Environmental Regulation of Polluting Firms:

Porter's Hypothesis Revisited

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Abstract

This paper provides a theoretical explanation for a regulation-driven win-win situation along the lines of Porter's hypothesis. Using a Cournot duopoly with polluting firms we show that in the absence of government intervention there exist parameter values such that in the resulting Nash equilibrium, both firms choose the old, high polluting technology even though adoption of a new, low polluting technology yields higher profits for both firms (prisoner's dilemma). We then show that government intervention in the form of direct emission controls can eliminate the prisoner's dilemma situation and induce both firms to adopt the modern, low polluting technology provided that the regulation is sufficiently strict. In this case, the reduction in market size for polluting firms is strong enough to reduce profits. By investing in a new, low polluting technology, firms avoid any quantity restrictions on output and enjoy higher profits despite the initial cost of investing in the new technology.

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1. Introduction

Much of the academic and public debate on environmental protection has been concerned with the issue to what extent government intervention to protect the environment is desirable. One question has been particularly contentious, namely whether government regulation could cause product or process adoption (or innovation) by firms which, in turn, would make them more and not less productive and, ultimately, profitable. An argument along this line was first presented by Porter [16], [17] and has become known as the 'Porter hypothesis'. Critics of Porter's view have stressed two points: First, that pollution control necessarily involves a cost to the complying firms that cuts into a firm's profits and undermines its international competitiveness; Second, that productivity gains which could offset these costs do not exist since profit maximizing firms would have adopted or invented the new technologies before any government-imposed regulation. Since any "regulation leads innovation and improves profitability" argument, such as Porter's hypothesis, is in conflict with the efficient market hypothesis, it is important to investigate whether the argument can be derived from first principles, i.e., within the framework of a standard economic model[1].

Previous papers which provide a formal analysis of Porter's hypothesis include Oates, Palmer, and Portney [15], Simpson and Bradford [19], Xepapadea and de Zeeuw [21], and Mohr [13]. With the exception of Mohr, none of these papers find strong evidence for the existence of a win-win

[1] There is some empirical evidence in support of the idea that regulation leads innovation. Gray and Shadbegian [9] find that new paper mills in states with strict environmental regulations are less likely to adopt the more polluting technologies. Jaffe and Palmer [10] report that lagged environmental compliance costs have a positive effect on R&D expenditures for manufacturing industries. There is also some anecdotal evidence in support of Porter's claim. In 1973, the Japanese government set an ambient standard for NO_X more stringent than any other country of the world: 0.02 parts per million in a daily average of hourly values. Usual NO_2 concentrations in large cities ranged from 0.2 to 0.06 parts per million at the time [1]. As a consequence of the tough new standard, Japanese firms invested heavily in R&D to invent new NO_X abatement technology. This research effort led not only to improved abatement technology that made it possible to meet the strict new government standards on air pollution but also, in subsequent years, to a reduction in the cost of the abatement technology itself. Between 1980-84, the cost of FGD (flue gas desulphurization) was lowered by one third [2]. Clearly, higher overall spending on pollution abatement by Japanese firms in the early to mid '70s did not prevent Japan from achieving higher growth rates, lower unemployment rates, and a larger trade surplus than most industrialized countries at the time [14]. Finally, while most likely unintentional, the cleaner, more fuel efficient cars developed by Japanese firms as a result of the strict government regulation became the basis for the success of Japanese car manufacturers in the U.S. automobile market in the aftermath of the oil price shocks of the '70s.

situation as a result of environmental regulation. Oates et al find that the case for the hypothesis rests on the existence of some pre-existing opportunities for cost-savings that have gone unrealized. However, no reasons are given why cost-saving opportunities remain unrealized in the absence of government intervention. Simpson and Bradford find that, for certain parameter values of the cost function, higher effluent taxes may raise both innovation expenditure and profits of the domestic firm. Nevertheless, they conclude that their result is more of a theoretical possibility and that regulation is unlikely to generate competitive advantage in general. Xepapadeas and de Zeeuw develop a model which confirms the main point of Porter's critics, namely the existence of a trade-off between pollution reduction and improved competitiveness. They then consider mitigating factors such as downsizing and modernization of firms that relax the trade-off considerably. They conclude that a win-win situation cannot generally be expected but that the trade-off is not as severe as suggested by Porter's critics[2]. Mohr establishes condition under which government regulation can improve environmental quality and productivity simultaneously. However, while Porter's result is possible in Mohr's framework, it is not optimal in general due to the fact technological improvement allows firms to produce more output per unit of waste. Since the marginal disutility of pollution is constant in his model, a social planner will allow pollution to increase as technology improves.

In this paper we analyze a policy scenario which is a variant of Porter's case, but is, at least a priori, more likely to produce a win-win situation. In contrast to Porter, who assumes unilateral government regulation, we consider the case of multilateral environmental standards as in Ulph [20]. In particular, we analyze an international agreement that sets upper limits on pollution levels for each country/firm[3]. We find that within the context of a simple, static partial equilibrium

[2]The term *win-win* is used because government regulation is supposed to improve both environment and profitability. A related and more widely investigated win-win argument concerns the potential double dividend from an environmental tax reform. See, for example, Goulder [8].

[3]An example for such an international environmental agreement is the Kyoto protocol which requires 38 industrialized countries to reduce the emissions of six major greenhouse gases by 2008-2012. See the text of the protocol at http://www.cnn.com/SPECIALS/1997/global.warming/stories/treaty.

model a regulation-driven win-win situation may indeed occur under certain conditions. However, we need to impose fairly strong restrictions to generate the result which casts doubt on the practical relevance of Porter's hypothesis.

The paper has two main results. First, we show that in a symmetric Cournot duopoly model with polluting firms, there exist parameter values such that in the resulting Nash equilibrium both firms choose the old, high polluting technology even though adoption of a new, low pollution technology would yield higher profits (prisoner's dilemma). Second, we show that government intervention in the form of direct emission controls (i.e., an upper bound on firm level emissions) provides an incentive for firms to invest in an environment-friendly technology and increases firm profits as long as the restriction on pollution levels is sufficiently strict.

The intuition for these results is straightforward. The central mechanism of the paper concerns the trade-off for firms choosing between an old technology with no fixed cost of investment but a high marginal cost of production, and a new technology with lower marginal cost but a certain fixed cost of investment. Given strong enough spillover effects (i.e., if one firm invests in the new technology, the other firm's marginal cost declines as well) and increasing returns to scale that are external to the firm (i.e., if both firms invest in the new technology, marginal costs decline even further for both firms), we can show the existence of a prisoner's dilemma situation in the absence of government intervention.

If direct emission controls are in place, two outcomes are possible. If government regulation is weak, the prisoner's dilemma situation remains intact but profits for both firms rise as the reduction in market size moves the market equilibrium toward the cartel solution. As emission controls become stricter, profits for polluting firms begin to decline at some point and eventually fall below the equilibrium level without government intervention. At some level of emission controls, the optimal strategy for firms becomes to invest in the new, low pollution technology. This technology choice allows firms to operate without government imposed quantity constraints which, together with the lower marginal cost of production, raise profits for each firm despite the cost of investing in the new technology. Therefore, the prisoner's dilemma situation no longer exists. This is the reason why, in contrast to Mohr [13], sufficiently strict environmmental regulation is optimal in our model.

The Cournot duopoly framework chosen in this paper is frequently used in the environmental economics literature, particularly in studies on optimal environmental taxation (see Requate [18] and Ebert [7], among others). With regard to environmental policy instruments, most of the literature has focused on Pigovian taxes and tradable emission permits (TEP), while direct emission controls have received little attention[4]. Formal models of the impact of environmental policies on pollution control innovation by firms have been developed by Downing and White [6], Milliman and Prince [12], and Malueg [11].

The remainder of this paper is organized as follows. We describe the basic model without government regulation in section 2. Section 3 examines the effects of government intervention. Section 4 concludes the paper. The proofs of the propositions are relegated to the Appendix.

2. The Basic Model

We consider a Cournot duopoly model with two firms, a domestic firm, H, and a foreign firm, F. Firm specific variables are indexed by $i = H, F$. Both firms simultaneously choose their respective output levels, Q_i, from the feasible set $Q_i = [0, \infty]$. They sell their output at the market clearing price $P(Q) = A - Q$ where $Q = Q_H + Q_F$. The firm's cost structure depends on the state of its production technology. A firm can choose between two technologies, a new and an old one. The old technology does not involve a fixed cost of investment but comes with a high marginal cost of

[4] For a survey of the literature on Pigovian taxes and TEPs, see the article by Cropper and Oates [5].

production, while the new technology has a lower marginal cost but a strictly positive fixed cost of investment, I. Furthermore, if both firms use the old technology, marginal cost (MC) is equal to α for both firms. If one firm chooses the new and the other the old technology, the marginal cost of the firm with the new technology falls to β (with $\beta < \alpha$), while the marginal cost for the other firm declines to δ (with $\alpha > \delta \geq \beta$ due to the assumption of within-industry spillover effects). Note that $\delta = \beta$ in the case of perfect spillover effects. When both firms use the new technology, marginal costs fall even further to γ (with $\gamma < \beta$) for both firms. This additional decline in the marginal cost of production reflects the assumption of economies of scale at the industry level.

We assume that pollutant emissions, E_i, are proportional to total output of firm i, i.e., $E_i = aQ_i$ where a is the pollution coefficient when both firms use the old technology. Naturally, the pollution coefficient varies with the state of the art of the chosen production technology. If only one firm uses the new, low pollution technology, the pollution coefficient of this firm is equal to b (with $b < a$), while the other firm's pollution coefficient is d (with $d < a$ due to environmental spillover effects). Also, $b \leq d$, with equality holding in the case of perfect spillovers. If both firms use the new technology, the pollution coefficient of each firm is equal to c (with $c < b$ due to external economies of scale).

We solve the model assuming perfect spillovers in both production and pollution, i.e., we set $\delta = \beta$ and $d = b$. To further simplify matters, we also assume that $\gamma = c = 0$. This assumption is purely a matter of convenience. The results of the model would hold for positive values of γ and c as well. Finally, it is worth noting that given the functional forms of demand and cost functions in this model, profit functions are differentiable, strictly concave and satisfy appropriate boundary conditions. We can therefore derive the reaction functions using the first order conditions.

Since each firm can choose between two production technologies, there are four combinations of investment strategies.

Case I: Both firms do not invest in the new technology. Profits are given by

$$\pi_H(Q_H, Q_F) = (A - Q_H - Q_F)Q_H - \alpha Q_H \tag{2.1}$$

$$\pi_F(Q_H, Q_F) = (A - Q_H - Q_F)Q_F - \alpha Q_F \tag{2.2}$$

Case II : Both firms invest in the new technology. Profits are given by

$$\pi_H(Q_H, Q_F) = (A - Q_H - Q_F)Q_H - I \tag{2.3}$$

$$\pi_F(Q_H, Q_F) = (A - Q_H - Q_F)Q_F - I \tag{2.4}$$

Case III (**IV**): Domestic firm (foreign firm) invests and foreign firm (domestic firm) does not. Profits for the case that domestic firm invests are given by

$$\pi_H(Q_H, Q_F) = (A - Q_H - Q_F)Q_H - \beta Q_H - I \tag{2.5}$$

$$\pi_F(Q_H, Q_F) = (A - Q_H - Q_F)Q_F - \beta Q_F \tag{2.6}$$

Solving the profit maximization problem for each firm for each of the four cases leads to the following matrices for profits, output, and pollution levels (Table 1a-c).

Table 1a: **Profit**

		F	
		Not Invest	Invest
H	Not Invest	$\left(\frac{A-\alpha}{3}\right)^2, \left(\frac{A-\alpha}{3}\right)^2$	$\left(\frac{A-\beta}{3}\right)^2, \left(\frac{A-\beta}{3}\right)^2 - I$
	Invest	$\left(\frac{A-\beta}{3}\right)^2 - I, \left(\frac{A-\beta}{3}\right)^2$	$\left(\frac{A}{3}\right)^2 - I, \left(\frac{A}{3}\right)^2 - I$

Table 1b: **Output**

		F	
		Not Invest	Invest
H	Not Invest	$\frac{(A-\alpha)}{3}, \frac{(A-\alpha)}{3}$	$\frac{(A-\beta)}{3}, \frac{(A-\beta)}{3}$
	Invest	$\frac{(A-\beta)}{3}, \frac{(A-\beta)}{3}$	$\frac{A}{3}, \frac{A}{3}$

Table 1c: **Pollution**

	F		
H		Not Invest	Invest
	Not Invest	$\frac{a(A-\alpha)}{3}, \frac{a(A-\alpha)}{3}$	$\frac{b(A-\beta)}{3}, \frac{b(A-\beta)}{3}$
	Invest	$\frac{b(A-\beta)}{3}, \frac{b(A-\beta)}{3}$	$0, 0$

Proposition 2.1. There exists a non-trivial set of parameter values such that in the resulting Nash equilibrium both firms will choose the old, high polluting technology even though the new, low polluting technology yields higher profits if chosen by both firms (prisoner's dilemma).

Proof: see Appendix A.

We illustrate the existence of a prisoner's dilemma situation with a numerical example. We set $A = 20$, $\alpha = 2$, and $\beta = 1$. Recall that $\gamma = c = 0$. Note that our choice of A and α satisfies condition 1 in Appendix A. To satisfy condition 2 and 3 (see Appendix A) we need to find a value for I such that $4.3 < I < 8.4$. We choose $I = 6$. The chosen parameter values yield the following payoff matrix (Table 2):

Table 2: **Profit**

	F		
H		Not Invest	Invest
	Not Invest	$36, 36$	$40.1, 34.1$
	Invest	$34.1, 40.1$	$38.44, 38.44$

As can be seen from Table 2, the dominant strategy for both firms is to adopt the old, high polluting technology. The outcome with the highest level of profits – to invest in the new, low-pollution technology – is not sustainable due to the free rider advantage of the non-investing firm caused by spillover effects between firms. Next, we examine whether government regulation can produce an equilibrium which improves both the profitability of firms and the quality of the environment.

3. Government Intervention

The objective of the domestic and the foreign government is to reduce the level of pollution in the industry. To achieve this goal both governments agree to impose a cap on the total level of pollutants emitted by each firm. Thus, the agreement specifies a pollution standard which firms cannot exceed. We assume that governments are fair and treat all the firms alike so that the environmental regulation is imposed equally on both firms. This can be thought of as handing out a non-tradable permit to each firm allowing each to emit at most $\overline{X}$ units of the pollutant.

One of the interesting effects of direct emission controls in a Cournot duopoly model is that government regulations imply restrictions on output levels which, in turn, will increase profits for both firms as long as regulation is sufficiently weak. This is due to the well-known result of overproduction in oligopoly models vis-a-vis the cartel outcome. For sufficiently strict restrictions on pollution and thus output levels, profits will decline and eventually be lower than without government regulation.

To determine the impact of direct emissions controls on profits, output, and emission levels, we repeat the previous exercise with the difference that government regulation constitutes a new constraint for firms. Instead of the previous four cases, we now have to distinguish between six scenarios depending on whether or not the new constraint is binding in case III and IV.

Case I : Both firms do not invest in the new technology and the constraint is therefore binding for each firm ($\overline{X} = aQ_H, \overline{X} = aQ_F$).

Case II : Both firms invest in the new technology and thus both firms operate without constraint.

Case IIIa (**IVa**): The domestic (foreign) firm invests, the foreign (domestic) firm does not invest, and the constraint is not binding for either firm.

Case IIIb (**IVb**): The domestic (foreign) firm invests, the foreign (domeistic) firm does not invest, and the constraint is binding for both firms ($\overline{X} = bQ_H$, $\overline{X} = bQ_F$).

Solving the profit maximization problem yields the following matrices for profit, output, and pollution (Table 3a-f):

Table 3a: **Profit - weak regulation**

		F	
		Not Invest	Invest
H	Not Invest	$\frac{\overline{X}}{a}\left(A-\alpha-2\frac{\overline{X}}{a}\right), \frac{\overline{X}}{a}\left(A-\alpha-2\frac{\overline{X}}{a}\right)$	$\left(\frac{A-\beta}{3}\right)^2 . \left(\frac{A-\beta}{3}\right)^2 - I$
	Invest	$\left(\frac{A-\beta}{3}\right)^2 - I, \left(\frac{A-\beta}{3}\right)^2$	$\left(\frac{A}{3}\right)^2 - I, \left(\frac{A}{3}\right)^2 - I$

Table 3b: **Profit - strict regulation**

		F	
		Not Invest	Invest
H	NI	$\frac{\overline{X}}{a}\left(A-\alpha-2\frac{\overline{X}}{a}\right), \frac{\overline{X}}{a}\left(A-\alpha-2\frac{\overline{X}}{a}\right)$	$\frac{\overline{X}}{b}\left(A-\beta-2\frac{\overline{X}}{b}\right), \frac{\overline{X}}{b}\left(A-\beta-2\frac{\overline{X}}{b}\right) - I$
	I	$\frac{\overline{X}}{b}\left(A-\beta-2\frac{\overline{X}}{b}\right) - I, \frac{\overline{X}}{b}\left(A-\beta-2\frac{\overline{X}}{b}\right)$	$\left(\frac{A}{3}\right)^2 - I, \left(\frac{A}{3}\right)^2 - I$

Table 3c: **Output - weak regulation**

		F	
		Not Invest	Invest
H	Not Invest	$\frac{\overline{X}}{a}, \frac{\overline{X}}{a}$	$\frac{(A-\beta)}{3}, \frac{(A-\beta)}{3}$
	Invest	$\frac{(A-\beta)}{3}, \frac{(A-\beta)}{3}$	$\frac{A}{3}, \frac{A}{3}$

Table 3d: **Output - strict regulation**

		F	
		Not Invest	Invest
H	Not Invest	$\frac{\overline{X}}{a}, \frac{\overline{X}}{a}$	$\frac{\overline{X}}{b}, \frac{\overline{X}}{b}$
	Invest	$\frac{\overline{X}}{b}, \frac{\overline{X}}{b}$	$\frac{A}{3}, \frac{A}{3}$

Table 3e: **Pollution - weak regulation**

		F	
		Not Invest	Invest
H	Not Invest	$\overline{X}, \overline{X}$	$\frac{b(A-\beta)}{3}, \frac{b(A-\beta)}{3}$
	Invest	$\frac{b(A-\beta)}{3}, \frac{b(A-\beta)}{3}$	$0, 0$

Table 3f: **Pollution - strict regulation**

		F	
		Not Invest	Invest
H	Not Invest	$\overline{X}, \overline{X}$	$\overline{X}, \overline{X}$
	Invest	$\overline{X}, \overline{X}$	$0, 0$

Comparing Table 1a with Table 3a reveals that weak government regulation does not change payoffs except for the case that both firms choose the old technology (in which case profits are higher with regulation). Therefore, under the conditions of the first proposition, the dominant strategy for both firms is still to choose the old, high polluting technology, while the "invest-invest" strategy would yield the best outcome in terms of profits. Weak environmental regulation is thus unable to alter the prisoner's dilemma outcome. In contrast, sufficiently stringent caps on pollution levels alter all payoffs except for the case that both firms choose the new technology (Table 3b). Sufficiently strict regulation, therefore, opens the door for government regulation to move the economy out of the prisoner's dilemma trap. This possibility is made precise in the following proposition.

Proposition 3.1. Provided that government regulation imposes a sufficiently strict limit on the overall level of pollution, there exists a non-trivial set of parameter values such that in the resulting Nash equilibrium both firms choose the new, low polluting technology.

Proof: see Appendix B.

To illustrate this result, we analyze the numerical example from the previous section for three different pollution limits: $\overline{X} = 10$, $\overline{X} = 5$, and $\overline{X} = 2$. Based on these values (all other parameter values are the same as in the previous section), we derive the following payoff matrices:

Table 4a: **Profit** ($\overline{X} = 10$)

		F	
		Not Invest	Invest
H	Not Invest	$40, 40$	$40.1, 34.1$
	Invest	$34.1, 40.1$	$38.44, 38.44$

Table 4b: **Profit** ($\overline{X} = 5$)

		F	
		Not Invest	Invest
H	Not Invest	$32.5, 32.5$	$70, 64$
	Invest	$64, 70$	$38.44, 38.44$

Table 4c: **Profit** ($\overline{X} = 2$)

		F	
		Not Invest	Invest
H	Not Invest	$16, 16$	$30, 24$
	Invest	$24, 30$	$38.44, 38.44$

When regulation is weak ($\overline{X} = 10$), the dominant strategy is still to choose the old, high polluting technology, but firm profits increase compared to the case without government intervention (Table 2). However, if regulation becomes more stringent ($\overline{X} = 5$), a dominant strategy no longer exists. There are two equilibria now: "invest - not invest" and "not invest - invest". When regulation is strict ($\overline{X} = 2$), the dominant strategy for both firms is to invest in the new pollution-free technology. In that case, profits are lower than in the case with weak regulation (Table 4a) but exceed profits in the case without government regulation (Table 2). This illustrates the existence of a regulation-driven win-win situation that combines higher profits with lower pollution levels.

4. Summary and Conclusions

In this paper, we consider a Cournot duopoly model of two polluting firms having to choose between an old and new production technology in two different political environments: with and without government restrictions on pollution levels. The paper has two main results. First, in the absence of government intervention, we demonstrate the existence of an equilibrium such that the dominant strategy for both firms is to choose the old, high-pollution technology. The more profitable outcome - both firms choose the new, low pollution technology - is not an equilibrium since each firm has an incentive to free ride on the other firm's investment decision (prisoner's dilemma). Second, we show that sufficiently strict direct emission controls eliminate the prisoner's dilemma situation and induce both firms to adopt the modern, low polluting technology, the outcome characterized by higher profits and lower pollution levels.

The paper provides a formal model that describes how environmental regulation can lead to a win-win situation. However, to achieve this goal, restrictive assumptions had to be imposed: imperfectly competitive market structure, asymmetric cost structure among alternative technologies, intra-industry spillover effects, and economies of scale at the industry level. Whether these restrictions hold in reality remains an open question. But even if they do hold, the existence of a prisoner's dilemma situation without government intervention also depends on certain parameter values. For other values, a prisoner's dilemma outcome may not exist, making the impact of government restrictions less predictable and/or less desirable. If, for example, a firm's choice to invest in the old, high polluting technology happens to be the most profitable outcome in the absence of government intervention, direct emission controls will not be able to increase profits independent of whether emission standards are weak or strict.

The goal of this research was to derive a simple, formal model that produces a win-win situation as a result of international environmental regulation. Given the restrictiveness of the imposed conditions, it seems unlikely - though not impossible - that international environmental agreements will improve both a country's environment and the profitability of its firms. An interesting topic for future research would be to see if the main results of this study continue to hold in a less restrictive framework. Any affirmative answer to this question would make a win-win situation more likely in practice and would lend, indirectly, more credibility to Porter's original hypothesis.

Appendix A

Proof of Proposition 2.1:

The general profit matrix for the Cournot duopoly is given by

		F	
		Not Invest	Invest
H	Not Invest	π_H^I, π_F^I	π_H^{IV}, π_F^{IV}
	Invest	π_H^{III}, π_F^{III}	π_H^{II}, π_F^{II}

where subscripts denote firms and superscripts denote investment strategies. To generate a prisoner's dilemma situation, the following inequalities must hold: $\pi_H^{II} > \pi_H^I$, $\pi_H^{III} < \pi_H^I$, $\pi_H^{IV} > \pi_H^I$, $\pi_H^{III} < \pi_H^{II}$, $\pi_H^{IV} > \pi_H^{II}$ and $\pi_H^{IV} > \pi_H^{III}$. Using Table 1a, these conditions translate into the following inequalities:

a) $\left(\frac{A}{3}\right)^2 - I > \left(\frac{A-\alpha}{3}\right)^2$ which implies $\frac{1}{9}\alpha(2A-\alpha) > I$.

b) $\left(\frac{A-\beta}{3}\right)^2 - I < \left(\frac{A-\alpha}{3}\right)^2$ which implies $\frac{1}{9}(\alpha-\beta)(2A-\alpha-\beta) < I$.

c) $\left(\frac{A-\beta}{3}\right)^2 > \left(\frac{A-\alpha}{3}\right)^2$ which implies $(\alpha-\beta)(2A-\alpha-\beta) > 0$.

d) $\left(\frac{A-\beta}{3}\right)^2 - I < \left(\frac{A}{3}\right)^2 - I$ which implies $\beta(2A-\beta) > 0$.

e) $\left(\frac{A-\beta}{3}\right)^2 > \left(\frac{A}{3}\right)^2 - I$ which implies $\frac{1}{9}\beta(2A-\beta) < I$.

f) $\left(\frac{A-\beta}{3}\right)^2 > \left(\frac{A-\beta}{3}\right)^2 - I$ which implies $I > 0$.

These six inequalities can be reduced to a set of four inequalities:

1) $A > \alpha$

2) $I < \frac{1}{9}\alpha(2A-\alpha)$

3) $I > \frac{1}{9}\beta(2A-\beta)$

4) $I > \frac{1}{9}(\alpha-\beta)(2A-\alpha-\beta)$

It is easy to show that there are non-trivial sets of parameter values that suffice these inequalities. The figures below illustrate this result for the case of $A = 20$ and $\beta = .5\alpha$ (Figure 2a) and for the case of $A = 20$ and $\beta = .33\alpha$ (Figure 2b). Note that with $\beta = .5\alpha$, the fourth inequality is non-binding and is thus omitted from Figure 2a. The area 0YZ in Figure 2a (area 0XYZ in Figure 2b) contains the combinations of I and α that will generate the prisoner's dilemma outcome from Proposition 1.

Figure 2a: Values of I and α consistent with Proposition 1

(for $A = 20$ and $\beta = .5\alpha$)

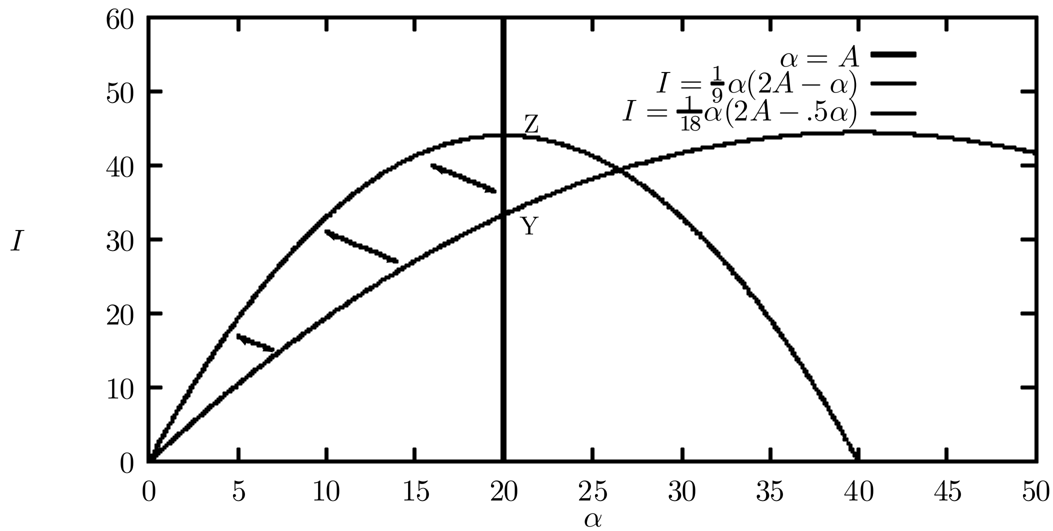
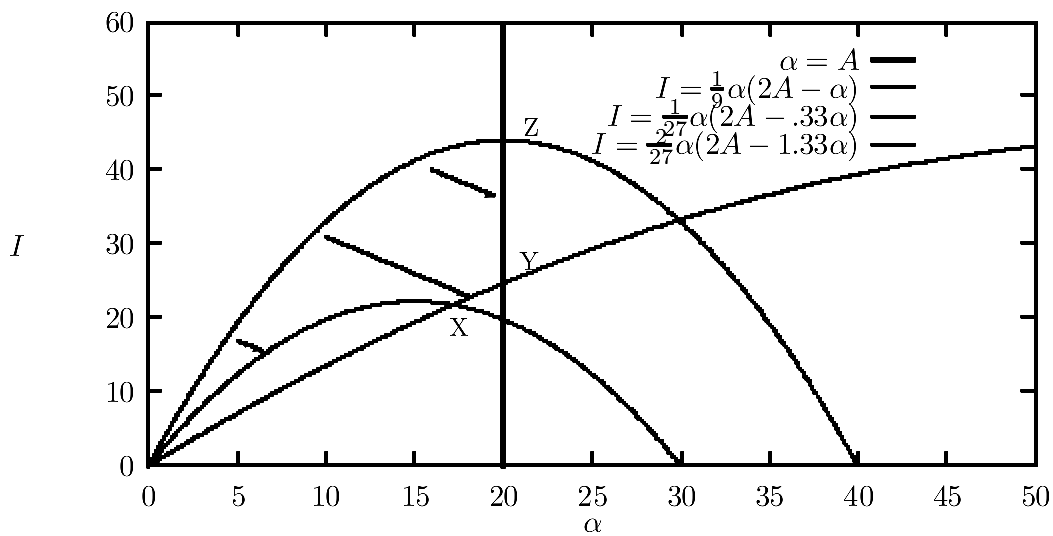


Figure 2b: Values of I and α consistent with Proposition 1

(for $A = 20$ and $\beta = .33\alpha$)



Appendix B

Proof of Proposition 3.1: For sufficiently strict environmental regulation (case IIIb and IVb), the relevant payoffs (profits) are given in Table 3b. In order for firms to invest in the new, low-pollution technology, the following inequalities are needed: $\pi_H^{II} > \pi_H^{IV}$, $\pi_H^{III} > \pi_H^{I}$, $\pi_F^{II} > \pi_F^{III}$, $\pi_F^{IV} > \pi_F^{I}$, $\pi_H^{II} > \pi_H^{I}$, and $\pi_F^{II} > \pi_F^{I}$. Given the symmetry of the model, three of these conditions are redundant. The remaining three conditions are:

a) $\left(\frac{A}{3}\right)^2 - I > \frac{\overline{X}}{b}\left(A - \beta - 2\frac{\overline{X}}{b}\right)$

b) $\frac{\overline{X}}{b}\left(A - \beta - 2\frac{\overline{X}}{b}\right) - I > \frac{\overline{X}}{a}\left(A - \alpha - 2\frac{\overline{X}}{a}\right)$

c) $\left(\frac{A}{3}\right)^2 - I > \frac{\overline{X}}{a}\left(A - \alpha - 2\frac{\overline{X}}{a}\right)$

Assuming that $a = \alpha$ and $b = \beta$, the inequalities can be rewritten as:

1) $I < \frac{1}{9}A^2 - \frac{\overline{X}}{\beta}\left(A - \beta - 2\frac{\overline{X}}{\beta}\right)$.

2) $I < A\overline{X}\left(\frac{1}{\beta} - \frac{1}{\alpha}\right) + 2\overline{X}^2\left(\frac{1}{\alpha^2} - \frac{1}{\beta^2}\right)$.

3) $I < \frac{1}{9}A^2 - \frac{\overline{X}}{\alpha}\left(A - \alpha - 2\frac{\overline{X}}{\alpha}\right)$.

Once again, it is easy to show that there are non-trivial parameter values of A, α, β, and $\overline{X}$ that suffice these inequalities (e.g., $\{A, \alpha, \beta, I, \overline{X}\} = \{20, 3, 2, 6, 3\}$.

An important question that needs to be addressed is whether there are non-trivial parameter values that simultaneously suffice the inequalities constraints from both propositions. That this is indeed the case can be demonstrated as follows. Choose $\alpha = \overline{X}$ and assume that $\beta = .5\alpha$, as in Figure 2a. The three inequalities can then be rewritten as:

1') $I < \frac{1}{9}A^2 - 2A + 8 + \alpha$

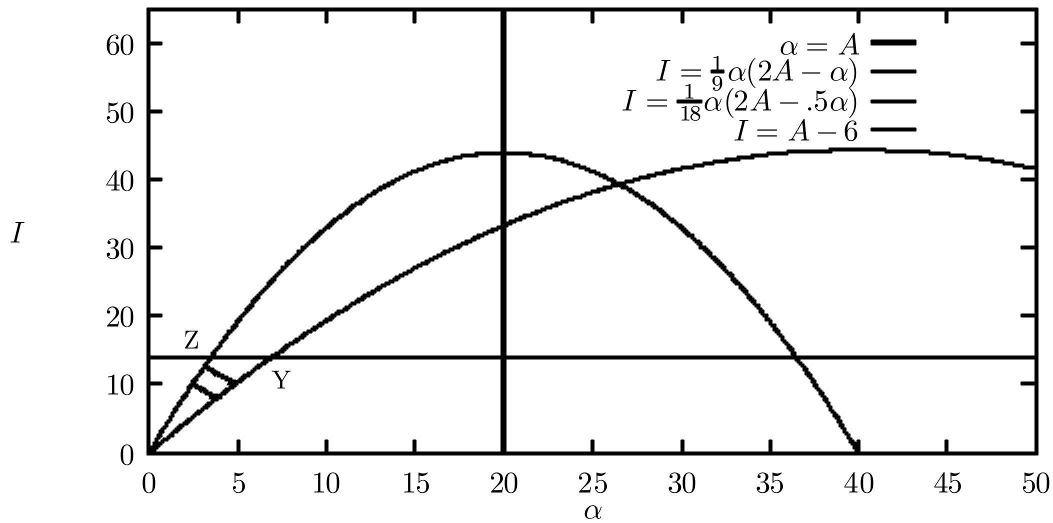
2') $I < A - 6$

3') $I < \frac{1}{9}A^2 - A + 2 + \alpha$

Clearly, if condition (2') is met, conditions (1') and (3') will hold as well. Figure 3 below is identical to Figure 2a except that condition (2') has been added (as equality). The area 0YZ contains the values of I and α $(= \overline{X})$ that are compatible with both propositions. The example used in section 3, $\{A, \alpha, \beta, I, \overline{X}\} = \{20, 2, 1, 6, 2\}$, belongs to this set.

Figure 3: Values of I and α consistent with Propositions 1 and 2

(for $A = 20$, $\beta = .5\alpha$, and $\alpha = \overline{X}$)



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