (i) an increase (decrease) of the charge levied on variant 1 and (ii) a decrease (increase) of the charge levied on variant 2 have similar effects on aggregate pollution. Indeed, both policies diminish (raise) total emissions.

The effects of Nonuniform Product Charges on Social Welfare

From (3.13), it follows that changes in consumers surplus are given by:

$$\frac{dCS}{d\tau_i} = \frac{\partial CS}{\partial e_2}\frac{\partial e_2}{\partial \tau_i} + \left(\frac{\partial CS}{\partial e_2}\frac{\partial e_2}{\partial \lambda} + \frac{\partial CS}{\partial \lambda}\right)\frac{\partial \lambda}{\partial \tau_i}; i = 1, 2. \tag{5.10}$$

In the Appendix we show that consumer surplus decreases with τ_1 and τ_2. It is intuitive that $dCS/d\tau_1 < 0$, since a charge levied on variant 1 raises both variants' unit emissions and alleviates firms' competition. A charge levied on variant 2 also increases both variants' unit emissions but, in contrast, increases competition between the firms. It turns out that the first (negative) effect offsets the second (positive) effect.

Second, firms' gross profits are given by (5.9). Using the Euler's theorem and equations (5.3) and (5.4) we can write

$$\Pi_T^{gross} = \frac{V^2}{\bar{\theta}(4\lambda - 1)^3 e_2}\left[(4\lambda - 1)(\lambda - 1)(1 + 4\lambda) + \frac{\lambda(4\lambda - 7)}{\alpha\tau_1} + \frac{4\lambda(4\lambda^2 - 3\lambda + 2)}{\alpha\tau_2}\right].$$

Then, the impact of non-uniform product charges on aggregate gross profits is given by

$$\frac{d\Pi_T^{gross}}{d\tau_i} = \frac{\partial \Pi_T^{gross}}{d\tau_i} + \left(\frac{\partial \Pi_T^{gross}}{\partial e_2}\frac{\partial e_2}{\partial \lambda} + \frac{\partial \Pi_T^{gross}}{\partial \lambda}\right)\frac{\partial \lambda}{\partial \tau_i}, i = 1, 2 \tag{5.11}$$

We show in the Appendix that $d\Pi_T^{gross}/d\tau_1 > 0$ while $d\Pi_T^{gross}/d\tau_2 < 0$. Let us define $\hat{\gamma}$ as the solution $\gamma = (dCS/d\tau_1 + d\Pi_T^{gross}/d\tau_1)/(dE_T/d\tau_1)$. Then, taking into account Lemmas 1 and 4, we can state that:

Proposition 10. *(a) A charge on variant 1 decreases consumer surplus, raises gross profits and lowers industrial aggregate emissions. Therefore, social welfare decreases for all $\gamma < \hat{\gamma}$.*
(b) A charge on variant 2 decreases consumer surplus and gross profits, and increases aggregate emissions. Therefore, social welfare decreases.

Note that these results are particularly interesting because they show that the impact of non-uniform taxation is sensitive to the type of product being taxed. A tax on variant 1 is less distortionary because it increases gross profits and reduces aggregate emissions. From the point of view of a regulator concerned about pollution, an increase in the charge of the cleaner variant is always undesirable; by contrast, an increase in the charge of the dirtier variant may be desirable on welfare grounds when the social concern about aggregate emissions is sufficiently high. Again, these results would be less dramatic if the shadow cost of public funding were sufficiently high.

6. Technology Subsidization

In addition to unit emission standards and product charges, direct subsidies on technological costs are widely used to impel firms' investments in abatement technology, or to mitigate the economic impact of compliance with other regulatory measures. The subsidization of technological acquisition results in lower capital costs through, generally, cheaper loans, or grants. For instance, France offer loans to control water pollution; Italy favors industries that commit themselves to introduce production processes that recuperate and recycle solid wastes; The Netherlands offers financial assistance to promote compliance with regulation, technology research and the introduction of pollution control; Sweden uses subsidies to diminish pesticide sprays (see Hanley et al. 1997). Generally, technology subsidies do not depend on emissions' reduction but on firms' investment. Indeed, most of government's financial aids to environmental investments are not subject to pollution abatement levels. That is the case for example in the PITMA program of the Spanish Ministry of Industry and Trade since 1991, or the US subsidies to construct water treatment plants and encourage soil conservation efforts of farmers.[19]

Consider that the industry we have described benefits from a subsidization policy that reduces abatement costs. Let the subsidized cost function be

$$C_i = (1-s)C(e_i) i = 1, 2 \tag{6.1}$$

The analysis of the incidence of subsidization is straightforward after noting that a technological subsidy has exactly the opposite impact as compared to a uniform product charge. To see this, notice that firm i's profit is given by:

$$\pi_i = p_i q_i - (1-s)C(e_i), i = 1, 2. \tag{6.2}$$

Dividing (6.2) by $1 - s$, we obtain:

$$\pi_i/(1-s) = p_i q_i/(1-s) - C(e_i), i = 1, 2, \tag{6.3}$$

which can be rewritten as

$$\tau\pi_i = \tau p_i q_i - C(e_i), i = 1, 2$$

where $\tau = 1/(1-s)$. As noted above, a firm's optimal strategy facing the cost function $(1-s)C(e)$ is equal to its optimal strategy when it is taxed such that $\tau = 1/(1-s)$ and faces the cost function $C(e)$. Therefore, basing upon the previous analysis on uniform product charges, the impact of s is the following:

Proposition 11. *A direct subsidy on abatement investment (a) reduces unit emissions and (b) has no impact on the equilibrium aggregate effluents. As to the* *welfare consequences, it increases consumers surplus and gross profits of the firms. Therefore, social welfare increases.*

In line with the case of uniform taxes, the welfare increase brought about by technology subsidization is sensitive to the assumption that the shadow cost of public funding is sufficiently low.

7. Concluding Remarks

In this paper we have examined the impact of various environmental policy instruments on aggregate emissions and social welfare in a duopolistic market where purchasers are willing to pay more for less polluting variants. The equilibrium is characterized by the co-existence of two different variants of the good in question, one more polluting than the other. Our results demonstrate that aggregate emissions may increase as a result of government's regulation due to the strategic responses of the firms. More precisely, in our model aggregate effluents increase after setting a unit emission standard, and after imposing a product charge to the variant with lower unit emissions. This counter-productive results are essentially due to the fact that even though firms reduce their variants' unit emissions as a result of regulation, they have to compete so vigorously that sales of the (still) polluting goods soar. As industrial aggregate emissions increase, environmental policies may result in social welfare losses. Our findings suggest that environmental policy in green markets must take into consideration not only its effects on the products' environmental features but also its implications on the consumers' allocation between the firms. To the best of our knowledge, this issue has not been pointed out by the literature so far.

The impact of other policy instruments such as Pigouvian taxes and marketable pollution permits on aggregate emissions in this type of markets remains to be investigated. Of particular interest are first-best schemes such as Pigouvian taxes. Since these charges are imposed directly on aggregate effluents, its efficacy to abate pollution may be granted. However, the strategic responses of the firms may require the use of large taxes, which may enhance the typical quantity distortion introduced by duopolists. Even though Pigouvian taxes introduce greater complexity in this type of models, it may be worthwhile to clarify its desirability on welfare grounds. We leave the analysis of these issues for further research.

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Appendix

PROOF OF PROPOSITION 3:

We first prove that the second order conditions of the firms' maximization problems are verified, i.e., it must be the case that

$$\frac{\partial^2 \Pi_1}{\partial e_1^2} = \frac{16V^2(2e_1 - 5e_2)}{\bar{\theta}(4e_1 - e_2)^4} - C''(e_1) < 0 \tag{7.1}$$

and

$$\frac{\partial^2 \Pi_2}{\partial e_2^2} = \frac{8V^2 e_1(16e_1^3 - 16e_1^2 e_2 + 6e_1 e_2^2 - 3e_2^3)}{\bar{\theta} e_2^3 (4e_1 - e_2)^4} - C''(e_2) < 0. \tag{7.2}$$

Using Euler's theorem and equation (3.8), equation (7.1) can be rewritten as

$$\frac{\partial^2 \Pi_1}{\partial e_1^2} = \frac{16V^2(2e_1 - 5e_2)}{\bar{\theta}(4e_1 - e_2)^4} + \frac{(\alpha - 1)V^2(4e_1 - 7e_2)}{\bar{\theta} e_1 (4e_1 - e_2)^3}. \tag{7.3}$$

Rearranging and using the variable λ, this expression can be reduced to

$$\frac{\partial^2 \Pi_1}{\partial e_1^2} = \frac{V^2(16\lambda(2\lambda - 5) + (\alpha - 1)(4\lambda - 7)(4\lambda - 1))}{\bar{\theta}\lambda(4\lambda - 1)^4 e_2^3} \tag{7.4}$$

which has negative sign whenever $\Psi(\lambda, \alpha) = 16\lambda(2\lambda - 5) + (\alpha - 1)(4\lambda - 7)(4\lambda - 1) < 0$. We can take logarithms in the equilibrium equation (3.12) to isolate α:

$$\alpha = \frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda}$$

Plugging α into the previous inequality we obtain

$$\Psi(\lambda) = 16\lambda(2\lambda - 5) + \left(\frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda} - 1 \right)(4\lambda - 7)(4\lambda - 1). \tag{7.5}$$

It is easy to check that $\Psi(\lambda)$ is a negative continuously decreasing function for all $\lambda > 1.75$. Therefore, the second order condition of the dirtier firm's maximization problem is always satisfied.

Proceeding analogously, the second order condition of the cleaner firm's maximization problem (7.2) can be rewritten as

$$\frac{\partial^2 \Pi_1}{\partial e_1^2} = \frac{4\lambda V^2(32\lambda^3 - 32\lambda^2 + 12\lambda - 6 + (\alpha - 1)(4\lambda - 1)(4\lambda^2 - 3\lambda + 2))}{\bar{\theta}(4\lambda - 1)^4 e_2^3} \tag{7.6}$$

This expression is negative whenever $\Phi(\lambda, \alpha) = 32\lambda^3 - 32\lambda^2 + 12\lambda - 6 + (\alpha - 1)(4\lambda - 1)(4\lambda^2 - 3\lambda + 2) < 0$. By using (3.12) again, this inequality reduces to

$$\Psi(\lambda) = 32\lambda^3 - 32\lambda^2 + 12\lambda - 6 + \left(\frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda} - 1 \right) (4\lambda - 1)(4\lambda^2 - 3\lambda + 2) \tag{7.7}$$

It is easy to see that $\Phi(\lambda) < 0$ for all $\lambda > 1.75$. Therefore, the cleaner firm's second order condition is satisfied too.

We now check that both firms obtain positive profits in equilibrium. Consider first the profits obtained by the firm producing the dirtier variant, given by (3.6). Using Euler's theorem and properly rearranging, firm 1's benefits can be rewritten as

$$\Pi_1 = \frac{V^2(\alpha(4\lambda - 1)(\lambda - 1) + \lambda(4\lambda - 7))}{\bar{\theta}\alpha(4\lambda - 1)^3 e_2} \tag{7.8}$$

This expression is positive as long as $F(\lambda, \alpha) = \alpha(4\lambda - 1)(\lambda - 1) + \lambda(4\lambda - 7) < 0$. Using (3.12) we have

$$F(\lambda) = \frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda}(4\lambda - 1)(\lambda - 1) + (4\lambda - 7). \tag{7.9}$$

It is easily checked that $F(\lambda) < 0$ for all $\lambda > 1.75$. Therefore, firm 1 obtains positive profits in equilibrium.

Consider now the profits obtained by the firm producing the cleaner variant, given by (3.7). This profits expression can be rewritten as

$$\Pi_2 = \frac{4\lambda V^2(\alpha(4\lambda - 1)(\lambda - 1) + 4\lambda^2 - 3\lambda + 2)}{\bar{\theta}\alpha(4\lambda - 1)^3 e_2} \tag{7.10}$$

This expression has a positive sign as long as $\Omega(\lambda, \alpha) = \alpha(4\lambda - 1)(\lambda - 1) + 4\lambda^2 - 3\lambda + 2) < 0$. By using (3.12) again, this inequality reduces to

$$\Omega(\lambda) = \frac{\ln \frac{4\lambda - 7}{4(4\lambda^2 - 3\lambda + 2)}}{\ln \lambda}(4\lambda - 1)(\lambda - 1) + 4\lambda^2 - 3\lambda + 2 < 0, \tag{7.11}$$

which is satisfied for all $\lambda > 1.75$. Therefore, firm 2's profits are positive.

Finally, we show that for the cost function $C(e) = k/e^2$, neither of the firms has an incentive to leapfrog its rival's choice. If this is so, the set of cost functions for which an equilibrium exists is not empty. For this particular cost function, the equilibrium given by the solution to equations (3.8), (3.9) and (3.12) is as follows:

$$\lambda^* \simeq 5.25123;\ e_1^* \simeq 41.461k\bar{\theta}/V^2;\ e_2^* \simeq 7.89544k\bar{\theta}/V^2$$

Suppose first that firm 2 chooses e_2^* and that firm 1 deviates by choosing some $e_1 < e_2^*$. Then, in the second stage, since product choices are observed before firms set their prices, firm 2 will optimally fix price p_1 in equation (3.2), while firm 1 will set price p_2 in (3.2). The profits firm 1 obtains from such a deviation are given by

$$\hat{\Pi}_1(e_1 < e_2^*, e_2^*) = \frac{4V^2 e_2^*(e_2^* - e_1)}{\bar{\theta}(4e_2^* - e_1)^2 e_1} - C(e_1). \tag{7.12}$$

For $C(e) = k/e^2$, we have

$$\hat{\Pi}_1(e_1, e_2^*) = \frac{31.5818kV^2(7.89544k\bar{\theta} - e_1V^2)}{e_1(31.5818k\bar{\theta} + e_1V^2)^2} - \frac{k}{e_1^2}. \tag{7.13}$$

The unique maximizer of this expression satisfying $e_1 > e_2^*$ and the second order condition is $\hat{e}_1 = 5.95014k\bar{\theta}/V^2$, which gives profits $\hat{\Pi}_1 = -0.00271284V^8/k\bar{\theta}^{-4} < 0$. Therefore, firm 1 has no incentives to leapfrog firm 2's choice.

Suppose secondly that firm 1 chooses e_2^* and that firm 2 deviates by choosing some $e_2 > e_1^*$. Then, as above, firm 2 will optimally fix price p_1 in equation (3.2), while firm 1 will set price p_2. The profits obtained by firm 2 from such a deviation are given by

$$\hat{\Pi}_2(e_1^*, e_2 > e_1^*) = \frac{V^2(e_2 - e_1^*)}{\bar{\theta}(4e_2 - e_1^*)^2} - C(e_2). \tag{7.14}$$

For the case under consideration we have

$$\hat{\Pi}_2(e_1^*, e_2) = \frac{0.0241192V^4(0.0241192e_2V^2 - k\bar{\theta})}{\bar{\theta}(k\bar{\theta} - 0.0964767e_2V^2)^2} - \frac{k}{e_2^2} \tag{7.15}$$

The only maximizer of this expression satisfying $e_2 > e_1^*$ and the second order condition is $\hat{e}_2 = 95.2009k\bar{\theta}/V^2$, which gives profits $\hat{\Pi}_2 = 0.00356346V^4/k\bar{\theta}^2$. These benefits are clearly lower than equilibrium profits, which can be shown to be equal to $\Pi_2^* = 0.0122193V^4/k\bar{\theta}^2$. Therefore, firm 2 does not have incentives to leapfrog firm 1's choice. The proof of Proposition 3 is now complete. ■

PROOF OF PROPOSITION 8:

Recall that gross profits are given by

$$\Pi_T^{gross} = \frac{V^2}{\bar{\theta}e_2(4\lambda - 1)^3} \left[(4\lambda - 1)(4\lambda + 1)(\lambda - 1) + \frac{\lambda(4\lambda - 7) + 4\lambda(4\lambda^2 - 3\lambda + 2)}{\alpha\tau}\right]$$

Then we have that the sign of $d\Pi_T^{gross}/d\tau$ equals the sign of the following expression:

$$\frac{1}{\tau e_2(\alpha + 1)} \left[(4\lambda - 1)(4\lambda + 1)(\lambda - 1) + \frac{\lambda(4\lambda - 7) + 4\lambda(4\lambda^2 - 3\lambda + 2)}{\alpha\tau}\right]$$
$$\frac{1}{e_2} \frac{\lambda(4\lambda - 7) + 4\lambda(4\lambda^2 - 3\lambda + 2)}{\alpha\tau^2}$$

The sign of this expression reduces to the sign of

$$-(4\lambda - 1)(4\lambda + 1)(\lambda - 1) + \frac{\lambda(4\lambda - 7) + 4\lambda(4\lambda^2 - 3\lambda + 2)}{\tau},$$

which is clearly positive in a neighborhood of the benchmark case, i.e., where $\tau = 1$ and (α, λ) satisfy (3.12). Therefore gross profits increase with the imposition of a small uniform ad valorem tax.

We now compare the joint impact of a uniform tax on consumer surplus and gross profits:

$$\begin{aligned}\frac{d(CS + \Pi_T^{gross})}{d\tau} &= \frac{V^2}{\bar{\theta}\tau(\alpha + 1)(4\lambda - 1)^3 e_2}\left[\frac{\lambda(4\lambda + 5)(4\lambda - 1)}{2}\right. \\ &\quad \left. + (4\lambda - 1)(4\lambda + 1)(\lambda - 1) - \frac{\lambda(4\lambda - 7) + 4\lambda(4\lambda^2 - 3\lambda + 2)}{\tau}\right]\end{aligned}$$

The first factor of this expression is negative. The second factor is positive in a neighborhood of the benchmark case. Therefore $d(CS + \Pi_T^{gross})/d\tau < 0$. Since aggregate emissions remain constant with τ, it is clear that social welfare declines with τ. ■

PROOF OF PROPOSITION 9:
The proof follows from Lemma 4 and from the following derivatives:

$$\frac{\partial e_2}{\partial \lambda} = \frac{-2e_2(5\lambda + 1)\tau_2}{(\alpha + 1)\lambda(4\lambda - 1)(4\lambda^2 - 3\lambda + 2)}$$

$$\frac{\partial e_1}{\partial \lambda} = \frac{2e_1(8\lambda + 7)\tau_1}{(\alpha + 1)\lambda(4\lambda - 1)(4\lambda - 7)}. \blacksquare$$

PROOF OF PROPOSITION 10:
Using (3.13), we need to calculate

$$\frac{dCS}{d\tau_1} = \left(\frac{\partial CS}{\partial e_2}\frac{\partial e_2}{\partial \lambda} + \frac{\partial CS}{\partial \lambda}\right)\frac{\partial \lambda}{\partial \tau_1}.$$

The following derivatives are needed here:

$$\frac{\partial CS}{\partial e_2} = \frac{-V^2\lambda(4\lambda + 5)}{2\bar{\theta}(4\lambda - 1)^2 e_2^2} < 0$$

$$\frac{\partial CS}{\partial \lambda} = \frac{-V^2(28\lambda + 5)}{2\bar{\theta}(4\lambda - 1)^3 e_2} < 0$$

Since earlier we have shown that $\partial e_2/\partial\lambda > 0$ and $\partial\lambda/\partial\tau_1 > 0$, it follows that $dCS/d\tau_1 < 0$. Therefore, consumer surplus declines with τ_1.

Now, we need to compute

$$\frac{\partial CS}{d\tau_2} = \frac{\partial CS}{\partial e_2}\frac{\partial e_2}{\partial \tau_2} + \left(\frac{\partial CS}{\partial e_2}\frac{\partial e_2}{\partial \lambda} + \frac{\partial CS}{\partial \lambda}\right)\frac{\partial \lambda}{\partial \tau_2}. \tag{7.16}$$

Notice that $\partial e_2/\partial\tau_2 = -e_2/((1+\alpha)\tau_2) > 0$. Since in this case $\partial\lambda/\partial\tau_2 < 0$ the first summand of (7.16) is negative while the second one is positive. We need to work out this derivative in more detail. Putting together these summands yields

$$\frac{\partial CS}{d\tau_2} = \frac{V^2}{2\bar{\theta}(4\lambda-1)^2\tau_2 e_2}\left[\frac{\lambda(4\lambda+5)}{\alpha+1} - \frac{1}{\frac{4}{4\lambda-7} - \frac{\alpha}{\lambda} - \frac{8\lambda-3}{4\lambda^2-3\lambda+2}}\left(-\frac{28\lambda+5}{4\lambda-1} + \frac{2\lambda(4\lambda+5)(5\lambda+1)\tau_2}{(\alpha+1)\lambda(4\lambda-1)(4\lambda^2-3\lambda+2)}\right)\right]$$

Evaluating this derivative in a neighborhood of the benchmark case (i.e. where $\tau_1 = \tau_2 = 1$ and α and λ satisfy (3.12)), it can be seen that it is negative. Therefore, consumer surplus falls with τ_2.

We now analyze the effects of product charges on gross profits given by (5.9). Using Euler's theorem and equations (5.3) and (5.4) we can write gross profits as

$$\Pi_T^{gross} = \frac{V^2}{\bar{\theta}(4\lambda-1)^3 e_2}\left((4\lambda+1)(4\lambda-1)(\lambda-1) - \frac{\lambda(4\lambda-7)}{\alpha\tau_1} - \frac{4\lambda(4\lambda^2-3\lambda+2)}{\alpha\tau^2}\right).$$

We need to calculate

$$\frac{d\Pi_T^{gross}}{d\tau_2} = \frac{d\Pi_T^{gross}}{\partial\tau_2} + \left(\frac{d\Pi_T^{gross}}{\partial\lambda} + \frac{d\Pi_T^{gross}}{de_2}\frac{\partial e_2}{\partial\lambda}\right)\frac{\partial\lambda}{\partial\tau_2}. \tag{7.17}$$

Then, the following derivative is useful:

$$\frac{\partial\Pi_T^{gross}}{\partial\lambda} = \frac{V^2}{\bar{\theta}e_2(4\lambda-1)^3}\left[11 + 4\lambda + \frac{8(5\lambda+1)}{\alpha\tau_2(4\lambda-1)} + \frac{16\lambda^2-48\lambda-7}{\alpha\tau_1(4\lambda-1)}\right]$$

whose sign is positive in a neighborhood of the benchmark case.

It is useful to see that the sign of the term in brackets of equation (7.17)

$$\frac{\partial\Pi_T^{gross}}{\partial\lambda} + \frac{\partial\Pi_T^{gross}}{\partial e_2}\frac{\partial e_2}{\partial\lambda} = \frac{V^2}{\bar{\theta}e_2(4\lambda-1)^3}\left[\frac{2(5\lambda+1)(4\lambda+1)(\lambda-1)}{(\alpha+1)\lambda(4\lambda^2-3\lambda+2)} + \frac{2(4\lambda-7)(5\lambda+1)}{(\alpha+1)\alpha\tau_1(4\lambda-1)(4\lambda^2-3\lambda+2)} + \frac{8(5\lambda+1)}{(\alpha+1)\alpha\tau_2(4\lambda-1)} + 11 + 4\lambda + \frac{8(5\lambda+1)}{\alpha\tau_2(4\lambda-1)} + \frac{16\lambda^2-48\lambda-7}{\alpha\tau_1(4\lambda-1)}\right]$$

is positive in a neighborhood of the benchmark case. Inspection of Π_T^{gross} yields that $\partial\Pi_T^{gross}/\partial\tau_2 < 0$, and since $\partial\lambda/\partial\tau_2 < 0$ (Lemma 4), if follows from (7.17) that $d\Pi_T^{gross}/d\tau_2 < 0$.

The sign of

$$\frac{d\Pi_T^{gross}}{d\tau_1} = \frac{\partial\Pi_T^{gross}}{\partial\tau_1} + \left(\frac{\partial\Pi_T^{gross}}{\partial\lambda} + \frac{\partial\Pi_T^{gross}}{\partial e_2}\frac{\partial e_2}{\partial\lambda}\right)\frac{\partial\lambda}{\partial\tau_1} \tag{7.18}$$

is more difficult to calculate because the first summand of (7.18) is negative while the second summand is positive, since $\partial\lambda/\partial\tau_1 < 0$ (Lemma 4). Putting together all components of (7.18) yields:

$$\begin{aligned}\frac{\partial\Pi_T^{gross}}{d\tau_1} = &-\frac{V^2}{\bar{\theta}e_2(4\lambda-1)^3}\frac{\lambda(4\lambda-7)}{\alpha\tau_1^2}+\\ &\frac{V^2}{\bar{\theta}e_2(4\lambda-1)^3}\left[\frac{2(5\lambda+1)(4\lambda+1)(\lambda-1)}{(\alpha+1)\lambda(4\lambda^2-3\lambda+2)}+\right.\\ &\frac{2(4\lambda-7)(5\lambda+1)}{(\alpha+1)\alpha\tau_1(4\lambda-1)(4\lambda^2-3\lambda+2)}+\frac{8(5\lambda+1)}{(\alpha+1)\alpha\tau_2(4\lambda-1)}\\ &\left.+11+4\lambda+\frac{8(5\lambda+1)}{\alpha\tau_2(4\lambda-1)}+\frac{16\lambda^2-48\lambda-7}{\alpha\tau_1(4\lambda-1)}\right]\\ &\frac{1}{\tau_1\left(\frac{4}{4\lambda-7}-\frac{\alpha}{\lambda}-\frac{8\lambda-3}{4\lambda^2-3\lambda+2}\right)}\end{aligned}$$

This derivative can be rewritten as:

$$\begin{aligned}\frac{\partial\Pi_T^{gross}}{d\tau_1} = &\frac{V^2}{\bar{\theta}e_2(4\lambda-1)^3}\left[\frac{-\lambda(4\lambda-7}{\alpha\tau_1^2}+\frac{1}{\tau_1\left(\frac{4}{4\lambda-7}-\frac{\alpha}{\lambda}-\frac{8\lambda-3}{4\lambda^2-3\lambda+2}\right)}\right.\\ &\left(\frac{2(5\lambda+1)(4\lambda+1)(\lambda-1)}{(\alpha+1)\lambda(4\lambda^2-3\lambda+2)}+\frac{2(4\lambda-7)(5\lambda+1)}{(\alpha+1)\alpha\tau_1(4\lambda-1)(4\lambda^2-3\lambda+2)}+\right.\\ &\left.\frac{8(5\lambda+1)}{(\alpha+1)\alpha\tau_2(4\lambda-1)}+11+4\lambda+\frac{8(5\lambda+1)}{\alpha\tau_2(4\lambda-1)}+\frac{16\lambda^2-48\lambda-7}{\alpha\tau_1(4\lambda-1)}\right]\end{aligned}$$

With the help of Mathematica 3.0 one can check that the sign of this derivative is positive. Therefore, gross profits increase with τ_1. ■

Notation

1: the dirtier variant subscript
2: the cleaner variant subscript
θ: purchaser θ's marginal valuation for the green features of a good
$\bar{\theta}$: upper bound of the distribution of θ
V: purchaser's gross valuation for the good

e_i: unit emissions of variant $i = 1, 2$
$\bar{e}$: level of the maximum unit emissions standard
p_i: price of variant $i = 1, 2$
q_i: demand of variant $i = 1, 2$
Π_i: profits of the firm selling variant $i = 1, 2$
E_i: aggregate emissions associated to variant $i = 1, 2$
$C(e)$: fixed cost of producing variant e
$C'(e)$: first derivative of $C(e)$
$C''(e)$: second derivative of $C(e)$
α: homogeneity degree of $C(e)$
SW: social welfare
CS: consumer surplus
Π_T: firms' aggregate net-of-taxes profits
Π_T^{gross}: firms' aggregate gross profits
GR: government's revenues (or expenditures)
E_T: industrial aggregate emissions
γ: marginal social damage associated to environmental pollution
λ: ratio e_1/e_2
k: shift parameter of the quadratic cost function
ln: natural logarithm operator
t_i: ad-valorem tax for firm $i = 1, 2$
s: technological subsidy

Notes

1. There is substantial work in markets for homogeneous products. In such markets environmental regulation generally induces an overinternalization of pollution as firms may react by reducing their output levels. As a result, optimal policies such as standards and Pigouvian taxes fall short of marginal environmental damage to account for additional reductions of output levels indirectly induced by the policy. Buchanan (1969), Barnett (1980), Misiolek (1980) and Oates and Strassman (1984) study the effects of optimal environmental policies in the monopoly case; Ebert (1991), Requate (1993) and Damania (1996) in duopoly; and Levin (1985), Katsoulakos and Xepapadeas (1992, 1995) and Katsoulakos et al. (1997) in the oligopoly case.
2. We thank an anonymous referee for bringing this work to our attention.
3. Markets for green products can also present some degree of horizontal differentiation. For simplicity, we assume that the rest of products' features are identical. Therefore, environmentalists are only concerned about the unit emissions associated to the product.
4. Moral hazard and observability problems limit the use of effluent fees and ambient charges in many real-world cases. However, unit emission standards' subsidies and product charges are amply employed in western European countries, such as Germany, The Netherlands, Norway, Spain, Sweden, etc. (Hanley et al. 1997).
5. See Gabszewicz and Thisse (1979), Mussa and Rosen (1978) or Shaked and Sutton (1982) for typical product differentiation models. The assumptions of our model are in line with Lehmann-Grube (1997), Motta (1993), Motta and Thisse (1999), Ronnen (1991) and Tirole (1988).
6. Purchasers may acquire more units. What is important here is that an individual's demand is inelastic.

7. As it is usual in models of externalities, zero-mass individuals do not affect industrial aggregate emissions by their consumption patterns. Therefore we do not need to take into account the negative externality consumers derive from aggregate emissions in their decision rule.
8. One could think of batteries as an illustrative example. A battery gives utility V (say 5 hours of radio music) to a consumer irrespective of the level of unit emissions associated to it. However, an environmentalist derives lower utility from purchasing a regular battery as compared to a low-cadmium battery. Dufour (1992) provides empirical support of the importance of the environmental features of goods for consumption patterns. He finds that buyers in some OECD countries are willing to pay more money for cleaner variants. For further evidence on this issue see Scherhorn (1993), Couton et al. (1996) and Soderqvist (1998).
9. If the reader feels uncomfortable with the fact that our purchasers are (voluntarily) willing to pay more for less polluting variants, he/she may consider that purchasers are a continuum of firms, non-competing among them, that employ the good in question as an input for their production processes. Unit emissions associated to the utilization of the input e are by-products of the firms production activities and have to be recycled or purified at a cost $t(e) = e$. Under this interpretation, the parameter θ would represent the firm-specific financial opportunity cost of paying the recycling cost, and V would stand for the net profits each firm would obtain when entering its respective market.
10. This example is available from the authors upon request.
11. We check that these inequalities are satisfied in equilibrium below.
12. Note that, as opposed to conventional models, the market is not covered at the upper end. This is due to the fact that unit effluents constitute a *bad* from the environmentalists' viewpoint.
13. This variable change simplifies computations and facilitates the interpretation of our findings (see Ronnen (1991) and Motta (1993)).
14. Our analysis assumes that the market structure remains unchanged after the regulatory policy. This is not necessarily the case as pointed out in Moraga-González (1997), where it is shown that standards may be so stringent that only one firm obtains positive profits after regulation. The purpose of our positive analysis is to show that unit emission standards may be undesirable on welfare grounds. Considering very restrictive standards would only reinforce our results, because monopolization would add an important quantity distortion in the market, increasing thus welfare losses.
15. Equation (4.2) is just the first order condition of firm 2's maximization problem.
16. This outcome is in line with the results on the effects of minimum quality standards obtained in Ronnen (1991), Motta and Thisse (1999) and Crampes and Hollander (1995).
17. This result only needs that the cost function is sufficiently convex. This is the role of our assumption $\alpha < -1$. However, as a referee has pointed out, this result does not depend on the assumption of homogeneity of the cost function. Indeed, from (3.8) and (3.9), it can be seen that unit emissions e_1 and e_2 are strategic complements. Then, provided that the cost function is sufficiently convex, both e_1 and e_2 fall after the introduction of the emission standard. From (3.11), since its LHS is decreasing in λ, it follows that λ falls as a result of the emission standard provided that $e_2^2 C'(e_2)$ is a decreasing function, which is guaranteed when the cost function is convex enough. Using Lemma (1) the result follows. In contrast, this result is strongly connected to assumption 1. Indeed, it is relatively easy to show that if the market was fully covered and the investments needed to reduce unit emissions were sunk, a unit emission standard would only reduce the unit emissions of variant 1, leaving unchanged the unit emissions of variant 2 and firms' market shares. Given that no negative quantitative effect would arise, industrial aggregate emissions would decline with the imposition of a unit emission standard.
18. See Hanley et al. (1997). Spain has also recently approved a product charge on plastic, glass and paper containers, known as the green point charge.
19. The main reason is that this type of financial aids avoid conflicts with the 'polluters-pay-principle,' which would be violated using subsidies defined over the emission reduction.

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