Equilibrium environmental policies under differentiated oligopoly

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Abstract

Constructing a model of differentiated oligopoly with environmental pollution, this paper studies how product differentiation, together with the presence and absence of free entry, affects the optimal environmental policies. We find that two parameters which measure pollution damage and product differentiation play a significant role for characterization of the optimal tax-subsidy policy.

Keywords: environmental policy, oligopoly, product differentiation, free entry and exit.

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1 Introduction

How should a government design the environmental policy scheme? This question has attracted a number of economists' interest. Looking at textbooks on microeconomics and environmental economics, Pigouvian taxation is explained as a benchmark scheme. They tell us that social efficiency can be decentralized via a tax-subsidy scheme which equates social marginal benefit to social marginal cost. Then, one has further question. How can we characterize such a policy scheme when the product market is noncompetitive? In the developments in the theory of imperfect competition and industrial organization, several answers have been provided.

This paper intends to derive and characterize the short-run and long-run environmental policies in a differentiated oligopoly. There has already been voluminous literature which theoretically assesses welfare effects of environmental policies under homogeneous oligopoly. Therefore, it is almost impossible to review all of it, but only several works need to be mentioned in relation to the present study.[1]

Katsoulacos and Xepapadeas (1995) characterize emission taxes with and without free entry in an oligopoly model. One of their main results is that the optimal tax can exceed the marginal external damage when free entry is allowed, which is never established under monopoly and oligopoly with the number of firms fixed.[2]

As another important contribution, Lahiri and Ono (2007) compare two policy instruments and discuss their relative effectiveness. They find that the relative emission standard (resp. emission tax) is Pareto superior to the emission tax (resp. relative emission standard) if free entry is prohibited (resp. allowed).

These works are so insightful that it might be helpful to comment some relationship between this paper and the above predecessors. First, let us consider what causes Katsoulacos and Xepapadeas's (1994) proposition. In oligopolistic models with pollution, there are two distorting factors: imperfect competition, i.e., the price above marginal cost, and pollution. In the short-run with entry restricted, an increase in emission tax

[1]Footnote 1 in Moraga-Gonzalez and Padron-Fumero (2002) gives a survey on environmental policies under homogeneous oligopoly.

[2]Simpson (1995) derives a similar result in a model of asymmetric duopoly. Yin (2003) revisits Katsoulacos and Xepapadeas's (1994) proposition by incorporating an inter-firm externality from pollution.

mitigates not only negative environmental externality but market distortion by monopoly. Hence, the tax rate is below the marginal damage. In contrast, in the long-run, an increase in tax can lower the negative effect coming from 'excess entry' which would happen without tax. In other words, an emission tax lower two distortions one of which comes from environmental damage and the other of which comes from excess entry. Accordingly, the optimal tax can be higher than the marginal environmental damage. Note that these results crucially hinge upon the assumption of homogeneous oligopoly.

Second, let us state what differentiates this paper from Lahiri and Ono (2007). There are at least three differences. First, they consider whether welfare improves by a small change in emission tax or emission standard, namely, they do not derive the welfare-maximizing level of tax and standard. In this sense, they regard environmental instruments as an exogenous parameter, not an endogenous variable. Second, they allow for pollution abatement by oligopolistic firms, while we do not. Third, their analysis is also based on homogeneous oligopoly.

Having reviewed these works, one may have a natural question: what will happen if the assumption of homogeneous products is relaxed? This paper answers this question by developing a differentiated oligopoly model with environmental pollution.

We make use of a model of differentiated oligopoly with a quadratic subutility function, which is intensively used in Cellini, Lambertini and Ottaviano (2004) and Vives (1999).[3] In the presence of product differentiation, environmental policies possibly add another dimension to the welfare effect, which we may call a variety contraction effect. Suppose that the government imposes a stricter environmental policy, e.g., raising the emission tax. As we will show, it decreases the number of varieties in free entry, which deteriorates welfare and is null under homogeneous oligopoly. Hence, the observations in homogeneous oligopoly models may not straightforwardly survive.

We derive the closed form of optimal environmental taxes in the short-run and long-run. It is shown that the optimal tax rates can naturally be both positive and negative. Moreover, we will examine how such policies respond to the degree of product differen-

[3] A differentiated Cournot or Bertrand duopoly model is possibly a simplest strategy to incorporate product differentiation. However, endogeneity of the number of firms can not be modeled. On the other hand, the Dixit-Stiglitz (1977) model of monopolistic competition makes it almost impossible to analytically compute the optimal tax due to nonlinearity of demand functions.

tiation. Two parameters which measure the marginal damage from pollution and the degree of product differentiation play a decisive role for these characterizations.

This paper is planned as follows. Section 2 constructs a basic model and introduces assumptions underlying the analysis. Section 3 considers the short-run equilibrium with restricted entry and derives the optimal tax. Section 4 derives the long-run pollution tax by allowing for free entry. Section 5 provides the concluding remarks.

2 A model

Consider an economy which produces a differentiated and a homogeneous goods. All goods are produced from one primary factor, labor. The homogeneous good, which serves as a numeraire, is produced with a unitary input coefficient so that the wage rate is fixed to unity. Labor is fully employed and inelastically supplied. The differentiated goods industry has potentially $n > 1$ varieties and firms. All the oligopolistic firms share the identical production technology. The production of x units of each differentiated good requires $cx + f$ units of labor, where $c > 0$ and $f > 0$ respectively denote the marginal and fixed labor inputs. One unit of differentiated good emits one unit of pollutant, on which a specific pollution tax τ is levied.

Concerning the consumer side, assume a representative consumer whose preference is specified by[4]

$$\begin{aligned} u &= \alpha \sum x_j - \frac{\beta - \gamma}{2} \sum x_j^2 - \frac{\gamma}{2} \left(\sum x_j \right)^2 + y - \frac{s}{2} Z^2, \\ & \qquad \alpha > c, \quad \beta > \gamma > 0, \quad s > 0, \end{aligned} \tag{1}$$

where u is utility, x_j and y the consumption of each differentiated good and the homogeneous good respectively, and Z the pollution flow. The parameter which will play a key role in the subsequent argument is γ.[5] When $\gamma \to \beta$, the above preference reduces to

$$u = \alpha \sum x_j - \frac{\beta}{2} \left(\sum x_j \right)^2 + y - \frac{s}{2} Z^2,$$

[4]This specification follows Cellini, Lambertini and Ottaviano (2004) and Vives (1999). Ottavibano, Tabuchi and Thisse (2002) adopt its continuous version.

[5]Following Cellini, Lambertini and Ottaviano (2004), we assume away the possibility of complements among differentiated goods.

i.e., only the aggregate quantity of differentiated goods affect utility and hence it is fair to say that the n commodities are homogeneous.

In the other limiting case with $\gamma \to 0$, (1) takes the form of

$$u = \alpha \sum x_j - \frac{\beta}{2} \sum x_j^2 + y - \frac{s}{2} Z^2,$$

from which each differentiated good is independent. In what follows, we sometimes say that 'the products become more differentiated' as γ decreases.

Since (1) is quasi-linear, the demand function of differentiated goods is independent of income and implicitly given by the first-order condition for utility maximization:

$$p_i = \alpha - (\beta - \gamma) x_i - \gamma \sum x_j. \tag{2}$$

(2) defines the inverse demand function firm i faces. Hence, from the cost function specified by $cx_i + f$, firm i's profit is defined by

$$\pi_i \equiv \left[\alpha - c - \tau - (\beta - \gamma) x_i - \gamma \sum x_j\right] x_i - f. \tag{3}$$

Assuming an interior maximum, the first-order condition for profit maximization with symmetry among differentiated products is

$$\begin{aligned} \frac{\partial \pi_i}{\partial x_i} &= \alpha - c - \tau - 2(\beta - \gamma) x_i - 2\gamma x_i - \gamma (n-1) x_j \\ &= \alpha - c - \tau - [2\beta + \gamma(n-1)] x \\ &= 0, \end{aligned}$$

where the second equality uses $x_i = x_j = x$. Solving this condition for x, the equilibrium output becomes

$$x^N = \frac{\alpha - c - \tau}{2\beta + \gamma(n-1)}, \tag{4}$$

where the superscript N refers to the Cournot-Nash equilibrium.

In the subsequent two sections, we derive the emission tax rates depending on whether entry is free or not.

3 Short-run equilibrium policies

This section uses the above-specified model to derive the optimal emission tax under restricted entry into the oligopolistic market, namely, n is exogenously fixed. Before doing it, let us state an auxiliary result which immediately follows from (4):

Lemma 1. x^N *is decreasing in* τ.

In order to derive the optimal tax, let us define the objective function of the government. Under symmetry among the differentiated products, social welfare is defined as

$$\begin{aligned} U^N &\equiv \alpha nx - \frac{\beta-\gamma}{2}nx^2 - \frac{\gamma}{2}n^2x^2 - npx + n\pi - \frac{s}{2}n^2x^2 + n\tau x \\ &= \alpha nx - \frac{\beta-\gamma}{2}nx^2 - \frac{\gamma}{2}n^2x^2 - npx + n(p-c-\tau)x - nf - \frac{s}{2}n^2x^2 + n\tau x \\ &= nx\left[\alpha - c - \frac{\beta-\gamma+n(\gamma+s)}{2}x\right] - nf, \end{aligned} \tag{5}$$

where the first-fourth terms in the top line give the consumer surplus, the fifth the aggregate profit, the sixth the damage from pollution, and the last the pollution tax revenue. Note here that use is made of $Z = nx$ from the symmetry assumption.

Substituting (4) into (5), the short-run welfare is obtained as

$$U^N = nx^N\left[\alpha - c - \frac{\beta-\gamma+n(\gamma+s)}{2}x^N\right] - nf. \tag{6}$$

The government seeks to choose τ so as to maximize U^N, which yields the first-order condition:

$$\begin{aligned} \frac{dU^N}{d\tau} &= n\left\{\alpha - c - [\beta-\gamma+n(\gamma+s)]x^N\right\}\frac{dx^N}{d\tau} \\ &= n\left\{\alpha - c - [\beta-\gamma+n(\gamma+s)]\frac{\alpha-c-\tau}{2\beta+\gamma(n-1)}\right\}\frac{-1}{2\beta+\gamma(n-1)} \\ &= 0, \end{aligned}$$

where the second equation is obtained by using (4). Solving this condition for τ, the short-run optimal tax rate is explicitly derived as

$$\tau^N = \frac{(-\beta+ns)(\alpha-c)}{\beta-\gamma+n(\gamma+s)}. \tag{7}$$

The second-order condition for welfare maximization is briefly checked. The second derivative of U^N with respect to τ becomes

$$\frac{d^2U^N}{d\tau^2} = -\frac{n[\beta-\gamma+n(\gamma+s)]}{[2\beta+\gamma(n-1)]^2} < 0,$$

from which, the second-order condition is safely guaranteed. Based on (7), we can state one of the main results:

Proposition 1. *Under* $-\beta+ns>0$ *(resp.* $-\beta+ns<0$*), the short-run optimal emission tax rate is positive (resp. negative) and decreasing (resp. increasing) in* γ*.*

Proof. Differentiating (7) with respect to γ, we have

$$\frac{d\tau^N}{d\gamma} = -\frac{(n-1)(-\beta+ns)(\alpha-c)}{[\beta-\gamma+n(\gamma+s)]^2}.$$

Thus, the sign of both τ^N and $d\tau^N/d\gamma$ is determined solely by that of $-\beta+ns$. If the consumer's damage from pollution is so large that $-\beta+ns>0$, we see that $\tau^N>0$ and that $d\tau^N/d\gamma<0$. Exactly the opposite sign pattern follows under $-\beta+ns<0$. **Q. E. D.**

Having algebraically established the proposition, the intuitions behind it are now provided. Note first that an increase in τ lowers each firm's output in the short-run with n fixed, which has two impacts on welfare. First, a smaller output raises the market price and deteriorates welfare. Second, the environmental damage is mitigated by a smaller production, which improves welfare. The government must tax or subsidize to balance these two conflicting effects.

Bearing the above fact in mind, suppose that the consumer's damage from pollution is large enough to satisfy $-\beta+ns>0$. Then, it naturally follows that taxation is optimal since the environmental concern is sufficiently large. Moreover, τ^N is increasing in γ, i.e., the tax rate becomes higher as products are more differentiated. This is because lower γ makes each firm's monopoly power more strong. Hence, a higher tax is needed to minimize the distortion from imperfect competition.

Under $-\beta+ns<0$, a contrasting reasoning applies. In this case, the government's goal is to expand each firm's output by subsidizing. Moreover, the smaller γ is, the higher the subsidy rate becomes. This is because each firm's market power becomes stronger with lower γ and the government should impose a high subsidy for firms to produce more.

Finally, it might be useful to briefly comment the case with $s=0$. In this situation, there is no damage from pollution and hence the optimal policy is subsidization, i.e., $\tau^N = -\beta(\alpha - c)/[\beta + (n-1)\gamma] < 0$. In addition, we can confirm that $d\tau^N/d\gamma < 0$. Now, the government has an incentive to restrict the market distortion from imperfect competition through subsidization. Furthermore, if γ is lower, i.e., products are more differentiated, each firm's market power increases and hence a higher subsidy is required. $d\tau^N/d\gamma < 0$ reflects this intuition.

At this stage, it may be helpful to comment that main implications of the above proposition are substantially the same as those in Katsoulacos and Xepapadeas (1995). As mentioned earlier, our model reduces to a model of homogeneous oligopoly under $\gamma \to \beta$. However, in deriving Proposition 1, γ plays no active role, namely, product differentiation does not matter. In other words, Proposition 1 holds for any $\gamma \in [0, \beta]$. In this sense, Proposition 1 could make the scope of Katsoulacos and Xepapadeas's (1994) proposition on the short-run environmental policy larger than is expected since it survives the presence of product differentiation.

4 Long-run policies

Having characterized the short-run tax rate, this section turns to the long-run equilibrium in which entry is free. In the long-run, any firm's profit is driven to zero and the number of firms is endogenously determined.

Substituting (4) into (3), the profit per firm is

$$\pi = \beta \left[\frac{\alpha - c - \tau}{2\beta + \gamma(n-1)} \right]^2 - f.$$

The number of firms is endogenously determined when $\pi = 0$. Thus, the free entry number of varieties is explicitly determined as

$$n^E = \frac{(\alpha - c - \tau)\sqrt{\frac{\beta}{f}} - 2\beta + \gamma}{\gamma}, \tag{8}$$

where the superscript E stands for the free entry equilibrium. Substituting (8) into (4), the equilibrium output in the long-run becomes

$$x^E = \frac{\alpha - c - \tau}{2\beta + \gamma\left(n^E - 1\right)} = \sqrt{\frac{f}{\beta}}. \tag{9}$$

(8) and (9) will be used to derive the long-run environmental tax. Before doing it, another auxiliary result is now stated:

Lemma 2. *n^E is decreasing in τ and x^E is independent of τ.*

Proof. Differentiating n^E with respect to τ, we see that

$$\frac{dn^E}{d\tau} = -\frac{\sqrt{\frac{\beta}{f}}}{\gamma} < 0, \tag{10}$$

and it is trivial that $dx^E/d\tau = 0$. **Q. E. D.**

Let us now define the objective function of the government in the long-run. It is given by

$$\begin{aligned} U^E &\equiv \alpha nx - \frac{\beta-\gamma}{2}nx^2 - \frac{\gamma}{2}n^2x^2 - npx + n\pi - \frac{s}{2}n^2x^2 + n\tau x \\ &= \alpha nx - \frac{\beta-\gamma}{2}nx^2 - \frac{\gamma}{2}n^2x^2 - npx - \frac{s}{2}n^2x^2 + n\tau x \\ &= nx\left[\alpha - p - \frac{\beta-\gamma+n(\gamma+s)}{2}x + \tau\right], \end{aligned}$$

where the second equality uses the zero profit condition. Noting that the price is $p = \alpha - [\beta + \gamma(n-1)]x$ under symmetry from (2), the above expression is alternatively written as

$$\begin{aligned} U^E &= n^E x^E \left\{ \left[\beta + \gamma\left(n^E - 1\right)\right] x^E - \frac{\beta-\gamma+n^E(\gamma+s)}{2}x^E + \tau \right\} \\ &= n^E x^E \left[\frac{\beta-\gamma+n^E(\gamma-s)}{2}x^E + \tau\right]. \end{aligned} \tag{11}$$

From Lemma 2, a change in τ has two impacts: a direct effect and an indirect effect through n^E. Hence, differentiating (11) with respect to τ, we have the following first-order condition:

$$\frac{dU^E}{d\tau} = x^E \left\{ \left[\frac{\beta-\gamma+2n^E(\gamma-s)}{2}x^E + \tau\right] \frac{dn^E}{d\tau} + n^E \right\} = 0,$$

Substitution from (8)-(10) into the above condition and some rearrangements make the above condition take an alternative form:

$$\frac{dU^E}{d\tau} = \frac{x^E \Delta}{2\gamma^2} = 0, \tag{12}$$

where

$$\Delta \equiv -2(\gamma+s)\sqrt{\frac{\beta}{f}}\tau + 2s\left[(\alpha-c)\sqrt{\frac{\beta}{f}} - 2\beta + \gamma\right] - \gamma(\beta-\gamma).$$

Consequently, the closed form of the long-run pollution tax is derived as

$$\tau^E = \sqrt{\frac{f}{\beta}} \cdot \frac{2s\left[(\alpha-c)\sqrt{\frac{\beta}{f}} - 2\beta + \gamma\right] - \gamma(\beta-\gamma)}{2(\gamma+s)}. \tag{13}$$

The second-order condition is satisfied since the second derivative of U^E with respect to τ is

$$\frac{d^2U^E}{d\tau^2} = -\frac{x^E(\gamma+s)\sqrt{\frac{\beta}{f}}}{\gamma^2} = -\frac{\gamma+s}{\gamma^2} < 0.$$

Characterization of the long-run optimal tax is not so simple as that of the short-run tax. However, several properties of it can be made clear. The following proposition summarizes them.

Proposition 2. *The long-run optimal emission tax rate is positive (resp. negative) if and only if*

$$s > (resp.\ <)\ F(\gamma) \equiv \frac{\gamma(\beta-\gamma)}{2\left[(\alpha-c)\sqrt{\frac{\beta}{f}}\right] - 2\beta + \gamma}. \tag{14}$$

Furthermore, it is increasing (resp. decreasing) in γ *if and only if*

$$G(s) \equiv 2s^2 + s\left[3\beta + 2\gamma - 2(\alpha-c)\sqrt{\frac{\beta}{f}}\right] + \gamma^2 > (resp.\ <)\ 0. \tag{15}$$

Proof. Setting $\tau^E > 0$ in (13), condition (14) is obtained. On the other hand, differentiating (13) with respect to γ, we have

$$\begin{aligned} \frac{d\tau^E}{d\gamma} &= \sqrt{\frac{f}{\beta}} \cdot \frac{2s^2 + s\left[3\beta + 2\gamma - 2(\alpha-c)\sqrt{\frac{\beta}{f}}\right] + \gamma^2}{2(\gamma+s)^2} \\ &\equiv \sqrt{\frac{f}{\beta}} \cdot \frac{G(s)}{2(\gamma+s)^2}. \end{aligned} \tag{16}$$

Hence, $d\tau^E/d\gamma > 0$ is equivalent to $G(s) > 0$. **Q. E. D.**

While the conditions obtained right above are merely algebraic results, we are now in a position to consider their economic interpretations. It is helpful to capture these conditions diagrammatically since conditions (14) and (15) are too complicated to interpret. Figures 1 and 2 provide a diagram for these conditions. In Figure 1, the distribution of s and γ which makes τ^E positive or negative is depicted. In the figure, the mountain-shaped locus gives $F(\gamma)$. Figure 2 gives a region of s which makes $d\tau^E/d\gamma$ positive or negative. The U-shaped locus corresponds to $G(s) = 0$.[6]

(Figures 1 and 2 around here)

From the figures, there arise various possibilities for the sign pattern of τ^E and $d\tau^E/d\gamma$. First, consider the case where $s > F(\gamma)$ and $G(s) > 0$, which is satisfied if the consumer is sufficiently concerned about pollution. Then, the optimal policy is taxation, and its response to γ is positive. In other words, the tax rate becomes lower as products are more differentiated. It is natural τ^E is positive since the environmental damage is so large. However, the more differentiated products are, the lower the tax rate is. This because the government has an incentive to expand the consumer's gain from variety by levying a lower tax.

In the limiting case with $\gamma \to \beta$, i.e., products are homogeneous, it is optimal to impose a very high tax to restrict entry since there no gain from variety. This corresponds to the case which Katsoulacos and Xepapadeas (1995) focus on. Under this situation, there are two sources of market distortion: (i) pollution and (ii) excess entry.[7] Hence, the government is motivated to levy a very high tax to remedy these two distortions by setting a tax which exceeds the marginal damage from pollution.

Then, someone may naturally guess that τ^E becomes negative in the other limiting case in the other limiting case with $\gamma \to 0$. However, such a conjecture is incorrect. To consider why, let us recall that the products are independent when $\gamma \to 0$, i.e., each firm's market power is quite large and so is the resulting market distortion. Therefore, it is the government's interest to levy a high tax not only to reduce pollution but to

[6]The derivation of the loci of $F(\gamma)$ and $G(s)$ is dropped since it is messy but not difficult.

[7]On the excess entry theorem in homogeneous oligopoly, see Mankiw and Whinston (1986) and Suzumura and Kiyono (1987).

restrict the number of firms. Figure 1 identifies these findings. Only if products are insufficiently differentiated, the equilibrium policy can be a subsidy. These aspects of product differentiation are null in Katsoulacos and Xepapadeas's (1994) homogeneous oligopoly model.

The second case worth addressing is given by $s < F(\gamma)$ and $G(s) < 0$. In this situation, subsidization is optimal. The reason is simple. Roughly speaking, these conditions mean that the consumer does not care about pollution. Hence, the government will promote entry by subsidizing. Moreover, the more differentiated products are, the larger the subsidy rate is. This is because it is welfare-improving to stimulate entry via higher subsidies since the consumer's gain from variety is quite large.

The last interesting case is given by $s = 0$. As Figure 1 shows, it is optimal to subsidize. On the other hand, Figure 2 convinces us that $G(0) > 0$ and $d\tau^E/d\gamma > 0$, which implies that the subsidy rate is larger as products are more differentiated. This finding is well-known in industrial organization.

Remark. In the foregoing arguments, our interest has been confined to how τ^N and τ^E are affected by s and γ. Now, let us compare τ^N and τ^E with a sufficiently large value of s. It is no surprise that both τ^N and τ^E are positive. But, the sign of $d\tau^N/d\gamma$ and $d\tau^E/d\gamma$ proves the opposite. Resorting to Propositions 1 and 2, we see that $d\tau^N/d\gamma > 0$ and $d\tau^E/\gamma > 0$. In words, a higher (resp. lower) tax rate is required in the short-run (resp. long-run). This finding documents an importance of free entry in considering optimal environmental policies and complements the arguments by Katsoulacos and Xepapadeas (1995) and Lahiri and Ono (2007).

5 Concluding remarks

Based on a model of differentiated oligopoly with pollution, we have identified some qualitative properties of the short-run and long-run environmental policies. We have found that they are highly sensitive to two parameters which measure the degree of product differentiation and marginal damage, together with the presence or absence of entry.

Let us close this paper by mentioning possible research agenda in the future. First, we have focused on the emission tax as a sole instrument. However it might be interesting to compare the emission tax and the (relative) emission standard as Lahiri and Ono (2007) examine in a model of homogeneous oligopoly.

Second, we have restricted attention to the closed economy. However, in view of the modern world, it may be inevitable to consider open economies to properly discuss the environmental policies.[8] Then, the model should be modified to accommodate a two-sage game in which each country's government strategically chooses the environmental policy in the first stage and firms play an oligopoly game in the second stage. It might be of another interest to pursue the consequences of such a policy game. These works are left as our future directions of research.

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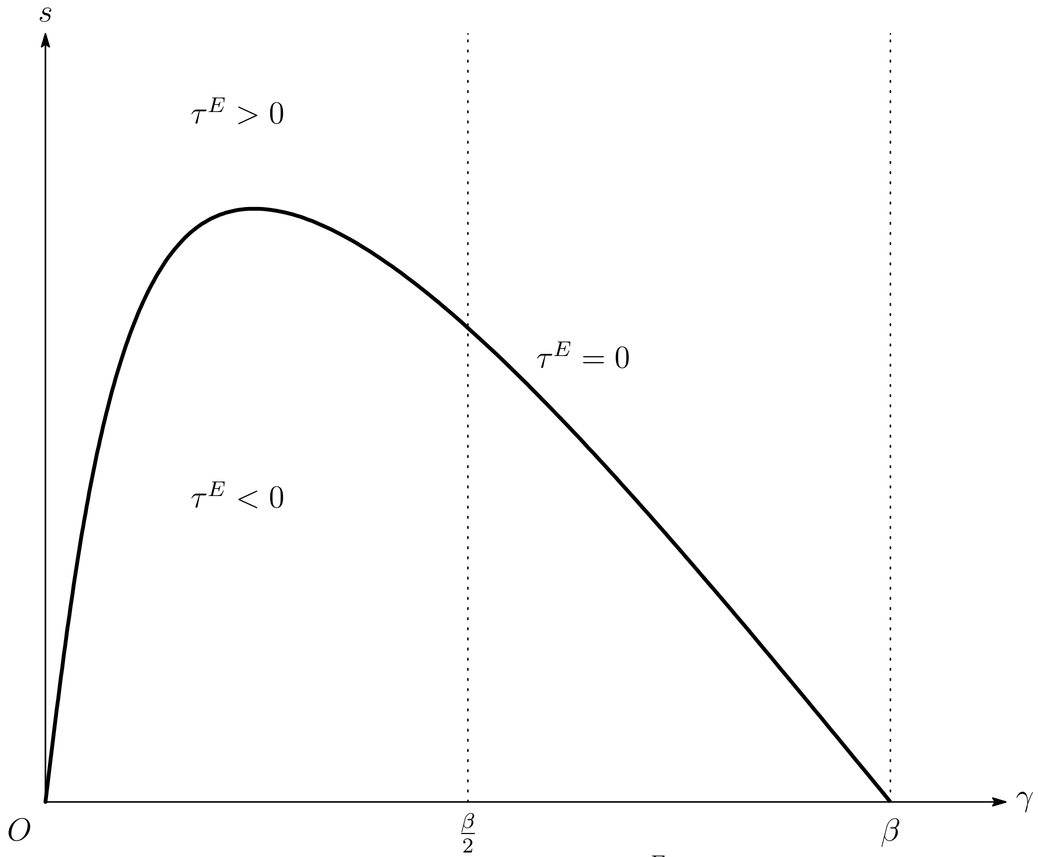

Figure 1: The region for $\tau^E > 0$

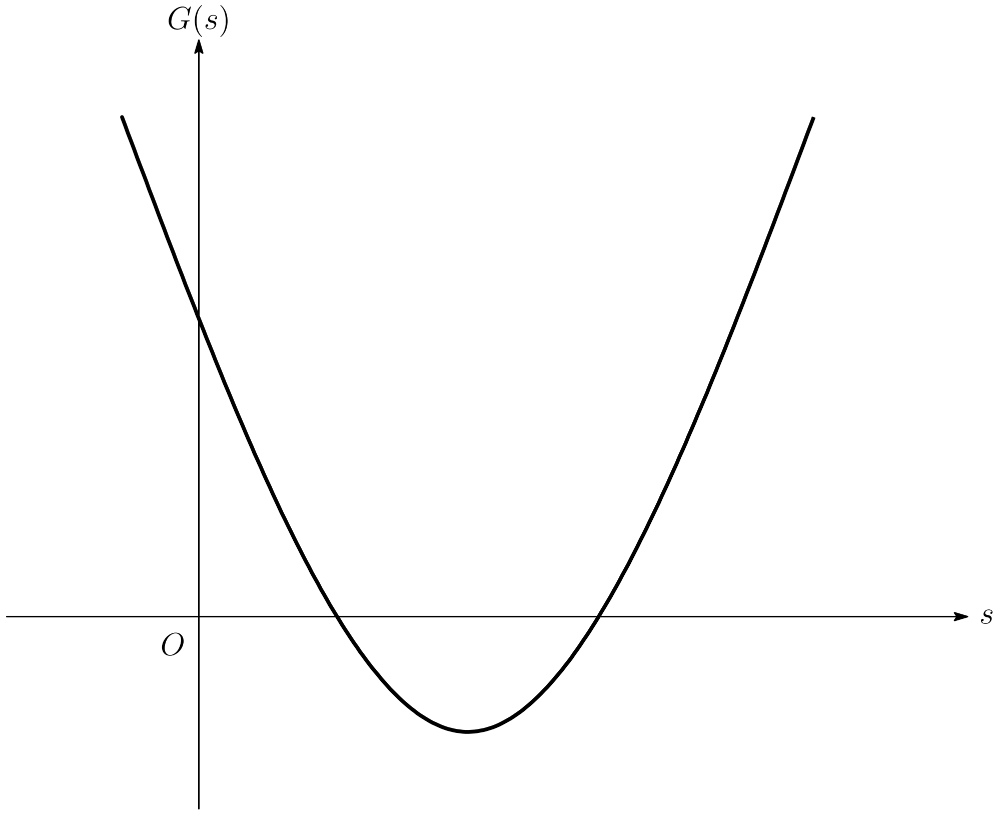

Figure 2: The range for $d\tau^E/d\gamma > 0$