To Commit or Not to Commit: Environmental Policy in Imperfectly Competitive Markets

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Abstract

This paper investigates the effect of the government's ability to commit, or not, to a specific level of environmental policy instrument, on environmental innovation and welfare in imperfectly competitive markets. We show that under monopoly if the government is unable to commit, and follows thus a time consistent policy, then in general emission taxes are lower, while environmental innovation, profits and welfare are higher relative to the precommitment case. The monopoly results extend to the small numbers oligopoly, but they are reversed for the large numbers oligopoly case. Thus for a sufficiently large number of firms, emission taxes can be lower and innovation effort and welfare can be higher under government commitment. The two policy regimes converge, regarding emission taxes, abatement effort and welfare, when the number of firms tends to infinity. Our findings indicate that, contrary to most of the results obtained previously, welfare gains can be achieved by either policy regime - precommitment or

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time consistent - depending on the number of firms in the industry.

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1. Introduction

Emission taxes are one of the major features of the market-based instrument approach to the design of environmental policy. The structure and the efficiency properties of the emission taxes have been almost exhaustively analyzed under perfect competition and monopoly.[1] More recently the analysis of emission taxes has been extended to oligopolistic markets.[2]

Once we start analyzing the impact of emission taxes under any market structure it is clear that emission taxes can affect firms' emissions in two basic ways. One is through the reduction of production of output that results in direct emission reduction, and the other is through increased abatement that reduces net emissions released into the ambient environment. In determining the optimal emission tax, the standard approach is to determine the tax that will induce firms to choose the socially-desirable level of output production and pollution abatement. This approach treats the firms which are under environmental regulation as Stackelberg followers that choose the optimal output and abatement levels by treating the *tax level* as given. On

[1] See for example, Baumol and Oates (1988), Buchanan (1969), Barnett (1980), Spulber (1985).

[2] See for example Levin (1985), Katsoulacos and Xepapadeas (1995), Carraro, Katsoulacos and Xepapadeas (1996), Petrakis, Sartzetakis and Xepapadeas (1999).

the other hand, the government - acting as environmental regulator - is considered a Stackelberg leader that chooses the *tax level* to maximize a social welfare indicator. This welfare indicator, usually the sum of producer and consumer surplus, less environmental damages, is defined as a function of the tax rate, since output and abatement in the social welfare function have been replaced by the firms' optimal output and abatement choices, which are themselves functions of the tax rate.

This approach, which has been used to determine optimal emission taxes under the main market structure forms, seems however to ignore a factor related to the temporal structure of the problem. On the one hand, while decisions about output adjustments can be regarded as short-term decisions, decisions about changing the abatement effort could involve investment in abatement equipment, or investment in 'cleaner' technologies and therefore should be regarded as longer term decisions. Thus, output and abatement decisions, or more generally decisions about environmental innovation, are not taken simultaneously but sequentially. The firms decide about the abatement investment and then output can be adjusted in the short-run *given* the level of abatement. On the other hand, the environmental regulator has the ability to change the emission tax level following normal legislative procedures, or emission taxes might change because governments change in office during the life span of a firm. The combination of the above factors leads to time consistency issues associated with environmental policy.

An emission tax level determined *ex ante*, i.e. *before* the firms make their abatement decisions, cannot be credible unless the regulator possesses a specific commitment mechanism. Once abatement has been chosen by the firms, the emission tax level determined *ex ante* is not *ex-post* optimal and therefore is not time consistent. This is because the *ex-post* government objective function is different from the *ex-ante*, since the former includes only the gross profits of the firms as abatement costs are already sunk. The firms rationally anticipate an adjustment in the emission tax rate once they have chosen their abatement effort. Therefore, when the government cannot credibly commit to a specific level of the environmental policy instrument and it is rationally expected to change the emission tax rate after abatement expenses have been chosen, then a time consistent emission tax i.e. a tax which is *ex-post* optimal, given abatement expenses and the firm's future output response to this emission tax, will be set by the government.

Although the credibility of government policies and the associated issues of time consistency have been analyzed mainly in the context of macroeconomic policies,[3] recently credibility issues related to certain microeconomic policies have also come under consideration.[4] A central issue in the microeconomic policy context is whether the ability of the government to precommit to a specific policy level has beneficial effects on various aspects of economic activity, such as the innovation rate, economic growth, or welfare.

In the context of environmental policy, time consistency issues have not been extensively examined,[5] although the temporal structure of environmental innovation decisions and output decisions clearly make environmental policy, when a government has the ability to commit or not to a certain policy level, worthy of analysis. In particular

[3] See, for example, the survey by Persson and Tabellini (1997).

[4] See, for example, Maskin and Newbery (1990), Leahy and Neary (1995, 1996, 1997), Goldberg (1995), Herguera et al. (1997).

[5] Ulph and Valentini (2001a) examine the effects of the timing of environmental policy adopted by non-cooperating governments in a model where the strategic decision of firms is their location. They show that the extend of environmental dumping depends on whether policies are set before or after firms decide where to locate. Kennedy and Laplante (1999) examine emission taxes and the permit supply policies which are time consistent and lead to the efficient adoption pattern of clean technologies by price taker firms. Laffont and Tirole (1996a, 1996b) consider time consistency problems arising from the non-unitary cost of public funds. They show that innovation incentives are weakened if a government follows time consistent policies. Biglaiser et al (1995) analyze regulation with tradeable emission permits adynamic setting and show that the permit system may not achieve the social optimum in a competitive market because of time consistency issues.

the welfare implications of the ex-ante and ex-post policy games are of major importance.[6] For instance, if ex-post policies imply higher welfare, then the government should adopt time consistent emission taxes. On the other hand, if there are substantial welfare gains from ex-ante policies, that is precommitment, then the government would have incentives to build potentially costly commitment mechanisms.

In this paper we explore the structure and the efficiency properties of emission taxes in the context of imperfectly competitive markets, by explicitly recognizing the possibility that the government can choose, on welfare maximizing grounds, whether to follow an ex-ante or ex-post optimal policy, by precommiting or not, to a specific emission tax level. Interestingly, the government's choice *does* make a difference on welfare grounds. This is due to the fact that the government has at its disposal only one instrument to correct for three market failures: the output and abatement effort distortions due to the firms' market power and the distortion due to the environmental externality.

Therefore our paper contributes to the literature by providing a

[6] Following Neary (1991), ex-ante refers to the precommitment, and ex-post to the time consistent policy games. In the former the government chooses the *level* of its policy instrument *after* firms have invested in their long run variable (and have thus incurred the sunk cost of their investment), while in the latter, the government chooses the *level* of its policy instrument *before* firms have undertaken their long-run investment.

methodological framework for analyzing the choice of the policy regime - precommitment vs. time consistent policies - in environmental taxation. We believe that this type of analysis can provide some useful insight into the way in which environmental taxes should be introduced, especially in concentrated industries.

In the development of our model we consider two alternative three-stage policy games. In the first, the *time consistent (or ex-post) policy game,* the firms first select their abatement effort, then the government sets its emission tax level, and finally the firms choose their output. This game emerges whenever the government's policy is non-credible, and the government sets its ex-post optimal emission tax rate. In this case, the firms acting as Stackelberg leaders towards the government can strategically select their abatement efforts in order to influence the emission tax rate that the government will eventually set. In the second, the *precommitment (or ex-ante) policy game*, the government commits to a specific emission tax level, then firms select their abatement effort, and finally they choose their output. This is the case that has been analyzed in the literature so far.

Our main finding is that the market structure affects to a large degree the outcome and welfare effects of each policy regime. In general, under monopoly optimal time consistent emission taxes are lower than optimal taxes determined under the familiar assumption of government commitment to an emission tax level. The monopolist, by strategically investing in abatement, induces the government to lower its emission taxes in the ex-post game. Since this strategic effect is absent in the ex-ante game, the equilibrium tax is higher under precommitment. Because of this, environmental innovation is in general higher under time consistent emission taxes (unless marginal abatement costs are relatively cheap, in which case the government subsidizes emissions in the ex-post game).[7]

Furthermore, private profits and welfare are higher under time consistent policies than under precommitment. The monopolist, having a first mover advantage in the ex-post game, achieves higher profits relative to precommitment. Welfare is also higher because higher abatement efforts and lower taxes lead to a higher output and consumer surplus. Since profits are higher too, the positive effects compensate for the (possible) negative effects due to increased environmental damages.

In the oligopoly case we show that, when the number of firms is small, the ranking of emission taxes, abatement efforts, profits and

[7]Contrary to Laffont and Tirole (1996a, 1996b) government commitment to a policy (typically) does not promote environmental innovation under monopoly.

welfare, between the time consistent and the precommitment policy games, is the same as in the monopoly case. The ranking is reversed for a large numbers oligopoly. The reason for this reversal is the public good characteristic of a firms' abatement effort in the ex-post game. When the number of firms is large, an individual firm's incentive to strategically invest in abatement in order to reduce the (common) emission tax level is weakened, because its rivals also benefit from this reduction. The individual firm has instead an incentive to reduce its abatement effort in order to impose on its rivals a higher emission tax rate and increase its market share by raising its rivals' costs. As a consequence, abatement effort is lower in a large numbers oligopoly, which in turns results in higher emission taxes and lower welfare under time consistent policies. Finally, in the limiting case where the number of firms tends to infinity and the market becomes perfectly competitive, emission taxes, abatement efforts, profits and welfare converge to common values.

It should be noted that in this paper, we do not consider emission tax schemes contingent on the firms' abatement efforts..As a matter of fact there is always a form of commitment, which is commitment to a *policy rule,.* that in our case would make the emission tax *conditional* on abatement decisions..If the government commits to a rule then the rule would not need to satisfy the time-consistency constraint. The removal of the time consistency constraint implies that commitment to a rule is at least weakly superior to non-commitment. In practice however it might be difficult to think of examples where the government commits to a rule in the environmental policy context.[8] This theoretical possibility however points out that apart from commitment itself as a notion, it is the form of commitment that is important in determining the effects of environmental policy.

Our results indicate, therefore, that when emission taxes which affect both short-run output decisions and long-run abatement decisions are introduced in imperfectly competitive markets, then the policy regime - government commitment or time consistent policies - matters in terms of welfare. It is also shown that contrary to the bulk of the literature, ex-post policies could lead to higher welfare relative to ex-ante policies, and these welfare gains are most likely to be realized in a concentrated industry.

We develop our results by analyzing first a simple monopoly model (Section 2) which allows for more compact presentation of the main findings. We then extend the analysis to the oligopoly case (Section 3).

[8] See Ulph and Valentini (2001b) for modeling commitment to a rule in the analysis of location decisions and ecodumping.

Finally, Section 4 concludes. In the Appendix we determine conditions under which our results extend to a general monopoly case.

2. The Monopoly Model

Following Ulph (1996), we consider a simple model of a monopolist producing a homogeneous good and facing a linear (inverse) market demand, $P(q) = a - q$. Pollution is a by-product of its production process with emissions released into the ambient environment defined as $s(q, w) = q - w$, where q denotes gross emissions (after some appropriate choice of units) and w denotes abatement effort or environmental innovation. The monopolist, faced with a tax on its emissions t, can undertake an abatement effort w to reduce its emissions level, and thus reduce its tax burden. Environmental innovation increases costs but reduces emissions. The cost function for the monopolist is assumed to be additively separable in production costs and environmental innovation costs, i.e. $c(q, w) = cq + \gamma\frac{w^2}{2}$. That is, there are constant returns to scale in production, i.e. the marginal cost c is constant. On the other hand, innovation costs are quadratic in innovation effort w, i.e. the marginal innovation cost is increasing in w, with γ representing the extent of decreasing returns to scale of innovation effort. The monopolist, by investing the amount of $\gamma\frac{w^2}{2}$ in environmental R&D, can reduce its emissions by w. Finally, the damage function is assumed to be quadratic in net emissions, i.e. $D(q,w) = \frac{1}{2}d(q-w)^2$, where d is a parameter indicating the steepness of marginal damages or equivalently the degree of convexity of the damage function. The convexity parameter could discriminate among pollutants according, for example, to the degree of hazardousness. For hazardous pollutants small additions to emissions will make marginal damages increase relatively faster. To guarantee interior solutions in all cases, we shall assume that $d > 1$, that is, environmental damages are not insignificant for the economy.

We compare two alternative three-stage games: The first is the *time consistent (or ex-post) policy game*, in which the monopolist first selects its abatement effort, then the government sets the emission tax rate, and finally the monopolist chooses its output. In the second, the *precommitment (or ex-ante) policy game*, the government commits to an emission tax level and then the monopolist, taking this tax rate as given, chooses its abatement and output. The time structure of those games is shown in Figures 1 and 2, respectively. To facilitate the comparison of the outcomes of those two games, we also consider a *reference two-stage game* in which in the first stage the monopolist and the government decide *simultaneously* the abatement effort and the emission tax level, respectively, and in the second stage the monopolist selects its output.

Since output selection is the last stage which is common to all the above games, we start with the analysis of this stage. The monopolist chooses its output to maximize profits:

$$\max_q [(a-q)q - cq - \frac{1}{2}\gamma w^2 - t(q-w)]$$

taking as given the emission tax rate, t. From the first-order condition $a - 2q - c - t = 0$, we get the monopolist's optimal output and profits:

$$q(t) = \frac{1}{2}(A-t); \quad \pi(t,w) = [q(t)]^2 + tw - \frac{1}{2}\gamma w^2 \tag{1}$$

where $A = a - c$, with A being a measure of the market size. Note that it can be checked that the monopolist's output and profits decrease with the emission tax, t, and increase with the market size, A.

Consider now the reference game. In the first stage, the monopolist, taking as given the emission tax t, chooses its abatement effort to maximize $\pi(.)$ in (1). At the same time, the government, taking as given the firm's abatement effort w, sets its emission tax rate to maximize total welfare. The latter is defined as the (unweighted) sum of consumer surplus, monopolist's profits and environmental damages due to the firm's emissions. Hence the government solves

$$\max_t\{\int_0^{q(.)}(a-c-x)dx-\frac{1}{2}d[q(.)-w]^2-\frac{1}{2}\gamma w^2\} \quad (2)$$

$$= \max_t\{Aq(.)-\frac{1}{2}q(.)^2-\frac{1}{2}d[q(.)-w]^2-\frac{1}{2}\gamma w^2\} \quad (3)$$

where $q(.)$ is given by (1). The reaction functions for the monopolist and the government are, respectively,

$$R_m(t) \equiv w = \frac{t}{\gamma} \quad (4)$$

$$R_G(w) \equiv t = \frac{(d-1)A-2dw}{1+d} \quad (5)$$

Note that since the slope of (4) is positive, abatement effort and emission tax are strategic complements from the monopolist's point of view. Conversely, as (5) has a negative slope, they are strategic substitutes from the government's point of view. Figure 3 depicts the two reaction functions in the (t, w) - space, with their intersection representing the (Nash) equilibrium emission tax and abatement effort of the reference game (point N).[9] In particular, the solution to (4)

[9]Note that w.l.o.g. we can set $A = 1$. In this case w and t stand for abatement effort and emission tax per unit of market size A, respectively; while π and TW stand for profits and welfare per square unit of market size A^2, respectively, and so on.

and (5) is given by

$$t^N = \frac{A(d-1)\gamma}{2d+\gamma(1+d)}; \quad w^N = \frac{A(d-1)}{2d+\gamma(1+d)} \tag{6}$$

Note that $\partial t^N/\partial d > 0$ and $\partial w^N/\partial d > 0$, i.e. as the environmental damages become more severe, the equilibrium emission tax and the monopolist's abatement effort increase.

The government's iso-welfare curves and the firm's iso-profit curves are also depicted in Figure 3. From (1) and (3), it can be seen that the monopolist's iso-profit curves are inverted U-shaped with profits increasing as we move towards the origin, and that the government's iso-welfare curves are C-shaped with welfare increasing as we move towards the southeast. For a given emission tax, the monopolist can attain the same profit level either by spending more on abatement and thus producing more output, or by spending less on abatement and thus producing less output. On the other hand, for a given abatement level, the government can attain the same welfare level either by setting a high emission tax, which leads to low output level and hence low profits and consumer surplus, but also low environmental damages, or by setting a low tax, resulting in higher output and hence higher profits, consumer surplus and environmental damages.

In Figure 3 are also depicted: (i) the point of tangency of the firm's iso-profit curves with the government's reaction function (point T), and (ii) the point of tangency of the government's iso-welfare curves with the monopolist's reaction function (point C). Point T represents the (subgame perfect) equilibrium outcome of the game where the monopolist is the Stackelberg leader, while point C is the equilbrium outcome when the government is the Stackelberg leader. Obviously, the first game corresponds to the time consistent policy game, while the second to the precommitment policy game. The next two subsections analyze those two policy games in detail.

2.1. The Time Consistent Policy Game

In this game, the monopolist selects its abatement effort in the first stage (Stackelberg leader), then the government sets the emission tax level (Stackelberg follower), and finally the monopolist chooses its output. The time structure of this game is shown in Figure 1. Given the firm's effort level, the government sets its emission tax rate in the second stage (taking into account the monopolist's reaction in the subsequent output selection stage). The government's best response emission tax function is then given by (5). It can be checked that the emission tax increases as the marginal damage function becomes steeper. More interestingly, it decreases with the monopolist's abatement effort, w. Therefore, the monopolist, by increasing its environmental innovation expenditures in the first stage, can *strategically* induce a lower tax rate on its emissions.

Now, substituting (5) into (1), we get the monopolist's output and profits:

$$q(w) = \frac{A + dw}{1 + d}; \quad \pi(w) = \frac{(A + 2dw + d^2 w)(A - w)}{(1 + d)^2} - \frac{1}{2}\gamma w^2 \quad (7)$$

That is, the monopolist's output (and gross profits) increase with its abatement effort.

In the first stage, the monopolist selects the abatement effort to maximize its profits $\pi(w)$ (taking into account that its decision will affect the government's optimal policy in the subsequent stage). From the first-order condition, we obtain the optimal abatement effort for the monopolist:

$$w^T = \frac{[(1 + d)^2 - 2]A}{F} > 0 \quad (8)$$

where $F = \gamma(1 + d)^2 + 2d(2 + d) > 0$. (Note that since $d > 1$, $w^T > 0$.) Then from (5), (7) and (3), we get the optimal time consistent emission tax, as well as the monopolist's output and profits and total welfare whenever the government is unable to commit to a specific policy level:

$$t^T = \frac{[(d^2 - 1)\gamma - 2d]}{F} A \lesseqgtr 0 \quad (9)$$

$$q^T = \frac{[(1+d)\gamma + d(3+d)]}{F} A > 0; \qquad \pi^T = \frac{[2\gamma + (1+d)^2]}{2F} A^2 > 0 \quad (10)$$

$$\begin{aligned} TW^T &= \frac{A^2}{2F^2} \left\{ (1+d)^3[\gamma^2 + d(3+\gamma)] \right. \\ &\left. +3d\gamma(3+3d+d^2) + 4d(d^2+d-1) - \gamma \right\} > 0 \end{aligned} \quad (11)$$

It can be checked that $q^T - w^T > 0$. Note also that $t^T < 0$ whenever $\gamma < \gamma_c \equiv \frac{2d}{d^2-1}$, where γ_c is decreasing in d with $\gamma_c(1) = +\infty$. The optimal time consistent emission tax is negative, that is, it is a *subsidy*, whenever, for a given d, the marginal abatement cost function is not too steep. The reason is that the government has at its disposal only one instrument to correct for the three market failures (output and environmental innovation distortions due to market power and distortion due to the environmental externality). Whenever abatement is relatively cheap, the monopolist can substantially decrease its emissions without spending much on environmental innovation. Then the government, through emission subsidies, will partially correct for the inefficiency provoked by the monopolist's market power. Finally, it can be seen from (11) that welfare under optimal time consistent policy is always positive $TW^T > 0$.

The optimal abatement effort and emission tax are shown by point

T in Figure 3. It is clear that $t^T < t^N$, while $w^T > w^N$. That is, when the monopolist decides its abatement effort before the government chooses its policy level, the monopolist spends more on environmental innovation and faces a lower emission tax than when those decisions are taken simultaneously. This is so because the monopolist's incentive to strategically invest in abatement in order to reduce the tax on its emission is absent in the simultaneous choice game. As expected, $\pi^T > \pi^N$, i.e. the monopolist attains higher profits when it acts as a Stackelberg leader. Interestingly, $TW^T > TW^N$, i.e. total welfare is higher in the time consistent policy game than in the reference game. In the former game, the monopolist's output is larger due to both the higher abatement effort and the lower emission tax. As a result, tax revenues do not significantly differ in those two games, while consumer surplus is larger in the former game, compensating thus for the higher innovation expenditures.

2.2. The Precommitment Policy Game

This is the standard optimal taxation problem (Barnett, 1980), with its time structure shown in Figure 2. The government acts as a Stackelberg leader by commiting to a specific emission tax rate in the first stage, while the monopolist is the Stackelberg follower in its abatement decision in the second stage.[10] Given the emission tax t, the monopolist selects its abatement effort to maximize profits $\pi(t,w)$ (see (1)). The monopolist's best response abatement effort function is given by (4). The higher the emission tax is, the larger the monopolist's optimal abatement effort is.

In the first stage, the government sets the emissions tax that maximizes total welfare, taking into account how the monopolist will react to its environmental policy. Substituting (1) and (4) into (3), we obtain:

$$TW(t) = \frac{A(A-t)}{2} - \frac{(A-t)^2}{8} - \frac{t^2}{2\gamma} - \frac{d[\gamma(A-t)-2t]^2}{8\gamma^2} \qquad (12)$$

From the first-order condition we get the optimal precommitment emission tax:

$$t^C = \frac{\gamma[2d+(d-1)\gamma]}{G}A > 0 \qquad (13)$$

where $G = 4d + (1+d)\gamma(4+\gamma) > 0$. Then from (1) and (4) we obtain the monopolist's abatement effort and output whenever the government can commit to a specific policy level:

$$w^C = \frac{[2d+(d-1)\gamma]}{G}A > 0 \qquad (14)$$

[10]In accordance with the bulk of the literature, the government sets the level of its emission tax. Hence, in this paper we *do not* consider government's commitment to emission tax schemes contingent on the firm's abatement effort

$$q^C = \frac{(2+\gamma)(d+\gamma)}{G} A > 0 \tag{15}$$

Note that the optimal precommitment emission tax is always positive. It is easy to see that $q^C - w^C > 0$. Further, from (4) and (12) we obtain the monopolist's profits and total welfare under government precommitment as:

$$\pi^C = \frac{8(d+\gamma)^2 + 6d\gamma(2d+2\gamma+d\gamma) + \gamma^3(9+2d+d^2+2\gamma)}{2G^2} A^2 > 0 \tag{16}$$

$$TW^C = \frac{(3+\gamma)(d+\gamma)}{2G} A^2 > 0 \tag{17}$$

Point C in Figure 3 depicts the optimal precommitment abatement effort and emission tax. Note that $t^C > t^N$ and also $w^C > w^N$. Whenever the government sets its policy level before the monopolist decides on its abatement effort, the monopolist faces a higher emission tax, and thus spends more on environmental innovation, than when those two choices are simultaneous. The government sets a higher emission tax in the former game because it anticipates that the firm will react by increasing its environmental expenditures in the subsequent stage. As a result, $\pi^C < \pi^N$. On the other hand, $TW^C > TW^N$, i.e. total welfare is higher in the precommitment policy game than in the reference game. As it has a first mover advantage in the the former game, the government can attain a higher level of welfare.

2.3. Time Consistent vs. Precommitment Policies

In this section we compare time consistent and precommitment emission taxes and innovation efforts, as well as the monopolist's profits and total welfare in these two policy games. The above analysis reveals that $t^C > t^N > t^T$, i.e. the government sets a lower emission tax if it is unable to commit to a policy level. This can also be seen from (9) and (13):

$$t^C - t^T = \frac{4[2d^2 + d\gamma(3+4d) + \gamma^2(1+d+d^2)}{FG}A > 0$$

The intuition is straightforward. When the government selects its policy after the monopolist's decision on environmental innovation, the monopolist has a strategic incentive to increase its abatement effort in order to induce a lower tax on its emissions or even to obtain an emission subsidy. In this sense the monopolist has a first mover advantage in affecting the emission tax through its behavior. This strategic effect is absent when the government can precommit to a specific emission tax rate before the monopolist chooses its abatement effort. As a result, the optimal time consistent emission tax is always lower than the optimal precommitment tax.

In contrast, the comparison of the equilibrium abatement efforts between the two policy games is not as straightforward. From Figure 3 we see that abatement efforts are higher in both games as compared to the reference game, but their relative strength seems to depend on the exact shape of the reaction functions. In fact, from (8) and (14), we have

$$w^C - w^T = \frac{2[2d + \gamma(2 - 3d - 3d^2) - d\gamma^2(1 + d)]}{FG}A$$

where the term in square brackets [..] is strictly decreasing in γ (since $d > 1$); it is equal to $2d > 0$ for $\gamma = 0$ and $2(1 - d - 2d^2) < 0$ for $\gamma = 1$. Therefore, there exists a $\widehat{\gamma}$, $0 < \widehat{\gamma} < 1$, such that $w^C > w^T$ for all $\gamma < \widehat{\gamma}$ and $w^C < w^T$ otherwise. Further, it can be checked that $\widehat{\gamma} < \gamma_c$ for all d. Therefore, the monopolist's abatement effort is lower in the time consistent policy game, but only if the marginal abatement cost is flat enough so that the government's optimal policy is to subsidize the firm's emissions. Then the only reason for the monopolist to spend on abatement is to (strategically) increase the government's subsidy on its emissions. On the other hand, when the government can commit to a policy, it always chooses a tax on the firm's emissions. In this case, the monopolist has a strong incentive to invest in abatement in order to decrease the tax burden due to its emissions. This latter case,

$w^C > w^T$, is demonstrated in Figure 4.

The above findings are summarized in Propositions 1 and 2.

Proposition 1 *The optimal time consistent emission tax is always lower than the optimal precommitment emission tax, i.e.* $t^T < t^C$.

Proposition 2 *The monopolist's environmental innovation is higher in the time consistent policy game, i.e.,* $w^T > w^C$*, whenever marginal abatement costs increase sufficiently fast. Otherwise, for low values of* γ, $w^T < w^C$.

Therefore, the government's inability to commit to an emission tax (typically) promotes environmental innovation relative to the precommitment case. This effect of a government's policy on environmental innovation seems to run contrary to the one obtained by Laffont and Tirole (1996a, 1996b), where government's commitment refers to distortions of future market prices for raising revenue.

Finally, we compare the monopolist's profits and the total welfare under time consistent and precommitment environmental policies. The welfare comparison is particularly important because it implies potential welfare benefits from choosing a certain policy regime.

Proposition 3 *The monopolist's profits and total welfare are always* *higher when the government is unable to commit to a specific emission tax level, that is, when it follows time consistent policies.*

This can be seen, since from (10) and (16) we get:

$$\pi^C - \pi^T = -\frac{2A^2}{FG^2}\Big\{\big[4d^2 + 2d\gamma(4+7d) + \gamma^2(4+22d+19d^2)\big] + \big[4\gamma^3(2+3d+2d^2) + \gamma^4(2+2d+d^2)\big]\Big\} < 0$$

Further, since $d > 1$, from (11) and (17) we have:

$$TW^C - TW^T = -\frac{2A^2}{F^2G}\Big\{\big[d^2(-1+d+d^2) + \gamma d(-2+4d+7d^2+3d^3)\big] + \big[\gamma^2(-1+3d+4d^2+2d^3+d^4) + d\gamma^3(1+d)\big]\Big\} < 0$$

The analysis in the previous section reveals that $\pi^C < \pi^N < \pi^T$. When the government is unable to commit to a specific emission tax rate and therefore has to follow time consistent policies by choosing the optimal emission tax in response to the monopolist's abatement effort, the monopolist has the first mover advantage. The monopolist is then able to increase its net profits by appropriately choosing its abatement effort to manipulate the government's choice of emission tax. Thus, the monopolist's profits are always higher under time consistent policies.

On the other hand, the comparison of the welfare levels in the time consistent and the precommitment policy games is not as straightforward. Interestingly, it turns out that the government's inability to commit to a specific policy level always leads to higher welfare. This is so, because the optimal tax is sufficiently higher under government commitment, while abatement efforts do not substantially differ across games (see Figures 3 and 4). Therefore, output level and consumer surplus are higher under time consistent policies and, as a result, environmental damages are higher too. However, the latter negative effect is not strong enough to counterbalance the positive effects resulting from the increase in consumer surplus and the monopolist's net profits and thus welfare is higher in the time consistent policy game.

The welfare comparison result indicates therefore that the government can obtain welfare gains by choosing not to commit to an emission tax rate. However, and as we shall see below, this result may be due to assuming a single polluting firm in the market and to the specific demand-cost structure adopted here. In particular, as we shall see, if the number of firms in the market is large enough, all our previous results are reversed. That is, only in very competitive environments is the government's commitment to a policy welfare improving.

3. The Oligopoly Model

In developing the model of the oligopoly we keep the same basic structure. We consider an oligopolistic industry where $i = 1, ..., n$ identical firms produce a homogeneous good. The firms compete in quantities in the market. The inverse market demand function is linear,

$$P(Q) = a - Q,\ Q = \sum_{i=1}^{n} q_i,$$

with q_i being the output of the ith firm. Pollution is a by-product of the production process. A firm i, faced with a tax on its emissions t, can undertake an abatement effort w_i to reduce its emissions level, and thus reduce its tax burden. The cost function for firm i is defined as: $c(q_i, w_i) = cq_i + \gamma\frac{w_i^2}{2}$, while its emissions are given by $s(q_i, w_i) = q_i - w_i$. Finally, as before, the damage function is assumed to be quadratic in aggregate emissions, i.e. $D(q_1, .., q_n, w_1, ..w_n) = \frac{1}{2}d[\sum_{i=1}^{n}(q_i - w_i)]^2$. To guarantee interior solutions, we shall assume that $d > \frac{1}{n}$.

We compare again the three alternative policy games. In the pre-commitment policy game, the government sets its emission tax level in the first stage, then the oligopolists select their abatement efforts and finally choose their outputs. In the time consistent policy game, the oligopolists first select their abatement efforts, then the government sets the emission tax rate, and finally the firms choose their output. (The time structures of those games are similar to the ones shown in Figures 2 and 1, respectively.) In the reference game, the government sets the emission tax rate and the firms select their abatement efforts simultaneously in the first stage, and the oligopolists select their outputs in the last stage.

In the last stage which is common to all three games, firm i chooses its output to maximize profits:

$$\max_{q_i}[(a - q_i - q_{-i})q_i - cq_i - \frac{1}{2}\gamma w_i^2 - t(q_i - w_i)]$$

where t is the tax per unit of emissions and $q_{-i} = \sum_{j\neq i} q_j$ is the total output of its rivals which is taken by the ith firm, as given. From the first-order condition, $a - 2q_i - q_{-i} - c - t = 0$, and by symmetry (i.e. $q_1 = q_2 = .. = q_n \equiv q$), we get firm i's equilibrium output and profits:

$$q(t) = \frac{(A-t)}{n+1}; \qquad \pi_i(w_i, t) = [q(t)]^2 + tw_i - \frac{1}{2}\gamma w_i^2 \tag{18}$$

In the first stage of the reference game, the firms select their abatement efforts simultaneously with the government which sets the emission tax level. Firm i, taking t as given, chooses w_i to maximize profits $\pi_i(w_i, t)$. At the same time, the government, taking $(w_1, .., w_n)$ as given, sets t to maximize welfare:

$$\max_t [Anq(.) - \frac{1}{2}[nq(.)]^2 - \frac{1}{2}d[nq(.) - \sum_{i=1}^{n} w_i]^2 - \frac{1}{2}\gamma[\sum_{i=1}^{n} w_i^2] \quad (19)$$

From the first-order conditions, we obtain the reaction functions of the ith firm and the government, respectively,

$$R_i(t) \equiv w_i(t) = \frac{t}{\gamma} \equiv R(t) \qquad i = 1, .., n \qquad (20)$$

$$R_G(w_i, w_{-i}) = t(w_i, w_{-i}) = \frac{(d - \frac{1}{n})A - d(1 + \frac{1}{n})(w_i + w_{-i})}{1 + d} \quad (21)$$

with $w_{-i} = \sum_{j \neq i} w_j$. In our simple model, all oligopolistic firms have the same reaction function $R(t)$,which moreover coincides with the reaction function of a monopolist (see (4)). This is due to the fact that equilibrium output is independent of the firms' abatement efforts. On the other hand, the government's reaction function depends on the firms' aggregate abatement effort, $W = w_i + w_{-i}$. Figure 5 depicts the reaction functions in the (t, w_i)-space, given the aggregate abatement effort of firm i's rivals, w_{-i}. Comparing Figures 3 and 5, we observe that while the firm's reaction function remains unchanged, the government's reaction function now becomes flatter and has a lower intercept (assuming that firm i correctly anticipates its rivals' aggregate abatement effort w_{-i}). Further, as the number of firms increases, R_G becomes flatter and intersects the vertical axis at a lower point. This implies that the individual firm's abatement effort and the equilibrium emission tax may increase or decrease with the number of firms, depending on the specific parameter values. In fact, solving (20) and (21), we obtain:

$$t^N(n) = \frac{A\gamma(d - \frac{1}{n})}{d(1+n) + \gamma(1+d)} \quad w^N(n) = \frac{A(d - \frac{1}{n})}{d(1+n) + \gamma(1+d)} \tag{22}$$

It can be checked that when environmental damages are significant (high values of d), then the equilibrium emission tax and the individual firm's abatement effort decrease with the number of firms. This result is, however, reversed for small enough values of d. Note further that, as in the monopoly case, $\partial t^N(n)/\partial d > 0$ and $\partial w^N(n)/\partial d > 0$.

Figure 5 depicts also the government's isowelfare[11] and the firm's isoprofit curves for a sufficiently high value of n. The isowelfare curves are again C-shaped with welfare increasing towards the southeast. However, in the neighborhood of N, the firm's isoprofit curves are U-shaped with profits increasing as we move away from the origin. This is due to the fact that the individual firm's profit function $\pi_i(w_i, t)$

[11] The government's iso-welfare curves can be represented in the (t, w_i)-space because the oligopolists' abatement efforts are identical in each particular game. *Ex-ante* identical firms will react in the same manner to the government's choice of t in the precommitment policy game. Similarly, these firms, anticipating the government's emission tax in the time consistent policy game, will choose the same abatement efforts. Setting $w_1 = .. = w_n$ in (19), one can construct the government's welfare map in the (t, w_i)-space.

has a saddle point along its reaction function $R(t)$. It can be checked that the saddle point S is $(\widehat{t}, \widehat{w}_i) = (\frac{2\gamma A}{1+2\gamma+n(n+2)}, \frac{2A}{1+2\gamma+n(n+2)})$ and it is such that $q(\widehat{t}) - \widehat{w}_i > 0$ for all $n \geq 2$. Observe moreover that point S moves towards the origin as the number of firms increases. As a consequence, the iso-profit curves are inverted U-shaped to the left of S and U-shaped to the right of S, with the individual firm's profits being increasing as we move away from the saddle point in either direction. The intuition for the profits being increasing in the northeast region of the $(t, w_i)-$ space is rather straightforward. If an individual firm i could set the common tax rate that would burden, besides its own emissions, the emissions of its rivals too, it might have an incentive to choose an emission tax high enough to raise its rivals' costs. It could thus increase its market share by investing more in abatement.[12] The gains from the latter compensate for the negative effects due to firm i's higher abatement and production costs resulting from the higher t. Hence, firm i's profits increase along $R(t)$ as we move away from S.

Interestingly, the equilibrium point N can be either to the left or to the right of S, depending on the number of firms (given d and γ).

[12] This is in line with the Raising Rivals' Cost (RRC) literature. See, for example, Salop and Scheffman (1983).

In particular, from (22) we see that $w^N > \widehat{w}_i$ if $n > n_{cr}$ and $w^N < \widehat{w}_i$ otherwise, where $n_{cr}(d, \gamma) = (1 + d + \sqrt{1 + 6d + d^2 + 8d\gamma})/2d$ with n_{cr} increasing in γ and decreasing in d; morever, $\lim_{d\to\infty} n_{cr} = 1$. For a small numbers oligopoly the situation resembles the monopoly case (the firm's iso-profit map in the neighborhood of N is as in Figures 3 or 4 (see also Figure 6)), while for the large numbers a case such as the one in Figure 5 arises.

Finally, the point C of tangency between the government's iso-welfare map and firm i's reaction function and the point T of tangency between firm i's iso-profit map and the government's reaction function are also depicted in Figures 5 and 6. As we shall see below, point C again represents the equilibrium where the government is the Stackelberg leader. In contrast to the monopoly case, point T does not correspond to the equilibrium where the oligopolists are the Stackelberg leaders.

3.1. The Time Consistent Policy Game

In the second stage, the government sets its emission tax rate after observing the abatement efforts of the oligopolists. The goverment's choice is given by (21) with the emission tax having similar properties to those in the monopoly case: it increases as the marginal damage becomes steeper and decreases with firm i's abatement effort, w_i. Therefore, firm i, by increasing its environmental innovation expenditures, can *strategically* induce a lower tax on its emissions. However, its rivals will also benefit from the tax reduction due to the increase in firm i's abatement effort. In other words, the emission tax reduction due to an individual firm's abatement effort has the characteristics of a public good. As a consequence, the larger the number of firms in the industry is, the smaller is the individual firm's strategic incentive to invest in abatement due to the free riding behavior.

From (21) and (18) we get firm i's output and profits:

$$q(w_i) = \frac{A + d(w_i + w_{-i})}{(1+d)n}; \quad \pi_i(w_i) = [q(w_i)]^2 + t(w_i, w_{-i})w_i - \frac{1}{2}\gamma w_i^2 \tag{23}$$

In the first stage, an individual firm i chooses its abatement effort to maximize its profits $\pi_i(w_i)$, given the aggregate abatement effort of its rivals. From the first-order condition and by symmetry ($w_1^T = .. = w_n^T \equiv w^T(n)$), we get the individual firm's optimal abatement effort in the time consistent policy game:

$$w^T(n) = \frac{[2d + n^2(1+d)(d - \frac{1}{n})]A}{F_n} > 0 \tag{24}$$

where $F_n = n[\gamma n(1+d)^2 - 2d^2 + d(1+d)(1+n)^2] > 0$ (note that $F_1 = F$). Then from (21) and (23) we get the optimal emission tax and the firm's equilibrium output:

$$t^T(n) = \frac{n[(d - \frac{1}{n})(1 + d)n\gamma + d^2(n - 1) - d(1 + \frac{1}{n})]}{F_n}A \tag{25}$$

$$q^T(n) = \frac{[n(1 + d)(\gamma + dn) + d(1 + n)]}{F_n}A \tag{26}$$

Finally, the individual firm's equilibrium profits and total welfare are obtained by substituting the above expressions into (23) and (19). It can be checked that $q^T(n) - w^T(n) > 0$, $\pi^T(n) > 0$ and $TW^T(n) > 0$. As in the monopoly case, $t^T(n) < 0$ when d and γ are sufficiently small. Whenever environmental damages are insignificant and abatement effort is cheap, the government, through emission subsidies, can partially correct for the inefficiency caused by the firms' market power.[13]

In contrast to the monopoly case, the time consistent equilibrium is not represented by the point T of tangency between the government's reaction function R_G and firm i's iso-profit map (see e.g. Figure 5). The reason is that R_G has been constructed with the presumption that firm i will correctly anticipate its rivals' aggregate abatement effort in the reference game. Nevertheless, firm i's expectation cannot be correct in the time consistent game, because each firm has an incentive to spend *strategically* on abatement in the first stage

[13] See also section 2.1.

in order to induce a favorable emission tax in the subsequent stage. Observe that the government's reaction function is negatively sloped, i.e. $\partial t/\partial w_i = -\frac{d(1+1/n)}{1+d}$, and that the absolute value of this slope is decreasing in n. In a large numbers oligopoly, an individual firm's ability to influence the government's choice of emission tax is so weak that the firm prefers instead to reduce its abatement effort in order to save on innovation expenditures, at the expenses of paying a higher tax per unit of unabated effluents. As a consequence, firm i's expectations about its rivals' aggregate abatement effort are now revised downwards and therefore the (perceived) government's reaction function, as well as its point of tangency with the firm's iso-profit map, will shift outwards. In Figure 5, the time consistent equilibrium is represented by point T_L which lies to the northeast of T.

In contrast, in a small numbers oligopoly, an individual firm will strategically invest more in abatement (compared to the Nash equilibrium) in order to lower the emission tax that the government will set in the subsequent stage. The firm's tax savings due to the emission tax reduction and its lower unabated effluents compensate now for the firm's higher environmental innovation expenditures. Firm i's expectations are now revised upwards, resulting in R_G shifting inwards. Moreover, this shift becomes smaller as the number of firms increases.

As the emission tax reduction due to firm i's increase in abatement effort will benefit all its rivals (having thus the characteristics of a public good), an individual firm's incentive to spend on abatement decreases as the number of firms increases. In Figure 6, the time consistent equilibrium is represented by point T_S which lies to the southwest of T.

Interestingly, the critical number of firms that distinguishes the above two cases is, in fact, n_{cr}. A large (small) numbers oligopoly is defined when the number of firms is larger (smaller) than n_{cr}. To see this, we take the difference $w^N - w^T$ and verify that it is positive if and only if $n > n_{cr}$. Note that the implications in these two cases may be quite distinct, with the exception that the firms' profits are always higher in the time consistent game where the firms have the first mover advantage ($\pi^T > \pi^N$). In the large numbers case, $t^T > t^N$, $w^T < w^N$ and $TW^T < TW^N$, while in the small numbers case all inequalities are reversed.

3.2. The Precommitment Policy Game

In the second stage, firm i chooses its abatement effort to maximize profits $\pi_i(\cdot)$, taking as given its rivals' aggregate abatement effort. The individual firm's reaction function is given by (20) which coincides with the monopolist's reaction function. As a consequence, the equilibrium abatement efforts are given by $w_1(t) = w_2(t) = .. = w_n(t) = \frac{t}{\gamma}$. Each oligopolist reacts to an increase in the government's emission tax rate by increasing its abatement effort. Substituting the firm's output (from (18)) and abatement efforts into (19) we obtain the total welfare as a function of t:

$$\begin{aligned} TW(t) &= n\left\{\frac{A(A-t)}{(n+1)} - \frac{n(A-t)^2}{2(n+1)^2} - \frac{t^2}{2\gamma} \right. \\ &\quad \left. -dn\frac{[\gamma(A-t)-(n+1)t]^2}{2(n+1)^2\gamma^2}\right\} \end{aligned} \tag{27}$$

In the first stage the gov0ernment sets the level of its emissions tax to maximize welfare. From the first-order condition we obtain the optimal precommitment emission tax:

$$t^C(n) = \frac{\gamma n[d(1+n)+(d-\frac{1}{n})\gamma]}{G_n}A > 0 \tag{28}$$

where $G_n = (dn+\gamma)(1+n)^2 + \gamma[2dn(1+n)+\gamma n(1+d)] > 0$. (Note that $G_1 = G$.) Then the equilibrium abatement effort and output of an individual firm under the government precommitment policy game are:

$$w^C(n) = \frac{n[d(1+n)+(d-\frac{1}{n})\gamma]}{G_n}A > 0 \tag{29}$$

$$q^C(n) = \frac{(1+\gamma+n)(dn+\gamma)}{G_n} A \tag{30}$$

It can be checked that $q^C - w^C > 0$ for all n. Finally, the firm's equilibrium profits and total welfare under government precommitment are obtained by substituting the above expressions into (18) and (27).

As in the monopoly case, point C in Figures 5 and 6, i.e. the point of tangency between the government's iso-welfare curves and the individual firm i's reaction function, represents the precommitment equilibrium and lies to northeast of the (Nash) equilibrium point N. This is so, because the government recognizes that all oligopolistic firms will react in the same way $R(t)$ to its emission tax, and thus considers firm i as a representative firm. The government then, acting as a Stackelberg leader, chooses t^C in the first stage and each firm, reacting optimally in the subsequent stage, will select an abatement effort w^C. Therefore, $w^C > w^N$ and $t^C > t^N$. As a result, $TW^C > TW^N$. Yet, π^N could be larger or smaller than π^C, depending on the specific parameter values. If n is small enough, the result obtained under monopoly is confirmed here too; otherwise, the individual firm's profits are larger in the precommitment policy game.

3.3. Time Consistent vs. Precommitment Policies

The previous analysis reveals that the comparison of the equilibrium outcomes of the time consistent and the precommitment policy games under oligopoly is not as simple as under monopoly. The strategic interaction among oligopolists in their abatement-then-output choices, as well as the firms' strategic incentives in their interaction with the government in the time consistent policy game, generate additional effects that often act in opposing directions. Nevertheless some general insight can be obtained from the above discussion: a small numbers oligopoly resembles the monopoly case, while reversals of some basic results are expected under a large numbers oligopoly.

In particular, we have seen that if the number of firms is smaller than a critical number n_{cr}, the relevant diagram is Figure 6. By inspection of Figure 6, we infer that the optimal emission tax is lower and the individual firm's profits are higher under time consistent emission taxes, while the equilibrium abatement effort and total welfare can be higher or lower, depending on the specific parameter values. On the other hand, the case of large numbers, $n > n_{cr}$, is represented by Figure 5. From the latter we infer that the equilibrium abatement effort and total welfare are lower in the time consistent policy game, while the emission tax and the individual firm's profits may be lower or higher than the precommitment policy game, depending on the specific parameter values. A more elaborate treatment of the above is provided in Propositions 4 and 5 (all proofs have been relegated to the Appendix).

Proposition 4 *For any given* γ *and* d, *there exists a* $\widehat{n}_t > n_{cr}$ *such that for all* $n < \widehat{n}_t$, *the optimal time consistent emission tax is lower than the optimal precommitment emission tax, i.e.* $t^T < t^C$; *and for all* $n > \widehat{n}_t, t^T > t^C$. *Furthermore,* $t^C - t^T \rightarrow 0$ *as* $n \rightarrow \infty$.

Proposition 5 *For any given* γ *and* d, *there exists a* $\widehat{n}_w < n_{cr}$ *such that for all* $n < \widehat{n}_w$ *the individual firm's abatement effort is higher in the time consistent policy game, i.e.* $w^T > w^C$, *and for all* $n > \widehat{n}_w$, $w^T < w^C$. *Furthermore,* $w^C - w^T \rightarrow 0$ *as* $n \rightarrow \infty$.

Proposition 4 indicates that the ranking of the emission tax rates is similar to the monopoly case when the number of firms is relatively small, while for a large numbers oligopoly a reversal is observed, i.e. the optimal precommitment tax is lower than the optimal time consistent emission tax. In fact, for the reversal to occur, the number of firms in the industry has to be sufficiently larger than the critical number n_{cr}. For example, if $d = 1$ and $\gamma = 10$, the precommitment tax is higher than the time consistent emission tax in oligopolies with at least $\widehat{n}_t = 23.46$ firms, while the critical number of firms is $n_{cr} = 5.69$ (See Table 1 in which various critical n-values are reported for a broad spectrum of (d, γ)- combinations.)

The economic reasoning behind this result lies predominantly in the public good characteristics of environmental innovation under time consistent policies. Since the innovation expenditures of an individual firm will reduce the emission tax rate for all the firms in the industry including its rivals, each firm has an incentive to free ride on the environmental innovation of the others. Moreover, the larger the number of firms is, the stronger an individual firm's free riding incentives are. Therefore, as the number of firms increases, the incentive of an individual firm to strategically invest in abatement in order to reduce the government's emission tax is weakened, reducing thus the gap between the optimal precommitment and time consistent emission taxes. Now if the number of firms is sufficiently large, an individual firm, moving before the government makes its choice of the emission tax level, prefers to select an abatement effort low enough to save on innovation expenditures, despite the fact that it will pay a higher tax per unit of its unabated effluents. Due to this additional cost savings (negative) effect on abatement effort, the government sets a higher emission tax under time consistent than under precommitment policies, in a large numbers oligopoly.

The ranking of abatement efforts is also similar to that of the monopoly case when the number of firms is relatively small, while a reversal is observed for a large numbers oligopoly. The individual firm's abatement effort is higher under the precommitment policy game even in oligopolies in which the number of firms is sufficiently smaller than the critical number n_{cr}. For example, if $d = 1$ and $\gamma = 10$, the individual firm's abatement effort is higher under government precommitment in oligopolies with at least $\widehat{n}_w = 3.26$ firms, a number which is smaller than $n_{cr} = 5.69$ (see Table 1). As mentioned above, due to both the free riding and the cost savings incentives, in the time consistent policy game, firms tend to reduce their abatement efforts as the number of firms increases. As a result, environmental innovation is higher under government precommitment even in oligopolies with a relatively small number of firms. Interestingly, in an oligopoly with $n = n_{cr}$ firms, both the time consistent emission tax and the individual firm's abatement effort are lower than under precommitment policies. Yet, the difference between emission taxes and abatement effort in the two regimes tends to zero as the number of firms tends to infinity and the market becomes perfectly competitive.

Finally, Proposition 6 compares total welfare in the two policy games.

Proposition 6 *For any given γ and d, there exists a $\widehat{n}_{TW} < n_{cr}$ such that for all $n < \widehat{n}_{TW}$ total welfare is higher in the time consistent policy game; otherwise, total welfare is higher when the government can precommit to an emission tax. Furthermore, $TW^C - TW^T \rightarrow 0$ as $n \rightarrow \infty$.*[14]

Regarding welfare comparison, the monopoly case result is naturally extended to a small numbers oligopoly. For a large numbers oligopoly, total welfare is higher under government precommitment than under time consistent emission taxes. Here too, a large numbers oligopoly turns out to be an industry with a number of firms sufficiently smaller than the critical number n_{cr}. For example, if $d = 1$ and $\gamma = 10$, total welfare is higher under government precommitment in oligopolies with at least $\widehat{n}_{TW} = 4.06 < n_{cr} = 5.69$ firms (see Table 1). Note, however, that $\widehat{n}_{TW} > \widehat{n}_w$, i.e. total welfare under government

[14] The comparison of the firms' profits is not as straightforward. Firms, when acting as Stackelberg leaders against the government, obtain higher profits but only if the number of firms in the industry is either sufficiently small (extending thus the result under monopoly) or sufficiently large. For intermediate numbers oligopolies, firms' profits are higher under government precommitment. In particular, this occurs if the number of firms is in the vicinity of n_{cr}, where the optimal emission taxes and the abatement efforts do not differ much across policy games.

precommitment is higher only in oligopolies where firms spend more on abatement than under time consistent policies. Yet, welfare could be higher in oligopolies where the optimal precommitment emission tax is lower than the time consistent emission tax (i.e. if $\widehat{n}_{TW} < n < \widehat{n}_t$).

The intuition is as follows. When the number of firms is sufficiently large, each individual firm spends more on abatement under precommitment policies and, moreover, faces a moderately higher, or even a lower (if $n > \widehat{n}_t$), tax on its emissions. This results in lower environmental damages, without at the same time bringing about a significant reduction in aggregate output. The positive effect from the lower environmental damages in the precommitment policy game dominates the negative effects due to the higher environmental expenditures and to the (possibly) lower aggregate output and consumer surplus, leading thus to higher welfare than under time consistent policies.

Yet, the difference between total welfare in the two regimes tends to zero as the number of firms tends to infinity and the market becomes perfectly competitive.[15]

[15] The result indicating that, as the number of firms tend to infinity government's commitment is irrelevant, is in contrast with the result obtained by Biglaiser et al (1995), where commitment matters even in perfectly competitive markets. Our result is due to the fact that as $n \to \infty$ in the *ex-post* game free riding and cost saving incentives tend to reduce the deviations between the two regimes. On the other hand in the *ex-ante* game the best response function is independent of the number of firms. Thus, as $n \to \infty$ the two regimes converge. This result may not

4. Concluding Remarks

Two policy regimes for implementing environment policy in the form of emission taxes are analyzed and compared in this paper. In the first the government can credibly commit to a specific emission tax level which is not however *ex-post* optimal, and thus is not time consistent - the traditional approach to the problem. In the second the government cannot precommit to a specific tax rate and thus sets its time consistent policy level. The two regimes are examined under monopoly and fixed numbers oligopoly.

We show that under monopoly if the government cannot precommit to an emission tax level, then the monopolist has a first mover advantage and can affect the government's choice of emission tax rate by strategically adjusting its abatement. Whenever the government sets its time consistent policy level, then in general emission taxes are lower, while environmental innovation, profits and welfare are higher relative to the precommitment case.

The monopoly results extend to the small numbers oligopoly, but they are reversed for the large numbers oligopoly case. This is because under time consistent government policy, environmental innovation

hold under a more complicated abatement function.

has public good characteristics since the innovation of an individual firm reduces the tax rate for all firms in the industry. The larger the number of firms, the weaker the individual firm's incentive to strategically invest in abatement effort is. As a result, for a sufficiently large number of firms, emission taxes can be lower and innovation effort and welfare can be higher under government precommitment. The two policy regimes converge regarding emission taxes, abatement effort and welfare, when the number of firms tends to infinity.

Our findings indicate that, contrary to most of the results obtained previously where government precommitment led to relatively higher welfare,[16] welfare gains can be obtained by either policy regime - ex-ante or ex-post optimal emission taxes - depending on the number of firms in the industry. Thus non-commitment to a policy might be preferable for concentrated industries, while precommitment might be preferable for industries with a large number of firms.

Our results regarding emission taxes suggest that an area of further research could be the analysis, in the same context of the two policy games, of tradeable emission permits, especially in cases where imper-

[16] See e.g. Leahy and Neary (1996) and Herguera et al. (1997) when the government's trade policy is a subsidy on the domestic firm's output. In contrast, if the government's policy is an import tariff, there are welfare gains under time consistent policies.

fections extend to the permit market. Given also the dependency of our results on the number of firms, another area of research could be the comparison of ex-ante optimal or ex-post optimal environmental policy in oligopolies where the number of firms is determined endogenously.

Appendix A

Proof of Proposition 4: From (28) and (25) we get:

$$t^C - t^T = \frac{(n+1)[B_0 + \gamma B_1 + \gamma^2 B_2]}{FG} A \tag{31}$$

where $B_0 = d^2 n(1+n)[1+n-dn(n-1)]$, $B_1 = d[1+2n+2n^2+n^3+dn\{3+4n+n^2+dn(n-1\}] > 0$, and $B_2 = n[1+d+2d^2+n(d+1)] > 0$. By plotting (31) for $n = n_{cr}(d,\gamma) \equiv (1+d+\sqrt{1+6d+d^2+8d\gamma})/2d$, we can see that it is always positive. Further, by plotting $t^C - t^T$ on a fine grid of (d,γ) values, we observe that this difference is positive and decreasing with n for small values of n, and is negative (initially decreasing and then increasing with n) for large values of n, with $t^C - t^T \to 0$ as $n \to \infty$. Therefore, there exists a unique $\widehat{n}_t(d,\gamma) > n_{cr}(d,\gamma)$ such that $t^C = t^T$ (see also Table 1). *Q.E.D.*∎

Proof of Proposition 5: From (29) and (24) we have,

$$w^C - w^T = \frac{C_0 + \gamma C_1 + \gamma^2 C_2}{FG} A$$

where $C_0 = dn[n(n+1)^2 - 2d + dn\{2(n^2+n-1) + d(n^2-1)\}]$, $C_1 = n(n+1)^2 - 2d + dn[n^2 - n - 4 - 3d - dn\{4+n-n(1+d)\}]$ and $C_2 = -2dn(1+d)$. By plotting $w^C - w^T$ for $n = n_{cr}$, we can see that it is always positive.

Further, by plotting $w^C - w^T$ on a fine grid of (d, γ) values, we observe that this difference is negative and increasing with n for small values of n, and is positive (initially increasing and then decreasing with n) for large values of n, with $w^C - w^T \to 0$ as $n \to \infty$. Therefore, there exists a unique $\widehat{n}_w(d, \gamma) < n_{cr}(d, \gamma)$ such that $w^C = w^T$ (see also Table 1). *Q.E.D.*

Proof of Proposition 6: By plotting the difference $TW^C - TW^T$ for $n = n_{cr}$, we can see that it is always positive. Further, by plotting $TW^C - TW^T$ on a fine grid of (d, γ) values, we observe that this difference is negative and increasing with n for small values of n, and is positive (initially increasing and then decreasing with n) for large values of n, with $TW^C - TW^T \to 0$ as $n \to \infty$. Therefore, there exists a unique $\widehat{n}_{TW}(d, \gamma) < n_{cr}(d, \gamma)$ such that $TW^C = TW^T$(see also Table 1). *Q.E.D.*

Appendix B

A general monopoly model

We locate sufficient conditions so that the results obtained for the simple monopoly model and presented in Figures 3 and 4 extend to a more general monopoly model.[17]

Using general revenue, cost of production, cost of abatement, emission and damage functions, the monopolist's profit in the last stage is defined as:

$$\Pi = B(q) - c(q) - \gamma(w) - ts(q,w)$$

where:[18]

$$\begin{aligned} B_q &> 0, B_{qq} < 0, c_q > 0, c_{qq} \geq 0, \gamma_w > 0, \gamma_{ww} > 0 \\ s_q &> 0, s_w < 0, s_{qq} \geq 0, s_{ww} \geq 0, s_{qw} \leq 0, s_{qq}s_{ww} - s_{qw}^2 \geq 0 \end{aligned}$$

The assumptions on the emission function s imply that it is convex and that an increase in output (weakly) reduces the marginal emission savings from abatement.

Using the first-order condition

$$\frac{\partial \Pi}{\partial q} = 0 \tag{32}$$

[17] It is straightforward but tedious to generalize to the oligopoly case.

[18] The notation $f_x = \frac{\partial f}{\partial x}$, $f_{xx} = \frac{\partial^2 f}{\partial x^2}$, $f_{xz} = \frac{\partial^2 f}{\partial x \partial z}$ is used interchangeably.

the last stage output and profits are defined as:

$$q_m = q(t,w) = \max_q \Pi \quad (33)$$

$$\pi(t,w) = \Pi(q(t,w), w, t) \quad (34)$$

By totally differentiating the first-order condition (32) and using the implicit function theorem we obtain:

$$\frac{\partial q(t,w)}{\partial t} = \frac{s_q}{\Delta} < 0, \; \frac{\partial q(t,w)}{\partial w} = \frac{ts_{qw}}{\Delta} \geq 0 \quad (35)$$

$$\Delta = B_{qq} - c_{qq} - ts_{qq} < 0$$

The derivatives of the profit function (34) are obtained by using the envelope theorem as:

$$\frac{\partial \pi(t,w)}{\partial w} = -\gamma_w(w) - ts_w(q_m,w)\big|_{q_m=q(t,w)} \lesseqgtr 0$$

$$\frac{\partial \pi(t,w)}{\partial t} = -s(q_m,w)\big|_{q_m=q(t,w)} < 0$$

$$\frac{\partial \pi^2(t,w)}{\partial w^2} = -\gamma_{ww} - ts_{wq}q_w - ts_{ww}$$

$$\frac{\partial \pi^2(t,w)}{\partial t^2} = -s_q q_t > 0$$

$$\frac{\partial \pi^2(t,w)}{\partial t \partial w} = \frac{\partial \pi^2(t,w)}{\partial w \partial t} = -s_w - s_q q_w = -s_w - ts_{qw}q_t$$

It is assumed that $\frac{\partial \pi^2(t,w)}{\partial w^2} = -\gamma_{ww} - ts_{wq}q_w - ts_{ww} < 0$ so that the profit function is strictly concave in w. Furthermore since $\frac{\partial \pi^2(t,w)}{\partial t^2} > 0$ the profit function is convex in t. The monopolist's reaction function is defined by the first-order condition

$$\frac{\partial \pi (t, w)}{\partial w} = 0 \tag{36}$$

as:

$$R_m (t) = w = \max_w \pi (t, w), \text{ with } R_m (0) = 0 \tag{37}$$

Since the reaction function is obtained by the solution of the first-order condition $\frac{\partial \pi(t,w)}{\partial w} = 0$, the slope of the reaction function can be obtained by differentiating the first-order condition (36) and using the implicit function theorem as

$$R_m^{'} (t) = \frac{\partial w}{\partial t} = -\frac{\partial^2 \pi / \partial w \partial t}{\partial^2 \pi / \partial w^2} \tag{38}$$

With a strictly concave in w profit function $R_m^{'} (t) > 0$ if $\partial^2 \pi / \partial w \partial t > 0$, or $-s_w - t s_{qw} q_t > 0$.

Since the profit function is concave in w and convex in t there will be a saddle point $\left(\hat{w}, \hat{t}\right)$, for which $\frac{\partial \pi\left(\hat{w},\hat{t}\right)}{\partial w} = 0$, $\frac{\partial \pi\left(\hat{w},\hat{t}\right)}{\partial t} = 0$. From (36) the saddle point will be on the monopolist's reaction function (37) which defines the profit maximizing w for any given t. Furthermore, since the slope of the iso-profit contours in the (w, t) space is $\frac{\partial \pi(t,w)}{\partial w} \Big/$

$\frac{\partial \pi(t,w)}{\partial t}$ the iso-profit contours will have zero slope at the point of intersection with the monopolist's reaction function. At $\left(\hat{w},\hat{t}\right)$ the profit function achieves a maximum with respect to w and a minimum with respect to t, therefore as we move away from $\left(\hat{w},\hat{t}\right)$ along the monopolist's reaction function, towards the southwest or northeast, the iso-profit contours will correspond to higher profit levels, and the upper contours will define convex sets.

For the government, total welfare is defined as:

$$TW = U(q) - c(q) - D(q) - \gamma(w) \quad , \quad U'(q) = P(q)\,,\ D_q > 0, D_{qq} > 0$$

Substituting in TW the profit maximizing output from (33) we obtain

$$TW(t,w) = U(q(t,w)) - c(q(t,w)) - D(q(t,w)) - \gamma(w) \quad (39)$$

where $TW(t,w)$ is assumed strictly concave in (t,w).

The reaction function for the government is defined by the first-order condition

$$\frac{\partial TW(t,w)}{\partial t} = 0 \quad (40)$$

as:

$$R_G(w) = t = \max_t TW(t,w) \quad (41)$$

It is assumed that $R_G(0) > 0$. Differentiating the first-order condition (40) and using the implicit function theorem, we obtain as before

$$R_G'(w) = \frac{\partial t}{\partial w} = -\frac{\partial^2 TW / \partial t \partial w}{\partial^2 TW / \partial t^2}$$

with a strictly concave total welfare function $R_G'(w) < 0$ if $\partial^2 TW / \partial t \partial w < 0$. Furthermore since the slope of the iso-welfare contours in the (w, t) space is $\frac{\partial TW(t,w)}{\partial w} \Big/ \frac{\partial TW(t,w)}{\partial t}$ the iso-welfare contours will be vertical at the point of intersection with the government's reaction function, because of (40).

The Nash equilibrium $\left(w^N, t^N\right)$ for the reference game is defined by the solution of the system

$$\begin{aligned} R_m(t) - w &= 0 \\ R_G(w) - t &= 0 \end{aligned}$$

The Jacobian determinant of the system is $|J| = R_m'(t) R_G'(w) - 1 < 0$, thus a solution exists. Since $R_m(0) = 0$, $R_G(0) > 0$ and the reaction functions are monotonic the solution is unique and positive. At the Nash equilibrium the iso-profit and the iso-welfare contours will be orthogonal.

The optimal time consistent abatement effort and emission tax can be obtained as the solution of the constrained optimization problem

$$\max_{t,w} \pi(w,t) \ , \ \text{ s.t. } \frac{\partial TW(t,w)}{\partial t} = 0 \tag{42}$$

Forming the Lagrangian for the problem and taking the first-order conditions, the optimal point $\left(w^T, t^T\right)$ is characterized by the tangency condition

$$\frac{\partial \pi / \partial w}{\partial \pi / \partial t} = R_G'$$

Since the objective function is convexo-concave, the possibility of multiple equilibria exists. In terms of Figure 3 this would imply tangency of R_G with the iso-profits contours both to the southeast and the northwest of N.[19] A unique solution exists if $\hat{t} > R_G(0)$ in which case only the inverted U-shaped contours are relevant for the optimization problem.

In a similar way the optimal precommitment abatement effort and emission tax can be obtained as the solution of the constrained optimization problem

$$\max_{t,w} TW(w,t) \ , \ \text{ s.t. } \frac{\partial \pi(t,w)}{\partial w} = 0 \tag{43}$$

With a strictly concave total welfare function, its upper contours define convex sets, the preference direction is towards the east, and a

[19] It turns out that in the linear model both for the monopoly and the oligopoly case we have unique solutions to problem (T).

unique solution exists. Since damages decrease with taxes and abatement we expect the preference direction of the iso-welfare curves to point towards the southeast, because damages can be reduced up to a certain level by abatement. Forming the Lagrangian for the problem and taking the first-order conditions, the optimal point $\left(w^C, t^C\right)$ is characterized by the tangency condition

$$\frac{\partial TW / \partial w}{\partial TW / \partial t} = R_m'$$

Taking into account:

1. the slopes of the reaction functions,
2. that the iso-profit contours are horizontal when they intersect the monopolist's reaction function, while the iso-welfare contours are vertical when they intersect the government's reaction function,
3. that in the time consistent equilibrium the iso-profit contours have a negative slope, while in the precommitment equilibrium the iso-welfare contours have a positive slope

the following results can be obtained:

- $\pi\left(w^T, t^T\right) > \pi\left(w^N, t^N\right)$ and $TW\left(w^C, t^C\right) > TW\left(w^N, t^N\right)$, since $\left(w^T, t^T\right)$ maximizes $\pi(w,t)$ for $(w,t) \in X = \{(w,t) : R_G(w) - t = 0\}$ and $\left(w^C, t^C\right)$ maximizes $TW(w,t)$ for $(w,t) \in Y = \{(w,t) : R_m(t) - w = 0\}$, and on the Nash equilibrium point the iso-profit contour and the iso-welfare contour are orthogonal.

- If $\hat{t} > R_G(0)$, so that there is a unique solution to the time consistent problem (T), then $\left(w^T, t^T\right)$ is in the south east of $\left(w^N, t^N\right)$ and $\left(w^C, t^C\right)$ is in the northeast of $\left(w^N, t^N\right)$.

  Then it holds that $t^C > t^N > t^T$, while on the other hand the comparison between w^T and w^C is not straightforward. Since $t^C > t^T$ and the preference direction of the iso-profit contours is towards the southwest it follows that $\pi\left(w^T, t^T\right) > \pi\left(w^C, t^C\right)$. The total welfare comparison again is not straightforward. A sufficient condition for comparison can be obtained as follows:

  Let (w^+, t^+) be the solution of the system $TW(w^+, t^+) - TW(w,t) = 0$, $R_G(w) - t = 0$. If $t^+ < t^T$, then the iso-welfare curve that passes through the point $\left(w^T, t^T\right)$ lies to the right of the iso-welfare curve that passes through the point (w^+, t^+) which corresponds to total welfare value $TW\left(w^C, t^C\right)$. Thus $TW\left(w^T, t^T\right) > TW\left(w^C, t^C\right)$. It turns out that this is always the case for the model analyzed in the text.

- If a multiple solution exists to the (T) problem, say $\left(w_1^T, t_1^T\right)$ and $\left(w_2^T, t_2^T\right)$ then the global optimum should be determined by direct comparison of $\pi\left(w_1^T, t_1^T\right)$ and $\pi\left(w_2^T, t_2^T\right)$. Then all the rest of the comparisons can be carried out.

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TABLE 1

$d\backslash\gamma$	1	10	100
1	$n_{cr} = 3$ $\widehat{n}_t = 4.885$ $\widehat{n}_w = 1.273$ $\widehat{n}_{TW} = 1.736$	$n_{cr} = 5.69$ $\widehat{n}_t = 23.458$ $\widehat{n}_w = 3.257$ $\widehat{n}_{TW} = 4.056$	$n_{cr} = 15.213$ $\widehat{n}_t = 203.641$ $\widehat{n}_w = 10.027$ $\widehat{n}_{TW} = 11.883$
10	$n_{cr} = 1.326$ $\widehat{n}_t = 1.405$ $\widehat{n}_w = 1.180$ $\widehat{n}_{TW} = 1.248$	$n_{cr} = 2.1$ $\widehat{n}_t = 2.389$ $\widehat{n}_w = 2.027$ $\widehat{n}_{TW} = 2.063$	$n_{cr} = 5.067$ $\widehat{n}_t = 6.258$ $\widehat{n}_w = 5.01$ $\widehat{n}_{TW} = 5.038$
100	$n_{cr} = 1.039$ $\widehat{n}_t = 1.046$ $\widehat{n}_w = 1.025$ $\widehat{n}_{TW} = 1.032$	$n_{cr} = 1.187$ $\widehat{n}_t = 1.204$ $\widehat{n}_w = 1.183$ $\widehat{n}_{TW} = 1.185$	$n_{cr} = 2.01$ $\widehat{n}_t = 2.04$ $\widehat{n}_w = 2.01$ $\widehat{n}_{TW} = 2.01$

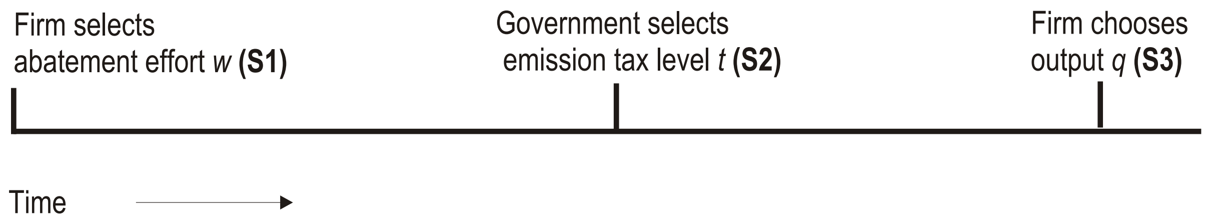

Figure 1: The time consistent policy game

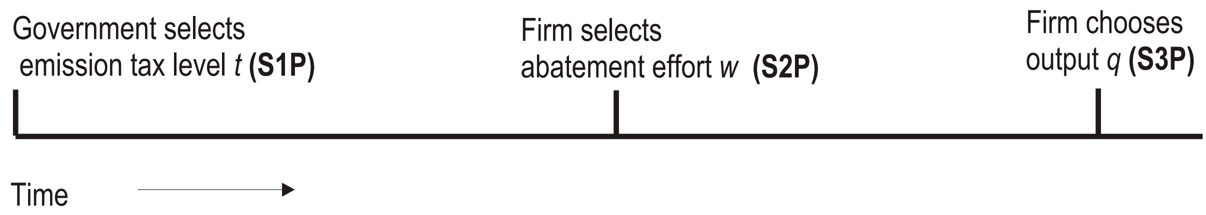

Figure 2: The precommitment policy game

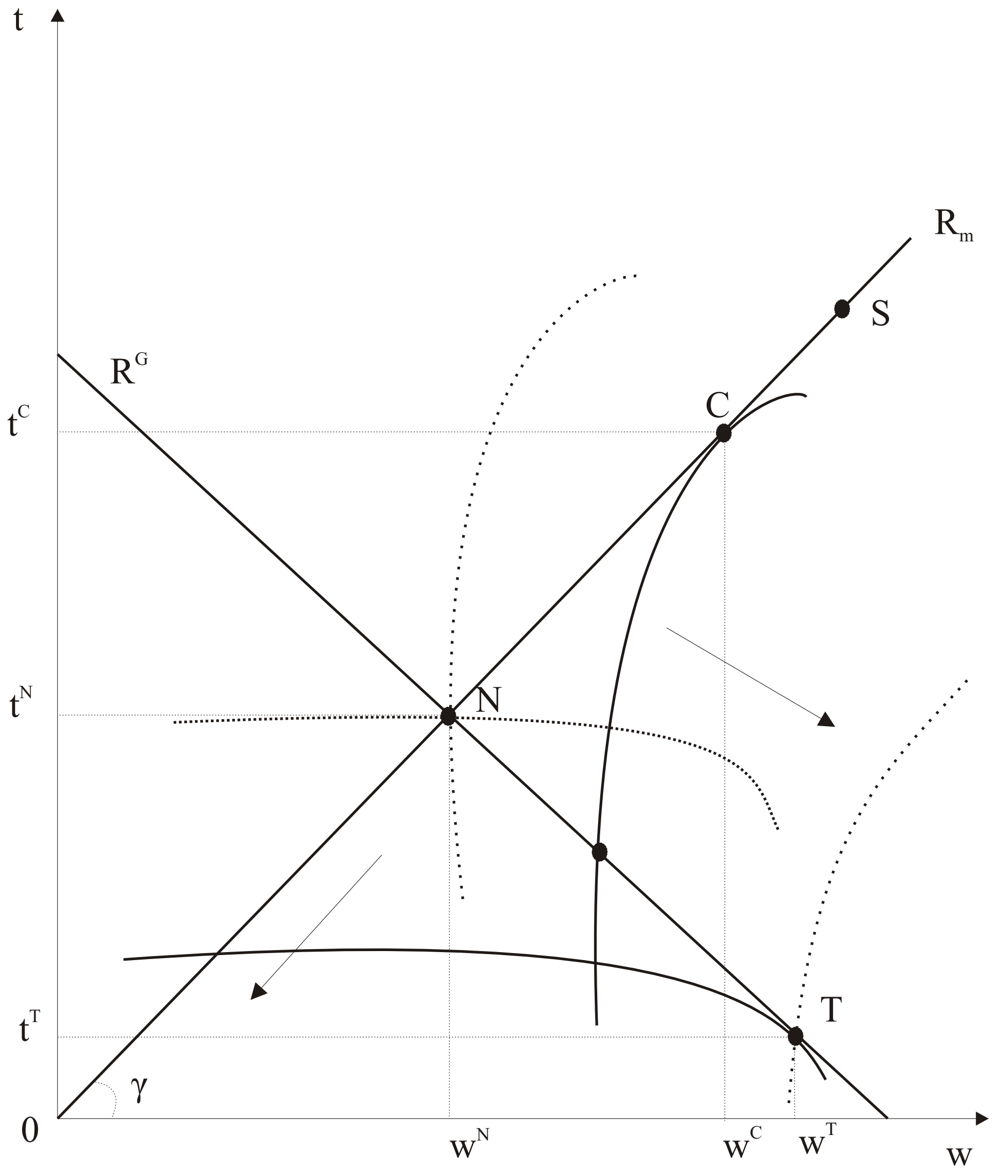

Figure 3: Monopoly

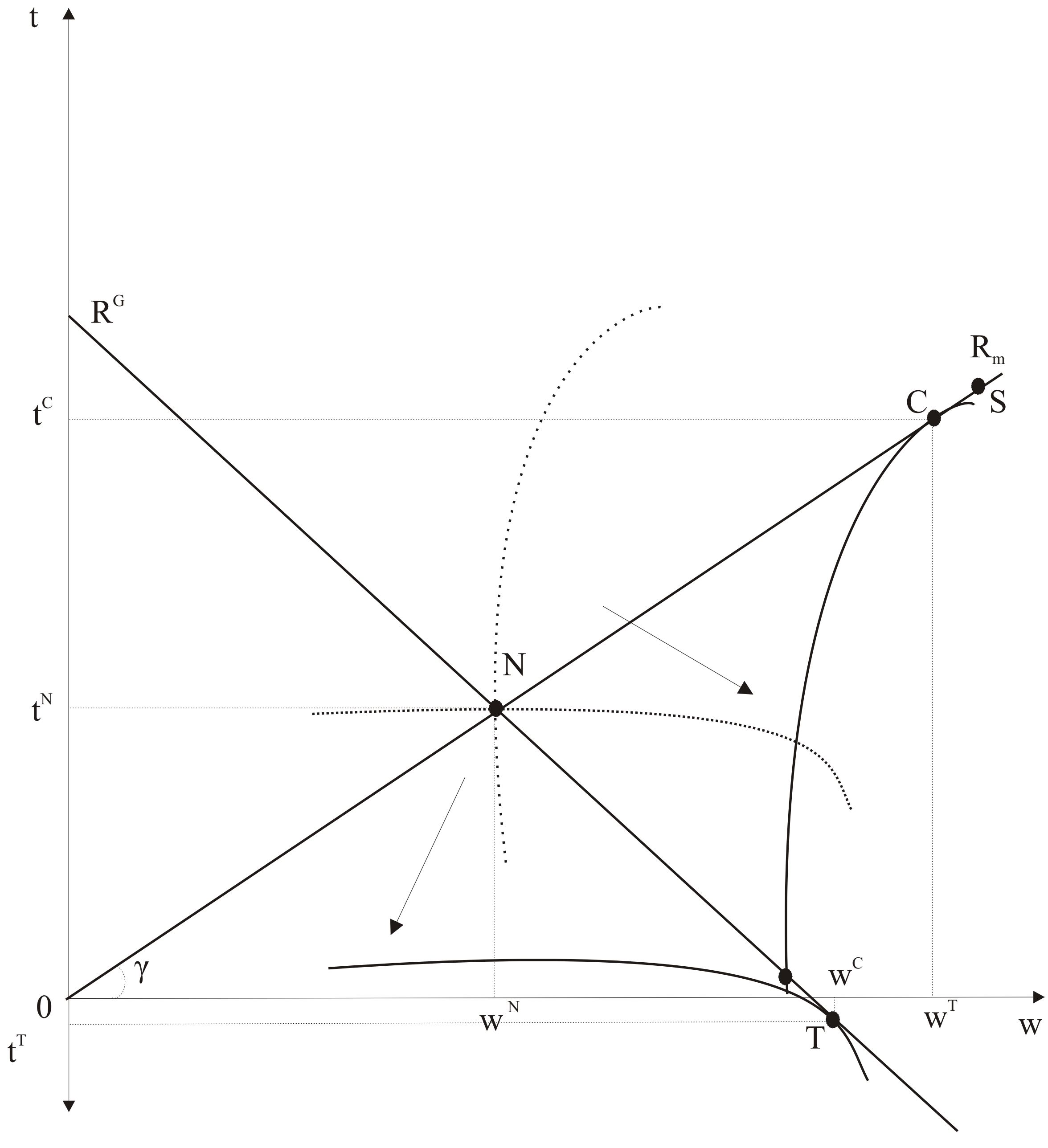

Figure 4: Monopoly

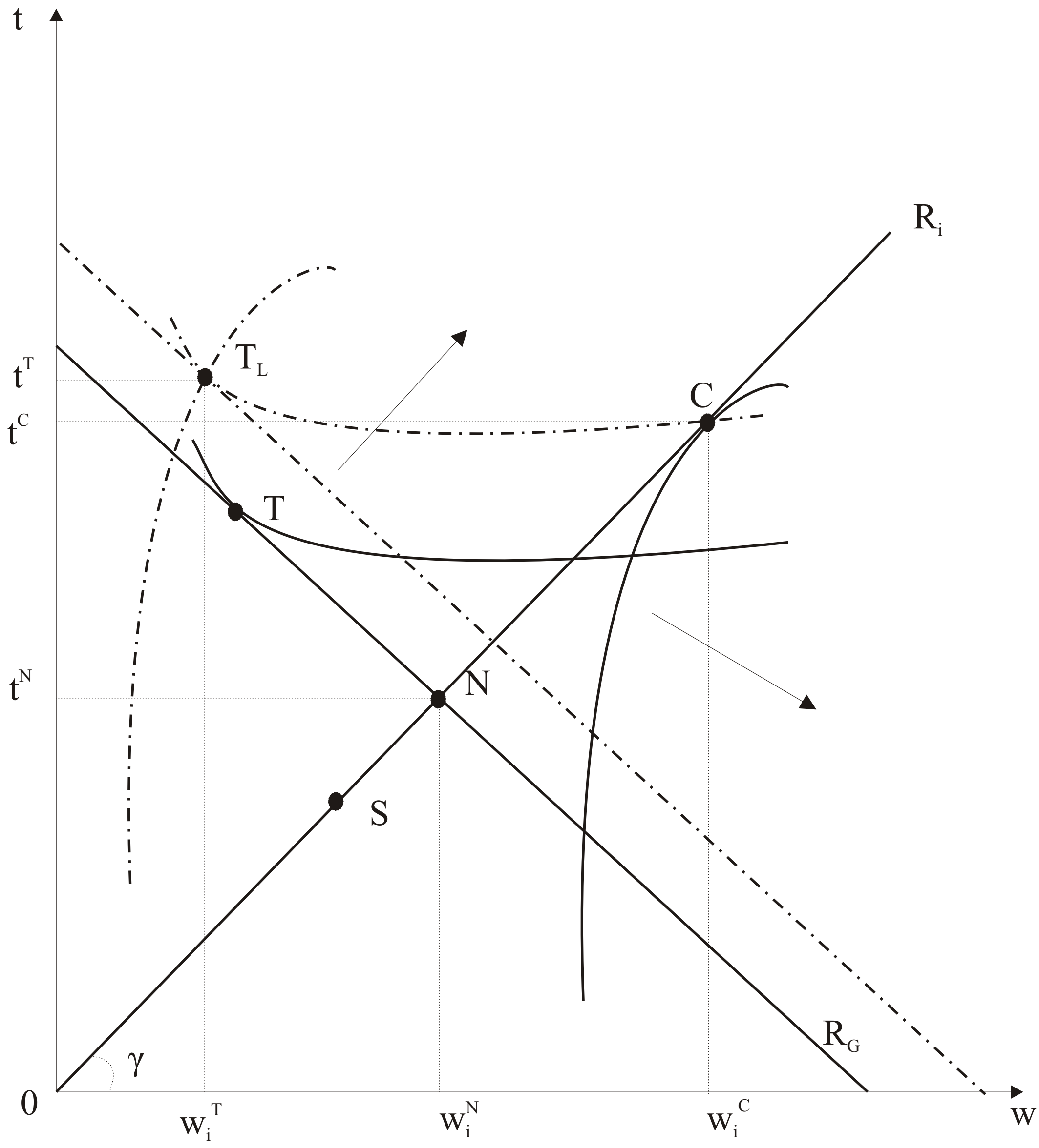

Figure 5: Large numbers oligopoly, $n>n_{cr}(d,\tilde{a})$

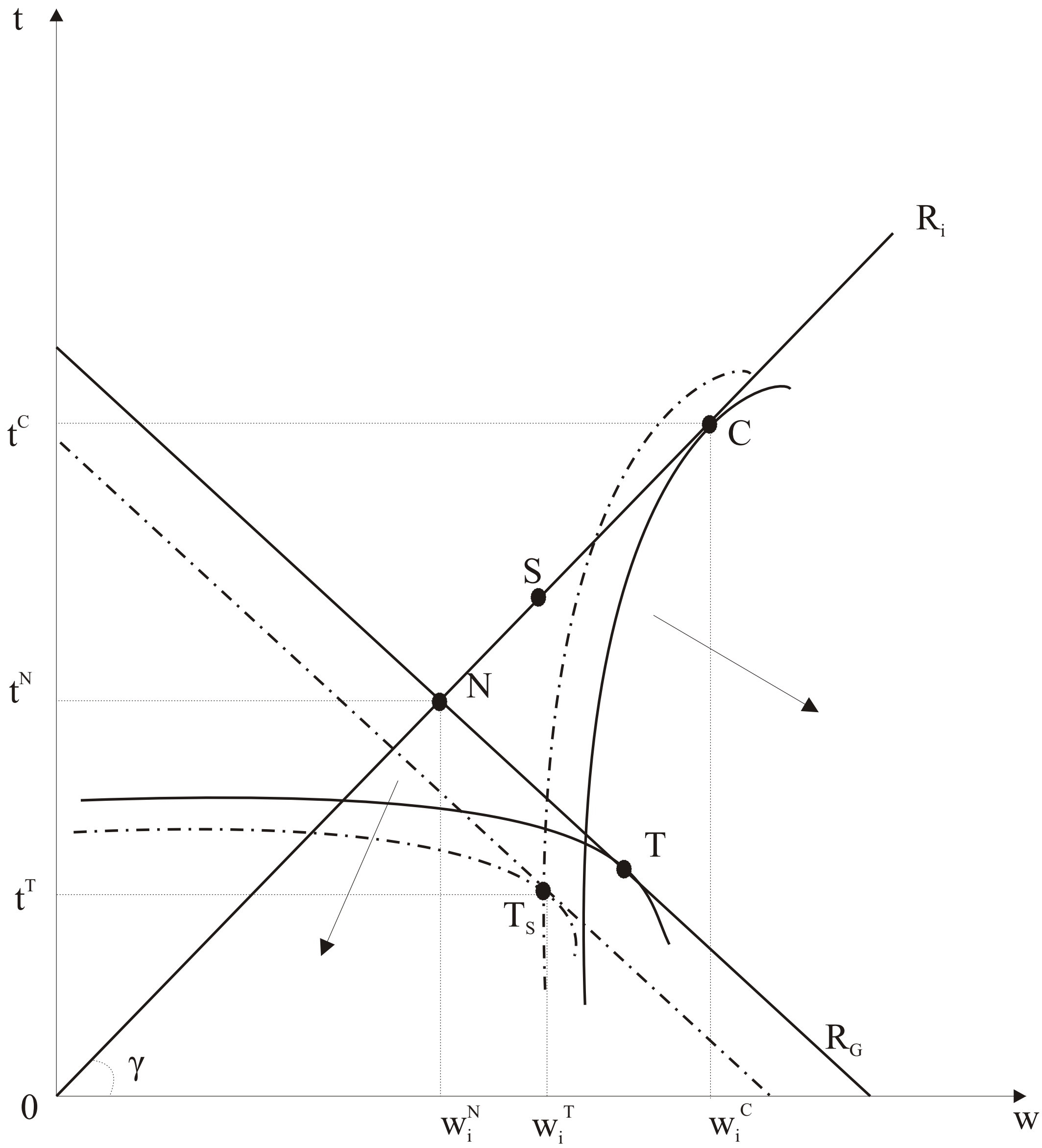

Figure 6: Small numbers oligopoly, $TW^C > TW^T$