"Pollution Havens" and the Regulation of Multinationals by Multiple Governments*

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ABSTRACT

This paper develops a common agency model to analyze the strategic interaction between governments in regulating "dirty" multinational firms. These firms possess private information about the degree of pollution associated with their production technologies. The study shows that the strategic behavior between non-cooperative governments, as a result of asymmetric information, works against the "pollution haven" hypothesis. The paper highlights the importance of factors that can dominate environmental costs in a government's welfare maximization decision rather than those in a firm's profit maximization decision. The paper also draw implications on the empirical studies of the "pollution haven" hypothesis.

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1 Introduction

Since countries with low environmental standards can gain a comparative cost advantage in the international commodity market, the "pollution haven" hypothesis suggests that foreign investors will flock to poorer countries to take advantage of their lax environmental standards. It has long been debated whether this fear is a legitimate concern in terms of preserving the global environment. This paper puts aside whether different environment standards would damage the global environment, but focuses on whether governments would set different environmental standards that would contribute to the "pollution haven" hypothesis. This naturally leads to the question how "dirty" multinational firms locate their production.

The "pollution haven" hypothesis is based on a simple intuition that people in a poorer country would have a lower marginal valuation on the environment (or a lower marginal disutility of pollution) and hence a lower marginal social cost of production.[1] To maximize social welfare, the government in a poorer country would set lower environment taxes or standards, which would result in a lower production cost. This would attract multinationals to reallocate their production from a richer country to a poorer country to minimize their marginal costs of production.

Not surprisingly, when we take into consideration the marginal private costs other than pollution taxes, the "pollution haven" hypothesis will break down. However, some empirical results show that the "pollution haven" hypothesis does not hold even after controlling for factors that can dominate environmental costs in a firm's profit optimization decision, such as transportation costs, factor costs, economies of scale, country risks, etc. For an example, Eskeland and Harrison (1997) show that there is almost no evidence that investors in developed countries flee environmental costs at home after they have controlled in their regressions for the openness of an economy, industrial concentration, the domestic regulatory environment, factor endowments, and wages in the hosting country.

If we have controlled for the major factors that work against the "pollution haven" hypothesis, we should be able to observe "pollution havens," and furthermore, we would be able to estimate the

[1] Empirical studies on the relationship between pollution and income growth, which affects one's marginal disutility of pollution, include Grossman and Krueger (1995), Komen et al. (1997), Selden and Song (1994), and the World Bank (1992).

contribution of each of these factors in making the "pollution haven" hypothesis invalid. If one or more of these factors are at work in a particular sector or country, we can be sure that there will be no "pollution havens," and we can put our minds to rest. Thus, the puzzle here is what else is missing besides the above factors.

To solve this puzzle, this paper turns attention to the role of governments instead of private firms and argues that the strategic behavior between non-cooperative governments changes the marginal social cost of production. This change affects a multinational firm's production allocation and works against the "pollution haven" hypothesis, but is ignored in most of the empirical tests of the "pollution haven" hypothesis. The model developed in this paper assumes two governments and a continuum of multinational firms. Pollution generated by the firms can be transboundary.

From a government's point of view, the simple intuition of the "pollution haven" hypothesis becomes more complicated once a government observes neither a firm's pollution level nor a firm's production technology that relates output to pollution. Although there have been many improvements in measuring pollution directly and accurately with reasonable costs, this asymmetric information is still the main obstacle in regulating pollution and is especially so when there are multinational firms.

First, since each competitive multinational firm can have a different production technology with which its production pollutes, there is no one-to-one relationship between output and pollution. The relationship depends on the technology used. If a government simply imposes a uniform output tax on all firms, then for a given output, a firm with a dirtier technology would pay the same tax as a firm with a cleaner technology though the "dirtier" firm emits more pollution and causes more damage to the environment. A welfare improving environmental policy requires governments to levy a higher tax on firms with a dirtier technology than on those with a cleaner technology. Thus, each government has to design a mechanism with which to induce firms to reveal their true production technologies.

Second, the existence of multinationals and transboundary pollution greatly complicates the above asymmetric information problem under non-cooperative governments. In the absence of multinational firms and transboundary pollution, asymmetric information is only a national problem. The degree to which a firm's production technology pollutes is only important to the local government. To regulate a "dirty" multinational firm, both the home and host governments have to know the firm's true production technology so as to implement an appropriate tax policy, even when pollution does not cross national boundaries. This leads to a common agency problem with governments as principals and multinational firms as comment agents.

Third, the above common agency problem creates strategic interaction between governments in their individual attempts to obtain information about a firm's production technology at the lowest possible cost. An information rent is paid to firms in terms of retained after-tax profits. Under asymmetric information, a firm must keep a minimum positive after-tax profit so as to be willing to reveal its true technology. Each government has an incentive to collect more taxes from a firm by increasing local production and forcing the other government to contribute more to meet a firm's minimum retained profit requirement. Thus, the attempt to minimize information rent payment provides both governments an incentive to increase local production so as to squeeze the tax revenue collected by the other government. The following analysis shows that this rent extraction behavior is more effective and thus production increases more in the developed countries with higher environmental standards than in the developing countries with lower environmental standards. This can cause the "pollution haven" hypothesis to break down.

Hoel (1991, 1997), Dockner and Long (1993), Folmer et al. (1993), and Markusen, Morey and Olewiler (1995) also focuses on how governments would strategically affect firms' production allocation, but their studies are all based on full information so that governments can extract all profits. Hoel (1991,1997), Dockner and Long (1993), and Folmer et al. (1993) study the case of transboundary pollution for local firms. Markusen, Morey and Olewiler (1995) leave out transboundary pollution and focus on the competition between governments in levying environmental taxes on multinational firms. The competition for additional tax revenues, which is their governments' major trade-off against the disutility of added pollution, is in terms of monopoly profits rather than information rents as in this paper.

In the common agency literature, Bernheim and Whinston (1985, 1986), Laffont and Tirole (1991), Martimort (1992), and Stole (1992) extend the bilateral principal-agent model with moral hazard of Holmstrom (1979) and Grossman and Hart (1983), and are the first to introduce the common agency problem with two uninformed principals and one common agent with either private information or unobservable action.[2] In their models as in this paper, the two principals have the same information set and the agent's type affects the principals in the same way. Many studies have generalized this homogeneity assumption, for examples, Bond and Gresik (1997) study the case where there is one informed and one uninformed government rather than two uninformed governments, while Biglaiser and Mezzetti (1993) and Mezzetti (1997) extend their study from homogeneous principals to vertically and horizontally differentiated principals, respectively. Other extensions include Gal-Or (1991), Ivaldi and Martimort (1994), Martimort (1996), and Bond and Gresik (1996).

In applying the common agency model to analyzing the "pollution haven" hypothesis, the model developed in this paper makes the following extensions to Stole (1992).[3] First, the model developed in this paper allows each government's utility to be determined not only by a multinational firm's production in the home country, but also by its production in the host country as well as by its production technologies both in the home and the host countries. Second, this paper proves the existence of a non-cooperative (incentive compatible) equilibrium when a multinational firm's productions are substitutes and symmetric in its profit function. Third, this study extends the analysis from an intrinsic common agent to a continuum of delegated common agents so that each multinational firm can choose to produce in either one of or both of the countries.

The remainder of the paper is organized as follows. Section 2 describes the model structure. Section 3 shows that cooperation leads to the first best equilibrium outcome even with asymmetric information. Section 4 demonstrates that non-cooperation and asymmetric information reinforce each other in distorting the first best outcome and the "pollution haven" hypothesis. Section 4 then discusses the possibilities of relaxing some assumptions and testing the results empirically. Section 5 concludes and makes suggestions for future research.

[2] Stole (1992) has a revised version Stole (1997).

[3] In terms of the model structure, there is an independent work by Olsen and Osmundsen (1999a, 1999b). They applied a similar common agency model to taxation issues. However, in their setup, there is only one firm as the common agent and its type does not affect its cost of production. Also, in their paper, production generates no negative externalities and governments' pure objective is to collect tax revenue.

2 The Structure of the Model

The model includes two governments, home and foreign, and a competitive industry with a continuum of firms. The production of this competitive industry generates a negative externality either by producing polluting by-products or by using polluting inputs. The amount of pollution is not observable to the governments.

The product of the polluting industry is homogeneous. Its price is determined in the international market by world demand and supply. All firms are price takers. The total output of this "dirty" industry in each country is only a small proportion of world production so that each government cannot affect the world price.[4] To rule out the possibility of using pollution regulation to attack any other existing distortions, such as existing taxes or monopoly power, the model assumes away tariffs together with any other trade barriers and the industry is assumed to be perfectly competitive. These assumptions allow the analysis to focus on distortions resulting from non-cooperative regulation of the multinationals under asymmetric information.

All firms are perfectly competitive and identical except in their production technologies indexed by θ. A firm's θ is private information. A higher θ is associated with a dirtier technology of production. It is assumed that a firm's technology parameter is determined by its technology knowhow so that each firm only knows one technology and θ is not a firm's choice variable. Otherwise, if each firm can choose from a set of technologies and can choose different θs at home and abroad according to different regulations, it would be a common agency problem with moral hazard rather than with adverse selection.[5]

This paper focuses on the adverse selection problem, which can be justified if the technology of reducing pollution is tied to human or physical assets, which are either too costly to change after a firm sets up its plant or is unavailable to all firms so that each firm inherits a unique θ. However,

[4] The two countries can be two small neighbors, like Belgium and Holland, or can be two small countries far apart, like Belgium and Korea.

[5] Some empirical studies suggest that firms usually use the same technology across countries (Bhagwati and Hudec, 1996; Caves, 1996; Ulph, 1998). One reason is that it is more efficient for a firm to specialize in one technology than to operate under different technologies. The other reason is that, when a firm sets up a new plant in a developing country, the firm tends to make its production complying to the higher environmental standards in the developed countries just to avoid any sunk costs that can occur in the future as regulators in the developing countries tighten their requirements.

if the fight against pollution is a matter of a firm's continuous effort input or if a firm can choose its technology after knowing the environment regulations, then it is more of a moral hazard problem than an adverse selection problem. In general, these two problems need to be analyzed separately. Under some circumstances, the moral hazard problem can be transformed to an adverse selection problem similar to that discussed in this paper, using the approach in Grossman and Hart (1983). The information cost of implementing a given effort under moral hazard is then equivalent to that of enforcing truth telling under adverse selection.

Although it is difficult for the home and the foreign governments to know the exact value of θ for each individual firm, they usually know the distribution of θ for the industry. Hence, θ becomes a random variable for the governments. It is assumed that the industry's technology parameter ranges from $\underline{\theta}$ to $\overline{\theta}$. Let $\Theta = [\underline{\theta}, \overline{\theta}]$ be the domain, $F(\theta)$ be the cumulative distribution function, and $f(\theta)$ be the density function of θ. $F(\theta)$ and $f(\theta)$ are continuous and differentiable with bounded derivatives.

Since regulation does not change an existing firm's θ, regulation does not change $F(\theta)$ and $f(\theta)$. It is further assumed that $f(\theta) \neq 0$ for all $\theta \in \Theta$ so that the reciprocal of the hazard rate, $\frac{1-F(\theta)}{f(\theta)}$, is defined for all $\theta \in \Theta$. This inverse hazard rate is assumed to be nonincreasing in θ, i.e. $\frac{d}{d\theta}(\frac{1-F(\theta)}{f(\theta)}) \leq 0$ for all $\theta \in \Theta$.

The total output produced by a representative firm is denoted by Y with $Y \geq 0$. Let's take a quadratic approximation of the total private cost function, $C(Y, \theta)$. The case of a general cost function is discussed later.

$$C(Y, \theta) = \frac{1}{2} c_1 \cdot Y^2 + (c_2 \cdot \theta + \xi) Y \tag{1}$$

where c_1 is the change of marginal cost with respect to a change of output, c_2 is that with respect to a change of technology, and ξ is a constant component of marginal cost. It is assumed that production exhibits decreasing returns to scale so that $c_1 > 0$.[6] It is also assumed that there is a social welfare trade-off between cost reduction and pollution reduction so that $c_2 < 0$.[7] For the private marginal cost to be positive for all Y and θ, $\xi \geq -c_2 \cdot \overline{\theta} > 0$.

[6] If there is constant returns to scale, i.e. $c_1 = 0$, production in the two countries would be independent of each other and there would be no strategic interactions between governments as shown later in the paper. If $c_1 < 0$, there would be increasing returns to scale resulting in an additional consideration for government regulation. To focus on the effect of pollution with asymmetric information, this case is only discussed at the end of the paper.

[7] Otherwise, if $c_2 = 0$, then the governments should have the same tax scheme for all the firms and asymmetric

Under free trade, all firms bid for the same inputs in both countries and have the same cost structure. It is therefore assumed that home production (y) and foreign production (y^*) are perfect substitutes in a firm's cost function so that they do not enter the total cost function individually, but only as a sum.[8] Hence, the total cost of production is given by $C(Y, \theta)$ defined above with $Y = y + y^*$. This rules out any potential reallocation of production as a result of input price differentials or economies of scale, which is already studied by Eskeland and Harrison (1997).

Let's also take a quadratic approximation of the pollution function ($\phi(y, \theta)$) for a representative firm with local output y and technology parameter θ.

$$\phi(y, \theta) = \frac{1}{2} b_1 \cdot y^2 + b_2 \cdot y\theta \tag{2}$$

where common wisdom suggests that b_1 and b_2 are both positive so that marginal pollution increases at a constant rate as output increases and as a "dirtier" technology is used. $\phi(0, \theta) = 0$ for all θ, as there is no pollution when output is zero.

To regulate pollution, a government can either use a direct mechanism, which would assign each firm an output level according to its reported technology parameter; or use an indirect mechanism, which would specify a tax scheme as a function of a firm's output. Choosing an output is *de facto* equivalent to announcing a type. The equivalence of a direct mechanism and an indirect mechanism is established by the "taxation principle" and the "revelation principle" for a single principal case. Martimort and Stole (1999) extends the "taxation principle" developed by Guesnerie (1981, 1995) and Rochet (1986) to a common agency model while the extension of the "revelation principle" is not without limitations (Martimort and Stole, 1999; Epstein and Peters, 1999).[9] With this caution in mind, this paper applies the direct mechanism approach in order to characterize the optimal outcome and hence to provide welfare comparisons between non-cooperative and cooperative outcomes without deriving explicitly the tax schemes that implement the optimal outcome.

information is no long a problem. If $c_2 > 0$, then once the information is revealed, the government should only allow the cleanliest firm(s) to produce at their minimum efficient scales to achieve the desired output and shut down all the other firms.

[8] A superscript $*$ is used to denote all the corresponding variables in the foreign country throughout the paper.

[9] For an example, when the principals optimize their communications with the common agents, they can use the agents as a collusive device so as to achieve an outcome which is not implementable under a direct mechanism. If we restrict these communications to rule out any mixed strategies and out-of-equilibrium output and transfer offers, then we may be able to apply the revelation principle to the common agency game with caution (Martimort and Stole, 1999).

If the governments cannot share information, then the home and the foreign governments separately assign each firm an output level and a transfer payment based on the firm's individual report of its true technology parameter, θ.[10] Such a direct mechanism can be denoted by a group of output schemes and transfer schemes, such as $\{y(\hat{\theta}),\ y^*(\hat{\theta}^*),\ t(\hat{\theta}),\ t^*(\hat{\theta}^*)\}$, where $\hat{\theta}$ and $\hat{\theta}^*$ are the reported technology parameters to the home and the foreign governments, respectively. In equilibrium, the direct mechanism induces the firm to reveal truthfully its technology parameter to both governments so that $\hat{\theta} = \hat{\theta}^* = \theta$.

It is assumed that the governments offer the output and transfer schemes simultaneously to firms and firms only have the choice of stay or exit. Firm's outside opportunities are zero. A firm's objective function is to maximize its profits plus any transfers from the governments as shown in (3). Under a direct mechanism, all firms with the same θ have the same output and receive the same transfer.

$$u(y, y^*, \theta) = \pi(y, y^*, \theta) + t(\theta) + t^*(\theta) \tag{3}$$

where

$$\pi(y, y^*, \theta) = p \cdot (y + y^*) - C(y + y^*, \theta) \tag{4}$$

p is the world price and is assumed to be greater than the private marginal cost of production so that all firms are active in the absence of regulation.

As in Copeland and Taylor (1995), it is assumed that pollution affects only the level of a consumer's utility and plays no role in determining the consumer's choice among goods. Thus, an indirect utility function for a domestic representative consumer with income I and that for a foreign representative consumer with income I^* can be written as

$$V = \ln I - \ln p - \gamma B \tag{5}$$
$$V^* = \ln I^* - \ln p - \gamma^* B^* \tag{6}$$

where

$$B(y, y^*) = \int_{\underline{\theta}}^{\overline{\theta}} \phi(y(s), s) f(s) ds + \alpha \int_{\underline{\theta}}^{\overline{\theta}} \phi(y^*(s), s) f(s) ds \tag{7}$$
$$B^*(y, y^*) = \int_{\underline{\theta}}^{\overline{\theta}} \phi(y^*(s), s) f(s) ds + \alpha \int_{\underline{\theta}}^{\overline{\theta}} \phi(y(s), s) f(s) ds \tag{8}$$

[10] Cheap talk between governments cannot convey any valuable information here, because there is an incentive for a government and a firm to collude on the technology parameter they would report to the other government. This incentive is discussed in detail in section 4.

$\alpha \in [0,1]$ is the rate at which pollution is transferred from one country to the other. γ is the home disutility per unit of pollution and γ^* is the foreign disutility per unit of pollution, and both are positive.

As in Grossman and Helpman (1994), each government's objective is to maximize a weighted average of consumer's surplus, producer's surplus and tax revenues. In the following discussion, it is assumed that the weights assigned to consumer's and producer's surpluses are the same so that social welfare is maximized. Cases of unequal weights are discussed later. It is also assumed that the shares of the multinational firms are sold to the citizens in the home and foreign countries only.[11] The objective functions of the home and the foreign governments are then the following:

$$\begin{aligned} W &= V + \beta(\pi + t + t^*) - t \\ &= V + \beta\pi - (1-\beta)t + \beta t^* \qquad (9) \\ W^* &= V^* + (1-\beta)(\pi + t + t^*) - t^* \\ &= V^* + (1-\beta)\pi - \beta t^* + (1-\beta)t \qquad (10) \end{aligned}$$

where $\beta \in [0,1]$ is the percentage of shares purchased by domestic citizens and hence is the share of a firm's profit accruing to domestic citizens.[12]

The timing of the model is as follows. First, each firm inherits a technology indexed by θ. Second, the governments simultaneously announce their policies to all existing firms. Under a direct mechanism, the governments' policies include their output schemes and either their cooperative transfer scheme, $\widetilde{t}$, or their independent transfer schemes, t and t^*, both as functions of the technology parameter. After learning the output and transfer schemes, all existing firms decide where to produce and report their technology parameters to the governments. Finally, production and transfers take place.

[11] This assumption can be easily relaxed. If the profit goes to a third country, then it affects the home and the foreign governments symmetrically. It works as if a third party levied a profit tax before the home and the foreign residents split the profit. Such a profit tax will not affect the optimization behavior of the home and the foreign governments.

[12] If a government's concern is only the employment level rather than producer's surplus, then β can be replaced by the proportion of a firm's domestic employment to its total employment. If a government cares about both employment and producer's surplus, then β can be calculated as a weighted sum of the two ratios.

3 Cooperative Governments

If the home and the foreign governments set their environmental regulations cooperatively, they can choose their output and transfer schemes based on a single report from the representative firm. The problem becomes the same as the one where a single principal regulates two production activities. From equations (9) and (10), the joint welfare function for a given θ is the following:

$$W + W^* = V(y, y^*) + V^*(y, y^*) + \pi(y, y^*, \theta) \tag{11}$$

It is easy to see that the joint welfare is independent of the transfers. The intuition is that both governments assign equal weights to producer's surplus, consumer's surplus, and tax revenue so that any transfer between governments and firms has no effect on their joint welfare.

As a result, to maximize their joint welfare, the governments can simply choose the output levels conditional on θ and then make firms to reveal their true technology parameters by giving them all the consumer surpluses, $V + V^*$, from their production. The separation of the output decision from the transfer decision simplifies the maximization problem to the following:

$$\max_{y(\theta), y^*(\theta)} \int_{\underline{\theta}}^{\overline{\theta}} (V(y, y^*) + V^*(y, y^*) + \pi(y, y^*, \theta)) f(\theta) d\theta \tag{12}$$

By the small-countries assumption, price is determined in the international market. Piecewise differentiating the integrand with respect to y and y^*, respectively, gives the following first order conditions:[13]

$$p - C_y - (\gamma + \alpha\gamma^*)\phi_y(y, \theta) = 0 \tag{13}$$
$$p - C_y - (\gamma^* + \alpha\gamma)\phi_y(y^*, \theta) = 0 \tag{14}$$

where $C_y = c_1(y + y^*) + c_2\theta + \xi$ and $\phi_y = b_1 y + b_2\theta$. C_y is the private marginal cost of production for a firm with technology θ. This private marginal cost is the same across countries.

The assumptions about the total cost function ensure that π is strictly concave and π_θ is linear in y and y^*. Since ϕ is strictly convex in y and y^*, $V + V^* + \pi$ is strictly concave in y and y^*, so

[13] There is no loss of generality here in restricting the analysis to piecewise differentiation as all the functions have second order derivatives.

that the first order conditions (13) and (14) are necessary and sufficient for characterizing an optimal mechanism. It is easy to see that there exists a unique solution to conditions (13) and (14). This set of output and transfer schemes is feasible as the governments want all firms to be active and all firms are willing to produce in both countries because both the private marginal cost of production and the marginal disutility of pollution are low at low output levels, while profit is still positive at low output levels. Proposition 1 summarizes these results.

Proposition 1. *If the home and foreign governments design their pollution regulation policies cooperatively, then equations (13) and (14) give the equilibrium output levels for each firm. One way to implement these output levels is to let each multinational firm be the residual claimants of all the consumer's surpluses from its production.*

From the first order conditions (13) and (14), the equilibrium output in each country is set where price (p) equals the private marginal cost of production (C_y) plus the home and foreign marginal disutility of pollution from local production (the third term on the left hand side of the conditions). The marginal disutility of pollution generated by the last unit of output for all firms is equalized across countries in equilibrium as the cooperative governments' joint objective here is to minimize the total pollution at any given total output. Since the information cost (i.e. the cost of transfers) of observing each firm's true θ is internalized, the equilibrium output levels are at the first-best levels.

Using the first order conditions, we can discuss the "pollution haven" hypothesis without solving the linear system explicitly. Conditions (13) and (14) together imply that

$$\frac{\phi_y(y,\theta)}{\phi_y(y^*,\theta)} = \frac{\gamma^* + \alpha\gamma}{\gamma + \alpha\gamma^*} \tag{15}$$

If $\gamma \geq \gamma^*$, then $\gamma + \alpha\gamma^* \geq \gamma^* + \alpha\gamma$ so that $y \leq y^*$ as $b_1 > 0$. Hence, all firms produce less in the country with the higher disutility per unit of pollution unless pollution is perfectly mobile ($\alpha = 1$). Although transboundary pollution reduces the magnitude of production differences between countries compared with the case without transboundary pollution ($\alpha = 0$) as $\frac{\gamma^*}{\gamma} > \frac{\gamma^*+\alpha\gamma}{\gamma+\alpha\gamma^*}$, the transboundary pollution effect by itself cannot reverse the "pollution haven" hypothesis.

In sum, cooperative governments can implement the first-best outcome even with asymmetric information. As predicted by standard theories of the first-best, the "pollution haven" hypothesis holds with cooperative governments regardless of asymmetric information, that is, a country with lower social marginal cost of pollution produces less than a country with a higher social marginal cost.

4 Non-Cooperative Governments

In the non-cooperative case, the governments no longer maximize their joint social welfare, so the transfer schemes affect each government's welfare independently. Even with symmetric information, the first-best outcome may not be achieved. With asymmetric information, each government wants to pay fewer information rents to firms to induce them to reveal their true technology parameters. Consequently, asymmetric information creates an additional distortion. To understand the nature of this distortion, it is helpful to know the non-cooperative equilibrium outcome under symmetric information before discussing that under asymmetric information.

4.1 Symmetric information

When governments know the technology parameters, they can regulate each firm's output without using any transfers. We are back to a two-player non-cooperative Nash game. Hence, the Nash equilibrium with symmetric information is given by the solution of the following maximization problems:[14]

$$\max_{y(\theta)} \quad W = V(y, y^*, \theta) + \beta\pi(y, y^*, \theta) \tag{16}$$

$$\max_{y^*(\theta)} \quad W^* = V^*(y, y^*, \theta) + (1-\beta)\pi(y, y^*, \theta) \tag{17}$$

The first order conditions are

$$\beta(p - C_y) - \gamma\phi_y(y, \theta) = 0 \tag{18}$$

$$(1-\beta)(p - C_y) - \gamma^*\phi_y(y^*, \theta) = 0 \tag{19}$$

Rearranging the first order conditions gives

$$\frac{\phi_y(y, \theta)}{\phi_y(y^*, \theta)} = \frac{\gamma^*}{\gamma}\frac{\beta}{1-\beta} \tag{20}$$

[14] There exists a unique Nash equilibrium as V, V^*, and π are strictly concave in y and y^*.

It is easy to see that the degree of transboundary pollution (α) has no effect on the equilibrium output levels under symmetric information as transboundary pollution is completely ignored in each government's decision making. The notion of "pollution haven" is the strongest under non-cooperative governments with full information and equal profit shares ($\beta = \frac{1}{2}$). However, when profits are distributed unevenly among the residents in both countries and when $\gamma \geq \gamma^*$, the "pollution haven" hypothesis breaks down if a sufficiently large proportion of profits ($\beta > \frac{\gamma}{\gamma+\gamma^*} > \frac{1}{2}$) goes to the home country.[15] In the extreme case, when a multinational firm originated in the home country repatriates all its profits in the foreign country ($\beta = 1$), then the foreign government would allow zero production ($y^* = 0$) as it gets no profit but pollution.

4.2 Asymmetric information

If the home and the foreign governments separately design their environmental polices and if there is no sharing of information, then the home government can condition its regulation only on a firm's report made specifically to the home government, and likewise for the foreign government.[16] The home government's mechanism, $\{y(\hat{\theta}), t(\hat{\theta})\}$, is only a function of $\hat{\theta}$ while the foreign government's mechanism, $\{y^*(\hat{\theta}^*), t^*(\hat{\theta}^*)\}$, is only a function of $\hat{\theta}^*$.

The crucial point of competition under asymmetric information is not about who produces less/more of the polluting product (as it would be determined by γ and γ^* once a firm's θ is revealed), but on who strategically extracts more information rent from the other through taxing away firms' profits. To provide an intuition about how asymmetric information affects the "pollution haven" hypothesis through the strategic interaction between governments, let's consider the following.

In the cooperative case, the governments can implement the first-best by making firms the residual claimants of consumer's surpluses so as to provide them the right incentive to reveal their true production technologies. In this non-cooperative case, each firm must also receive a non-zero after tax profit as an information rent for revealing its true technology parameter. However, each government has an

[15] If a government cares about employment, then "pollution haven" hypothesis breaks down if local production significantly increases local employment (refer to footnote 12).

[16] The incentive of collusion between a firm and a government that discredits any information sharing is discussed later in this section.

incentive to levy a higher tax so that each firm will have a lower retained profit and hence less room for the other government to tax. Furthermore, for a multinational firm, each government has an additional incentive to leave less surpluses to firms because part of these surpluses will contribute to the other government's welfare through profit sharing. Thus, each government has no incentive to give away any consumer's surpluses and every incentive to tax away a bigger proportion of a firm's profit so as to squeeze the other government's tax revenue and to make the other government pay more information rent to the firm.

To extract rent from the other government, each government will attempt to induce firms to produce less in the other country and hence pay less taxes to the other government.[17] If allowed to produce more in the home country, each firm will want to produce less in the foreign country as domestic output and foreign output are perfect substitutes and the total production exhibits decreasing returns to scale. To cut its output abroad, each firm has an incentive to report a lower θ to the foreign government. This forces the foreign government to increase a firm's information rent in order to induce truth telling. The firm's retained profit is therefore higher, which in turn, relaxes the home government's incentive compatibility constraint and allows the home government to levy a higher tax.

Since the (first order) benefit from the increase in tax revenue outweighs the additional (second order) disutility from more pollution, the home government gains, at the expense of the foreign government, by implementing a higher output accompanied with a higher tax than those implemented in the absence of any rent extraction consideration. Of course, the foreign government wants to do the same. In equilibrium, all regulatory schemes are incentive compatible so that all such attempts are fruitless, but the possibility of these attempts imposes constraints on the set of equilibrium outcomes and tends to increase output more in a country with a higher marginal disutility of pollution.

When pollution is transboundary, by increasing its local output to extract information rents, each government reduces not only its information rent payment to firms, but also the transboundary pollution coming from the other country. Although the degree of transboundary pollution by itself has no effect on the non-cooperative output levels under symmetric information, asymmetric information and transboundary pollution do reinforce each other in raising the non-cooperative equilibrium output in

[17] The discussion here has presumed that both output levels and taxes are increasing functions of θ. This presumption is proved in the appendix.

the home country more than that in the foreign country, which works against the "pollution haven" hypothesis.

To prove the above arguments, let's solve the common agency problem. A firm's net profit as a function of the true type and the reported types is:

$$U(\hat{\theta}, \hat{\theta}^*, \theta) \triangleq u(y(\hat{\theta}), y^*(\hat{\theta}^*), t(\hat{\theta}), t^*(\hat{\theta}^*), \theta) \tag{21}$$

In equilibrium, a pair of output functions, $\{y(\hat{\theta}), y^*(\hat{\theta}^*)\}$, must be commonly implementable and commonly feasible so that $U(\hat{\theta}, \hat{\theta}^*, \theta)$ is maximized at $\hat{\theta} = \hat{\theta}^* = \theta$.

Applying the trick in Mirrlees (1971) to incorporating a firm's incentive compatibility constraints (details in part 4 of the appendix), the non-cooperative Nash equilibrium is given by the solution to the following pair of maximization problems:

$$\max_{y(\theta)} \int_{\underline{\theta}}^{\overline{\theta}} \Lambda(y, \theta \mid y^*) f(\theta) d\theta \tag{22}$$

$$\max_{y^*(\theta)} \int_{\underline{\theta}}^{\overline{\theta}} \Lambda^*(y^*, \theta \mid y) f(\theta) d\theta \tag{23}$$

where Λ and Λ^* are defined as:

$$\Lambda(y, \theta \mid y^*) \triangleq V + \pi(y, y^*(\hat{\theta}^*[\theta \mid y]), \theta) + t^*(\hat{\theta}^*[\theta \mid y]) - (1-\beta)\frac{1-F(\theta)}{f(\theta)}\pi_\theta(y, y^*(\hat{\theta}^*[\theta \mid y]), \theta) \tag{24}$$

$$\Lambda^*(y^*, \theta \mid y) \triangleq V^* + \pi(y(\hat{\theta}[\theta \mid y^*]), y^*, \theta) + t(\hat{\theta}[\theta \mid y^*]) - \beta\frac{1-F(\theta)}{f(\theta)}\pi_\theta(y(\hat{\theta}[\theta \mid y^*]), y^*, \theta) \tag{25}$$

As in Fudenberg and Tirole (1991), taking the other's output and transfer schemes as given, each government chooses its output scheme to maximize its expected total return (Λ or Λ^*) as discussed below.

Given that a firm produces y in the home country, $y^*(\hat{\theta}^*[\theta \mid y])$ is the foreign government's optimal output scheme and $t^*(\hat{\theta}^*[\theta \mid y])$ is the corresponding optimal transfer scheme as a function of its type θ. $\pi_\theta(y, y^*(\hat{\theta}^*[\theta \mid y]), \theta)$ gives the increase in profit for a firm with a higher θ but the same output y. Following the discussion in Stole (1992), the home government has to pay $\frac{1-F(\theta)}{f(\theta)}\pi_\theta(y, y^*(\hat{\theta}^*[\theta \mid y]), \theta)$ amount of expected information rent to a firm for it to reveal its true technology θ. A proportion β of this rent contributes to home welfare because it is a pure transfer from government revenue to domestic producer's surplus. The remaining portion $1-\beta$ of this rent contributes to foreign welfare through profit sharing. Thus, the home government's total expected net gains (domestic consumer's surplus plus total profit less taxes paid to the foreign government, $V+\pi-(-t^*)$), less the expected information rent losses, i.e. the part of the expected information rents paid by the home government, but collected by the foreign government $((1-\beta)\frac{1-F(\theta)}{f(\theta)}\pi_\theta(y, y^*(\hat{\theta}^*[\theta \mid y]), \theta))$, gives the home government's expected total return (Λ). Similarly, the foreign government's total expected return is given by Λ^*.

Restricting our analysis to differentiable output schemes, the appendix proves that the transfer schemes are also differentiable (in part 1) and Λ and Λ^* are strictly concave in y and y^*, respectively, and both have an interior maximum (in part 3). The first order conditions of (22) and (23) by piecewise differentiation form a differential system of equations in y and y^*. Given a specific initial condition, part 4 in the appendix proves that there exists a unique solution of y and y^* as increasing functions of θ. Thus, we have the following proposition.

Proposition 2. *If the home and foreign governments design their pollution regulation policies non-cooperatively, and if the reduction of marginal cost by using a dirtier technology is greater than the resulting increase in marginal disutility (i.e. $-c_2 > \gamma^* b_2$), then there exists a pure-strategy Nash equilibrium.*[18] *In this equilibrium, the output levels are given by the first order conditions of (22) and (23) and the following boundary condition*[19]

$$y'(\overline{\theta}) = 0 \text{ if } \gamma \geq \gamma^*. \tag{26}$$

[18] If $-c_2 = \gamma^* b_2$, then there will be a pooling equilibrium as in Mezzetti (1997). Here, it implies that governments should just impose a uniform tax on all types of firms and there will be no need for the governments to screen the firms. Asymmetric information becomes irrelevant in this case. If $-c_2 < \gamma^* b_2$, then the optimal output should be decreasing in θ. Under asymmetric information, any output scheme decreasing in θ will not be implementable when the marginal cost of production decreases in θ, i.e. $c_2 < 0$. This is because $y' > 0$ and $y^{*'} > 0$ are necessary and sufficient for implementability under the single crossing condition $\pi_{y\theta} = -c_2 > 0$ (Chapter 7, Fudenberg and Tirole (1991)). Hence, when $\gamma^* b_2 > -c_2 > 0$, the optimal outcome will not be implementable. However, if $c_2 > 0$, then there will be a second-best implementable output scheme which is decreasing in θ. In this case, the cost effect and the pollution effect both favor a firm with a lower θ. There is no real social trade-off between cost reduction and pollution reduction. Hence, this case is not interesting.

[19] If $\gamma < \gamma^*$, then replacing $y'(\overline{\theta}) = 0$ by $y^{*'}(\overline{\theta}) = 0$. The boundary condition implies that, for a firm with type $\overline{\theta}$, cheating in the neighborhood of its true type will not affect its contracted output level with the home government. Neither will cheating affect its tax payment to the home government from equation (A.2). Thus, for firms with $\overline{\theta}$, all distortions are concentrated in the foreign country. This boundary condition minimizes the home government's information rent payment.

The corresponding transfer schemes are given by (A.2) and (A.3) in the appendix. This set of output and transfer schemes is implementable and feasible.

From Proposition 2, the non-cooperative equilibrium outcome can be characterized by the first order conditions of (22) and (23). To facilitate the understanding of the rent extraction effect, consider first the case where there is no transboundary pollution, i.e. $\alpha = 0$. The first order conditions by piecewise differentiation are:[20]

$$p - C_y - \gamma\phi_y(y,\theta) \quad = \quad -(1-\beta)\frac{1-F}{f}c_2(1+\frac{c_1 y^{*'}}{c_2+c_1 y'}) \tag{27}$$

$$p - C_y - \gamma^*\phi_y(y^*,\theta) \quad = \quad -\beta\frac{1-F}{f}c_2(1+\frac{c_1 y'}{c_2+c_1 y^{*'}}) \tag{28}$$

where $\frac{c_1 y^{*'}}{c_2+c_1 y'}$ and $\frac{c_1 y'}{c_2+c_1 y^{*'}}$ characterize the strategic effect of a change of government interaction, namely how a government changes its output so as to affect a firm's report to the other government.

Rearranging the above equations and dividing (27) by (28), we have

$$\frac{y}{y^*} > 1 \text{ iff } \frac{\phi_y(y,\theta)}{\phi_y(y^*,\theta)} = \frac{\gamma^*}{\gamma}\frac{p - C_y + (1-\beta)\frac{1-F}{f}c_2(1+\frac{c_1 y^{*'}}{c_2+c_1 y'})}{p - C_y + \beta\frac{1-F}{f}c_2(1+\frac{c_1 y'}{c_2+c_1 y^{*'}})} > 1 \tag{29}$$

The above condition holds if and only if [21]

$$\frac{\gamma^*}{\gamma}\frac{1-\beta}{\beta}\frac{c_2+c_1 y^{*'}}{c_2+c_1 y'} < 1 + \frac{\gamma-\gamma^*}{\gamma}\frac{p-c_y}{\beta\frac{1-F}{f}c_2(1+\frac{c_1 y'}{c_2+c_1 y^{*'}})} < 1 \tag{30}$$

Condition (29) clearly indicates that output is higher in a country with a higher marginal disutility of pollution. Besides the common γ and γ^* terms representing the "pollution haven" hypothesis, condition (30) shows that under non-cooperative governments with asymmetric information, there is also a profit sharing effect captured by the term, $\frac{1-\beta}{\beta}$, as in the non-cooperative case with symmetric

[20] For $\theta = \overline{\theta}$, $F(\overline{\theta}) = 1$ and the right hand side of equations (27) and (28) becomes zero. The non-cooperative output is the same as the cooperative output. The marginal disutility of pollution is also equalized across countries at $\theta = \overline{\theta}$. There are no distortions for the most polluting firms. However, for firms with $\theta < \overline{\theta}$, the marginal disutility of pollution is likely to differ across countries. Rearranging production can reduce total pollution at any given level of total output. This result is consistent with the standard outcome for a single dimensional principal-agent problem.

[21] Since $1 + \frac{c_1 y'}{c_2+c_1 y^{*'}} = \frac{c_2+c_1 y^{*'}+c_1 y'}{c_2+c_1 y^{*'}} > 0$ as both the numerator and the denominator are negative as shown in the appendix, $\frac{\gamma-\gamma^*}{\gamma}\frac{p-c_y}{\beta\frac{1-F}{f}c_2(1+\frac{c_1 y'}{c_2+c_1 y^{*'}})} < 0$, given $\gamma > \gamma^*$ and $c_2 < 0$.

information. In both cases, a higher profit share leads to a higher output. In addition, the ratio, $\frac{c_2+c_1 y^{*'}}{c_2+c_1 y'}$, reflects the direct effect of the rent extraction behavior between non-cooperative governments with asymmetric information. Since both $c_2 + c_1 y^{*'}$ and $c_2 + c_1 y'$ are negative while $c_1 y^{*'}$ and $c_1 y'$ are both positive, the ratio is smaller, the bigger is a "dirtier" firm's marginal production increase in the foreign country relative to that in the home country, $\frac{y^{*'}}{y'}$, which measures the relative effectiveness of the home government's rent extraction behavior to that of the foreign government.

Since the foreign government has a lower marginal disutility of pollution and since a firm with a "dirtier" technology has a lower marginal private cost of production, the foreign government is more willing to assign a higher production to a "dirtier" firm than the home government, i.e. $y^{*'} > y'$, which can easily be shown by substracting (A.21) from (A.22). This indicates that, compared with the foreign government, the foreign government's output scheme is more elastic to the reported θ and hence the home government is more effective in reducing the foreign government's output and tax revenue via affecting a firm's reported θ to the foreign government. Thus, the home government is more willing to increase its production to extract information rent from the foreign government even though the home government has a higher marginal disutility of pollution. This strategic interaction between non-cooperative governments with asymmetric information has a direct effect against the "pollution haven" hypothesis.

If there is some transboundary pollution, so that $\alpha \neq 0$, then the first order conditions become

$$p - C_y - \gamma\phi_y(y,\theta) = \alpha\gamma\phi_y(y^*,\theta)\frac{c_1 y^{*'}}{c_2 + c_1 y'} - (1-\beta)\frac{1-F}{f}c_2(1 + \frac{c_1 y^{*'}}{c_2 + c_1 y'}) \tag{31}$$

$$p - C_y - \gamma^*\phi_y(y^*,\theta) = \alpha\gamma^*\phi_y(y,\theta)\frac{c_1 y'}{c_2 + c_1 y^{*'}} - \beta\frac{1-F}{f}c_2(1 + \frac{c_1 y'}{c_2 + c_1 y^{*'}}) \tag{32}$$

Hence, the strategic interaction between non-cooperative governments with asymmetric information has another indirect effect on "pollution haven" hypothesis via transboundary pollution, which is represented by $\alpha\gamma\phi_y(y^*,\theta)\frac{c_1 y^{*'}}{c_2+c_1 y'}$ and $\alpha\gamma^*\phi_y(y,\theta)\frac{c_1 y'}{c_2+c_1 y^{*'}}$, both are negative. Following the previous derivations,

$$\frac{y}{y^*} > 1 \text{ iff } \frac{\phi_y(y,\theta)}{\phi_y(y^*,\theta)} = \frac{\gamma^*}{\gamma}\frac{p - C_y + (1-\beta)\frac{1-F}{f}c_2(1 + \frac{c_1 y^{*'}}{c_2+c_1 y'})}{p - C_y + \beta\frac{1-F}{f}c_2(1 + \frac{c_1 y'}{c_2+c_1 y^{*'}})}\frac{1 + \alpha\frac{c_1 y^{*'}}{c_2+c_1 y'}}{1 + \alpha\frac{c_1 y'}{c_2+c_1 y^{*'}}} > 1 \tag{33}$$

The last fraction term in the above condition reflects the additional transboundary pollution effect. If

$y^{*'} > y'$, then $1 + \alpha\frac{c_1 y^{*'}}{c_2+c_1 y'} > 1 + \alpha\frac{c_1 y'}{c_2+c_1 y^{*'}} > 0$.[22] Thus, as discussed earlier, transboundary pollution reinforces the rent extraction behavior in working against the "pollution haven" hypothesis. This is consistent with the empirical result in Bui (1998) that gain from cooperation is large when there is severe transboundary pollution.

4.3 Empirical implications

The above results can be extended to cases where unequal weights are assigned to producers and consumers in each government's objective function. The restrictions on the cost function can also be relaxed. The direct and indirect effects of asymmetric information on the "pollution haven" hypothesis still prevail. However, there will be an addition effect due to the economies or diseconomies of scale.

With these extensions, the results in the paper have two general implications on empirical studies. First, if time-series data are collected for a particular country, then we will always observe that production falls as a country's marginal disutility of pollution rises. However, if cross-section data are collected for two or more countries, then we may fail to observe that production is lower in a country with a higher marginal disutility of pollution as a result of asymmetric information. Second, since different firms can use different technologies, we need micro-based firm specific data. Aggregate data at the industry level can be misleading. For an example, Low and Yeats (1992) and Xu (1999) use panel data at the industry level to test the "pollution haven" hypothesis and reached different conclusions.

More specifically, the major results in this paper can be examined empirically and can enrich the empirical studies on the "pollution haven" hypothesis. First, the theory suggests that a poorer country with a lower marginal disutility of pollution should allow dirtier firms to produce more. Firms can be ranked in an ascending order according to their revealed output levels and a cleaner firm would have a lower ranking. We can then check whether a firm's production increases faster in a poorer country than in a richer country as a firm's ranking increases, i.e. whether $y^{*'} > y'$, as predicted by the model.

Second, if we can estimate the ratio of $y^{*'}$ over y', then we can test the effect of the strategic interaction between governments with asymmetric information on the relative output levels. The theory

[22] This is because under the second order necessary conditions for implementation, both $1+\alpha\frac{c_1 y^{*'}}{c_2+c_1 y'}$ and $1+\alpha\frac{c_1 y'}{c_2+c_1 y^{*'}}$ are positive when $\alpha < 1$. Also, since $\frac{c_1 y^{*'}}{c_2+c_1 y'} < 0$, $\frac{c_1 y'}{c_2+c_1 y^{*'}} < 0$, and $y^{*'} > y'$, $\frac{c_1 y^{*'}}{c_2+c_1 y'} - \frac{c_1 y'}{c_2+c_1 y^{*'}} = \frac{c_1(y^{*'}-y')(c_2+c_1(y^{*'}+y'))}{(c_2+c_1 y')(c_2+c_1 y^{*'})} > 0$.

predicts that the ratio of y over y^* should be inversely related to the ratio of $y^{*'}$ over y'. The intuition is that, if $\gamma > \gamma^*$, then compared with the foreign government, the home government is more effective in extracting information rent from the foreign government (i.e. $y^{*'} > y'$) so that the home government is more willing to raise its production to exercise rent extraction.

Third, the analysis shows that the rent extraction effect should be stronger when there is transboundary pollution. This result can be tested, for an example, by comparing the acid rain study between two neighboring countries to that between two countries which are far apart.

In sum, the strategic interaction between governments with asymmetric information suggests that the output levels in a country should not only depend on that country's marginal disutility of pollution, but also depend on that country's profit share, the degree of transboundary pollution, and most importantly, the increase of marginal production of a "dirtier" firm that captures governments' competition in reducing information rents. If we can incorporate these terms into Eskeland and Harrison's regression, then we can put the effect of government regulation together with the other private factors that influence the "pollution haven" hypothesis. If we can observe "pollution havens" after controlling for all these effects, we can further analyze the significance of each of these factors on the break down of the "pollution haven" hypothesis.

5 Conclusions and Extensions

This paper develops a common agency model to analyze the strategic interaction between two governments in regulating polluting multinationals. When the multinational firms possess private information about their levels of pollution and the cleanliness of their production technologies, the governments have to provide incentive schemes for firms to reveal their true production technology parameters in order to set the marginal social cost equal to the marginal benefit of production.

There are three main forces at work. First, each government has an incentive to minimize its information rent payment to multinationals, which is done by increasing local production so as to squeeze the other government's tax revenue. This rent extraction effect is absent under full information and works against the "pollution haven" hypothesis. Second, the existence of multinational firms creates a profit sharing effect. Since after-tax profits are shared between the residents of the two countries, the strategic interaction between governments with asymmetric information has an indirect effect on the "pollution haven" hypothesis via sharing firms' retained profits as information rents. Third, when pollution crosses national boundaries, home production imposes an externality on the residents of the other country, which makes no difference to the "pollution haven" hypothesis in the non-cooperative full information case as any externality is ignored in each government's welfare maximization decision. With asymmetric information, this transboundary pollution effect reinforces the rent extraction effect and causes another indirect effect of the strategic interaction between governments against the "pollution haven" hypothesis.

The paper argues that the strategic interaction between governments with asymmetric information brings each government an additional marginal social cost of reducing production. This addition marginal cost comes from the loss of information rent payments to the other government. As a result, the rent extraction behavior between governments has both direct and indirect effects against the "pollution haven" hypothesis. The paper suggests that once we control for factors as a result of this strategic interaction and other private factors that affect a multinational firm's production allocation across countries, we would be able to observe "pollution havens" and evaluate the impact of each of these factors on the breakdown of the "pollution haven" hypothesis.

As an extension to the theoretical analysis in this paper, it would be interesting to see whether empirical results support the findings in this paper. Although the paper provides some guidelines of possible empirical studies, such studies are beyond the scope of this paper to carry out an appropriate test. Also, this paper analyzes the case where a "dirtier" technology is associated with a lower marginal cost of production. This may not be true in some industries and hence the results in this paper need to be modified and cannot be applied to those industries directly. Finally, the paper focuses on the adverse selection problem where the technologies are not in a firm's choice set. An extension of this research is to examine the moral hazard problem where firms have a choice among a set of technologies both at home and abroad.

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Appendix

1. Necessary conditions for common implementability

The incentive compatibility constraints require that the representative firm's true technology parameter solves the firm's maximization problem:

$$\max_{\hat{\theta},\hat{\theta}^*} \ U(\hat{\theta},\hat{\theta}^*,\theta) = \pi(y(\hat{\theta}), y^*(\hat{\theta}^*),\theta) + t(\hat{\theta}) + t^*(\hat{\theta}^*) \tag{A.1}$$

The first order necessary conditions for implementability are

$$t'(\theta) = -\pi_y(y(\theta), y^*(\theta),\theta)y'(\theta) \tag{A.2}$$

$$t^{*'}(\theta) = -\pi_{y^*}(y(\theta), y^*(\theta),\theta)y^{*'}(\theta) \tag{A.3}$$

Applying Theorem 12 in Chapter 2 of Hurewicz (1958), quasi-linearity guarantees the existence of a pair of transfer schemes $t(\theta)$ and $t^*(\theta)$ which satisfies (A.2) and (A.3) at all points where y and y^* are differentiable.

The second order necessary conditions are

$$\pi_{yy^*}y'y^{*'} + \pi_{y\theta}y' \geq 0$$

$$\pi_{yy^*}y'y^{*'} + \pi_{y^*\theta}y^{*'} \geq 0$$

$$\pi_{y\theta}\pi_{y^*\theta}y'y^{*'} + \pi_{yy^*}y'y^{*'}(\pi_{y\theta}y' + \pi_{y^*\theta}y^{*'}) \geq 0$$

Since $\pi_{y\theta} = \pi_{y^*\theta} > 0$, the last condition becomes

$$(\pi_{y\theta} + \pi_{yy^*}(y' + y^{*'}))y'y^{*'} \geq 0$$

These conditions imply that if a pair of output schemes are commonly implementable, then they cannot be both decreasing over any interval of Θ.

If both of the output schemes are nondecreasing, i.e. $y' \geq 0$ and $y^{*'} \geq 0$, then the second order necessary conditions become

$$\pi_{yy^*}y^{*'} + \pi_{y\theta} \geq 0$$

$$\pi_{yy^*}y' + \pi_{y^*\theta} \geq 0$$

$$\pi_{y\theta} + \pi_{yy^*}(y' + y^{*'}) \geq 0 \tag{A.4}$$

Since $\pi_{y\theta} = \pi_{y^*\theta} = -c_2 > 0$ and $\pi_{yy^*} = -c_1 < 0$, all the above three conditions are satisfied as long as (A.4) holds. The necessary conditions for implementability are (A.2), (A.3) and (A.4) if both output schemes are nondecreasing in θ. If one of the schemes is nonincreasing ($y^{'} \leq 0$) and the other one is nondecreasing ($y^{*'} \geq 0$), then the second order necessary conditions become $\pi_{yy^*}y^{*'} + \pi_{y\theta} \leq 0$, $\pi_{yy^*}y^{'} + \pi_{y^*\theta} \geq 0$ and $\pi_{y\theta} + \pi_{yy^*}(y^{'} + y^{*'}) \leq 0$.

2. Strategic revelation effects

Totally differentiating the incentive compatibility constraints (A.2) and (A.3) gives $t^{''} = -\pi_{yy}(y^{'})^2 - \pi_{yy^*}y^{'}y^{*'} - \pi_{y\theta}y^{'} - \pi_y y^{''}$ and $t^{*''} = -\pi_{y^*y^*}(y^{*'})^2 - \pi_{yy^*}y^{'}y^{*'} - \pi_{y^*\theta}y^{*'} - \pi_{y^*}y^{*''}$. Substituting these equations into $U_{\hat{\theta}\hat{\theta}}$ and $U_{\hat{\theta}^*\hat{\theta}^*}$ derived from equation (A.1) gives

$$
\begin{aligned}
U_{\hat{\theta}\hat{\theta}} &= -(\pi_{yy}y^{*'} + \pi_{y\theta})y^{'} \\
U_{\hat{\theta}^*\hat{\theta}^*} &= -(\pi_{y^*y^*}y^{'} + \pi_{y^*\theta})y^{*'}
\end{aligned}
$$

If the monotonicity conditions are satisfied, i.e. either $y^{'} > 0$ and $y^{*'} > 0$ or $y^{'} < 0$ and $y^{*'} > 0$ for all $\theta \in \Theta$, then from the second order necessary conditions derived in Part 1, $U_{\hat{\theta}\hat{\theta}} < 0$ and $U_{\hat{\theta}^*\hat{\theta}^*} < 0$. $U_{\hat{\theta}\hat{\theta}}U_{\hat{\theta}^*\hat{\theta}^*} - (U_{\hat{\theta}\hat{\theta}^*})^2 = \pi_{y^*\theta}y^{*'}y^{'}(\pi_{y\theta} + \pi_{yy^*}(y^{*'} + y^{'})) > 0$ as $U_{\hat{\theta}\hat{\theta}^*} = \pi_{y^*y^*}y^{'}y^{*'}$. Hence, $U(\hat{\theta}, \hat{\theta}^*, \theta)$ is strictly concave in $\hat{\theta}$ and $\hat{\theta}^*$ under the monotonicity conditions and the second order necessary conditions for common implementability.

Given that $U(\hat{\theta}, \hat{\theta}^*, \theta)$ is strictly concave in $\hat{\theta}$ and $\hat{\theta}^*$, Theorem 8 in Stole (1992) gives the formulae for the strategic revelation effects in a pure-strategy differentiable Nash equilibrium as the followings.

$$
\frac{\partial \hat{\theta}^*}{\partial y} = \begin{cases} \frac{c_1}{c_2 + c_1 y^{'}} & \text{if } y^{*'} \neq 0 \\ 0 & \text{if } y^{*'} = 0 \end{cases} \tag{A.5}
$$

$$
\frac{\partial \hat{\theta}}{\partial y^*} = \begin{cases} \frac{c_1}{c_2 + c_1 y^{*'}} & \text{if } y^{'} \neq 0 \\ 0 & \text{if } y^{'} = 0 \end{cases} \tag{A.6}
$$

Under the second order necessary conditions derived in Part 1,

$$
\frac{\partial \hat{\theta}^*}{\partial y} \begin{cases} < 0 & \text{if } y^{*'} > 0 \\ = 0 & \text{if } y^{*'} = 0 \\ > 0 & \text{if } y^{*'} < 0 \end{cases} \tag{A.7}
$$

$$
\frac{\partial \hat{\theta}}{\partial y^*} \begin{cases} < 0 & \text{if } y^{'} > 0 \\ = 0 & \text{if } y^{'} = 0 \\ > 0 & \text{if } y^{'} < 0 \end{cases} \tag{A.8}
$$

Hence, $y^{*'}\frac{\partial \hat{\theta}^*}{\partial y} \leq 0$ and $y^{'}\frac{\partial \hat{\theta}}{\partial y^*} \leq 0$ regardless of the slopes of the output schemes. Equality holds only when either $y^{'} = 0$ or $y^{*'} = 0$.

3. Strict concavity of the objective functions for non-cooperative governments

Given the incentive compatibility constraints and the assumption that all the cross-partial derivatives are constant, the second order derivatives of Λ defined by equation (24) and Λ^* defined by equation (25) with respect to y and y^*, respectively, are the following:

$$\Lambda_{yy} = \pi_{yy} + (V_{y^*} - (1-\beta)\frac{1-F(\theta)}{f(\theta)}\pi_{y^*\theta})\frac{d}{dy}(y^{*'}\frac{\partial\hat{\theta}^*}{\partial y}) \tag{A.9}$$

$$\Lambda_{y^*y^*} = \pi_{y^*y^*} + (V^*_{y^*} - \beta\frac{1-F(\theta)}{f(\theta)}\pi_{y\theta})\frac{d}{dy^*}(y^{'}\frac{\partial\hat{\theta}}{\partial y^*}) \tag{A.10}$$

Because the optimal output schemes are only functions of the true technology parameter (θ), $y^{*'}$ and $y^{'}$, representing the rates of changes of the optimal output with respect to changes of θ, are independent of the variations of y and y^* in the process of maximizing the integrand (Λ and Λ^*) at any given θ. Suppose the monotonicity conditions are satisfied so that $U(\hat{\theta}, \hat{\theta}^*, \theta)$ is strictly concave in $\hat{\theta}$ and $\hat{\theta}^*$ over Θ^3, then from (A.5) and (A.6),

$$\frac{d}{dy}(y^{*'}\frac{\partial\hat{\theta}^*}{\partial y}) = \frac{d}{dy}(\frac{y^{*'}\pi_{yy^*}}{\pi_{y^*\theta} + \pi_{yy^*}y^{'}}) = 0$$

$$\frac{d}{dy^*}(y^{'}\frac{\partial\hat{\theta}}{\partial y^*}) = \frac{d}{dy^*}(\frac{y^{'}\pi_{yy^*}}{\pi_{y\theta} + \pi_{yy^*}y^{*'}}) = 0$$

Substituting the above expressions into (A.9) and (A.10) gives

$$\Lambda_{yy} = \pi_{yy} < 0 \tag{A.11}$$

$$\Lambda_{y^*y^*} = \pi_{y^*y^*} < 0 \tag{A.12}$$

Hence, $\Lambda(y, \theta \mid y^*)$ is strictly concave in y and $\Lambda^*(y^*, \theta \mid y)$ is strictly concave in y^*.

4. Properties of the non-cooperative implementable Nash equilibrium

1) First order conditions

The home government's maximization problem is:

$$\max_{y(\theta),t(\theta)} \int_{\underline{\theta}}^{\overline{\theta}} (V + \beta\pi - (1-\beta)t + t^*)f(\theta)d\theta \tag{A.13}$$

$$s.t. \quad (IC)\ u(y(\theta), y^*(\theta), \theta) \geq u(y(\hat{\theta}), y^*(\hat{\theta}^*), \theta) \tag{A.14}$$

$$(IR)\ u(y(\theta), y^*(\theta), \theta) \geq 0 \tag{A.15}$$

where

$$u(y(\theta), y^*(\theta), \theta) = \pi(y(\theta), y^*(\theta), \theta) + t(\theta) + t^*(\theta)$$
$$u(y(\hat{\theta}), y^*(\hat{\theta}^*), \theta) = \pi(y(\hat{\theta}), y^*(\hat{\theta}^*), \theta) + t(\hat{\theta}) + t^*(\hat{\theta}^*)$$

Following Mirrlees (1971), let $U(\theta)$ be a firm's indirect utility function. Thus, (IC) implies that $U(\theta) = \max_{\hat{\theta},\hat{\theta}^*} u(y(\hat{\theta}), y^*(\hat{\theta}^*), \theta) = \pi(y(\theta), y^*(\theta), \theta) + t(\theta) + t^*(\theta)$. From the envelope theorem, $\frac{dU}{d\theta} = u_\theta = \pi_\theta$ so that $U(\theta) = \int_{\underline{\theta}}^{\theta} u_\theta(y(s), y^*(s), s)ds + u(\underline{\theta})$. Since it is never profitable for the home government to leave any information rent to the lowest type firm, $u(\underline{\theta}) = 0$. We can then write

$$U(\theta) = \int_{\underline{\theta}}^{\theta} \pi_\theta(y(s), y^*(s), s)ds \tag{A.16}$$

Since $t = U - \pi - t^*$, the home government's objective function becomes:

$$V + \beta\pi - (1-\beta)(U - \pi - t^*) + t^* = V + \pi + t^* - (1-\beta)\int_{\underline{\theta}}^{\theta} \pi_\theta(y(s), y^*(s), s)ds \tag{A.17}$$

Partial integration gives:

$$\int_{\underline{\theta}}^{\overline{\theta}} \int_{\underline{\theta}}^{\theta} \pi_\theta(y(s), y^*(s), s) f(\theta) ds d\theta = \int_{\underline{\theta}}^{\overline{\theta}} \frac{1-F(\theta)}{f(\theta)} \pi_\theta(y(\theta), y^*(\theta), \theta) f(\theta) d\theta \tag{A.18}$$

Ignoring monotonicity conditions, the home government's relaxed problem reduces to the following under the tax schemes given by equations (A.2) and (A.3).

$$\max_{y(\theta)} \quad \int_{\underline{\theta}}^{\overline{\theta}} (V + \pi + t^* - (1-\beta)\frac{1-F}{f}\pi_\theta) f(\theta) d\theta \tag{A.19}$$

Similarly, we can derive the relaxed problem for the foreign government.

2) Existence and monotonicity

Since $\pi_{y\theta} = \pi_{y^*\theta}$, rearranging the first order conditions (31) and (32) gives the following system of differential equations if neither $y^{'}$ nor $y^{*'}$ is zero. Let $\phi_y = \phi_y(y, \theta)$ and $\phi_{y^*} = \phi_y(y^*, \theta)$.

$$\begin{vmatrix} MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2 & (1-\beta)\frac{1-F}{f}c_2 - \alpha\gamma\phi_{y*} \\ \beta\frac{1-F}{f}c_2 - \alpha\gamma^*\phi_y & MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 \end{vmatrix} \begin{vmatrix} y^{'} \\ y^{*'} \end{vmatrix}$$
$$= -\frac{\pi_{y\theta}}{\pi_{yy^*}} \begin{vmatrix} MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2 \\ MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 \end{vmatrix} \tag{A.20}$$

where

$$MC_y = p - C_y - \gamma(\phi_y - \alpha\phi_{y*})$$
$$MC_{y^*} = p - C_y - \gamma^*(\phi_{y*} - \alpha\phi_y)$$

Applying the Cramer's rule,

$$y' = \frac{1}{\Delta}(-\frac{\pi_{y\theta}}{\pi_{yy*}})MC_y(MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2) \quad (A.21)$$
$$y^{*'} = \frac{1}{\Delta}(-\frac{\pi_{y\theta}}{\pi_{yy*}})MC_{y^*}(MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2) \quad (A.22)$$

where

$$\Delta = (MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2)MC_y + ((1-\beta)\frac{1-F}{f}c_2 - \alpha\gamma\phi_{y^*})MC_{y^*} \quad (A.23)$$

The expressions for checking the second order necessary conditions are

$$\pi_{y^*\theta} + \pi_{yy^*}y' = \pi_{y\theta}\frac{((1-\beta)\frac{1-F}{f}c_2 - \alpha\gamma\phi_{y^*})MC_{y^*}}{\Delta}$$
$$\pi_{y\theta} + \pi_{yy^*}y^{*'} = \pi_{y\theta}\frac{(\beta\frac{1-F}{f}c_2 - \alpha\gamma^*\phi_y)MC_y}{\Delta}$$
$$\pi_{y^*\theta} + \pi_{yy^*}(y' + y^{*'}) = -\pi_{y\theta}\frac{MC_yMC_{y^*}}{\Delta}$$

If one of y' and $y^{*'}$ is zero, for example, $y' = 0$, then first order conditions (31) and (32) become

$$MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2 = (\frac{\alpha\gamma\phi_{y*}}{c_2} - (1-\beta)\frac{1-F}{f})c_1y^{*'} \quad (A.24)$$
$$MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 = 0 \quad (A.25)$$

To solve for a definite solution to the system of differential equations (31) and (32) in the main text, it is necessary to impose an initial/boundary condition to pin down a particular solution from a general solution. Suppose $\gamma \geq \gamma^*$, then consider the following boundary condition:

$$y'(\overline{\theta}) = 0 \quad (A.26)$$

From the first order conditions, both MC_y and MC_{y^*} cannot be zero for all $\theta \in \Theta$. Suppose at some $\theta_1 \in \Theta$, $MC_y\ |_{\theta=\theta_1} = 0$. If $y' \neq 0$ and $y^{*'} \neq 0$, then these assumptions are inconsistent with differential equations (A.21) and (A.22). If $y' \neq 0$ and $y^{*'} = 0$, then condition (31) implies that $(1-\beta)\frac{1-F}{f}c_2 = \alpha\gamma\phi_{y*}$. Since $\frac{d}{d\theta}(\frac{1-F}{f}) \neq 0$ and c_2 is a constant, $y^{*'} \neq 0$ at $\theta = \theta_1$. This contradicts the assumption. If $y' = 0$, then (A.24) gives $y^{*'} = -\frac{c_2}{c_1}$ as $(1-\beta)\frac{1-F}{f}c_2 \neq \alpha\gamma\phi_{y*}$. Then, totally differentiating $MC_y = 0$ at $\theta = \theta_1$ and substituting in the expression for $y^{*'}$ give $-\frac{c_2}{c_1} = \frac{1-\alpha}{\alpha}\frac{b_2}{b_1}$. Hence, $y^{*'} = -\frac{c_2}{c_1} = \frac{1-\alpha}{\alpha}\frac{b_2}{b_1}$. Then totally differentiating (A.25) at $\theta = \theta_1$ gives $\frac{d}{d\theta}(\frac{1-F}{f}) = -\frac{\gamma^* b_2}{\alpha\beta c_2}$. This implies that $\frac{d}{d\theta}(\frac{1-F}{f})$ is a constant, which is contrary to the assumption. Therefore, there exists no $\theta \in \Theta$ such that $MC_y = 0$. As all functions are continuous, MC_y must be either positive or negative for all $\theta \in \Theta$. Similarly, MC_{y^*} must be either positive or negative for all $\theta \in \Theta$. As a result, $\Delta \neq 0$ for all $\theta \in \Theta$.

Given the boundary condition, $y^{'}(\overline{\theta}) = 0$, from equation (A.25), MC_{y^*} is positive at $\theta = \theta_1$ and hence for all $\theta \in \Theta$. To consider the sign of MC_y, totally differentiating equation (A.25) at $\theta = \overline{\theta}$ gives

$$y^{*'} = \frac{-c_2 - \gamma^* b_2}{c_1 + \gamma^* b_1} > 0 \tag{A.27}$$

if $-c_2 > \gamma^* b_2$. Substituting (A.27) into condition (A.24) gives

$$MC_y \mid_{\theta=\overline{\theta}} = \frac{\gamma^*(b_1 - \frac{c_1 b_2}{c_2})}{c_1 + \gamma^* b_1} > 0 \tag{A.28}$$

MC_y is positive at $\overline{\theta}$ and hence for all $\theta \in \Theta$.

Suppose at some $\theta_2 \in \Theta$, $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 \mid_{\theta=\theta_2} = 0$, then (A.21) implies that $y^{'}(\theta_2) = 0$. Equation (31) then becomes (A.24). Totally differentiating $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 \mid_{\theta=\theta_2} = 0$ gives

$$y^{*'} = \frac{-c_2 - \gamma^* b_2 + \beta\frac{d}{d\theta}(\frac{1-F}{f})c_2}{c_1 + \gamma^* b_1} > 0 \tag{A.29}$$

This expression for $y^{*'}(\theta_2)$ is inconsistent with condition (A.22) unless $\theta = \overline{\theta}$. Therefore, there exists no $\theta_2 \in [\underline{\theta}, \overline{\theta})$ such that $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 \mid_{\theta=\theta_2} = 0$. Similarly, there exists no $\theta_3 \in \Theta$[23] such that $MC_y - \alpha\gamma\phi_{y*} + (1 - \beta)\frac{1-F}{f}c_2 \mid_{\theta=\theta_3} = 0$.

From conditions (A.26) and (A.27),

$$MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2 \mid_{\theta=\overline{\theta}} = \alpha\gamma\phi_{y^*}\frac{-c_2 - \gamma^* b_2}{c_1 + \gamma^* b_1}\frac{c_1}{c_2} < 0 \tag{A.30}$$

Hence, $MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2$ is negative for all $\theta \in \Theta$. To examine the sign of $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2$, evaluating condition (32) in the main text at $\theta = \overline{\theta}$ gives

$$p - C_y(y^*, \overline{\theta}) - \gamma^*\phi_{y*} \mid_{\theta=\overline{\theta}} = 0 \tag{A.31}$$

Totally differentiating (A.31) gives

$$-c_2 - \gamma^* b_2 - (c_1 + \gamma^* b_1)y^{*'}(\overline{\theta}) = 0 \tag{A.32}$$

[23] $MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}C_{y\theta} \neq 0$ even at $\theta = \overline{\theta}$ because $y^{*'}(\overline{\theta}) \neq 0$.

To consider the slope of $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2$ at $\theta = \overline{\theta}$, substituting condition (A.32) into the derivative of $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2$ gives

$$\frac{d}{d\theta}(MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2) \mid_{\theta=\overline{\theta}} = \beta c_2 \frac{d}{d\theta}(\frac{1-F}{f}) \tag{A.33}$$

Since $c_2 < 0$ and $\frac{d}{d\theta}(\frac{1-F}{f}) \leq 0$, the slopes of $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2$ is positive at $\theta = \overline{\theta}$. Given $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 = 0$ at $\theta = \overline{\theta}$, $MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2$ is negative in the left neighborhood of $\overline{\theta}$ and hence for all $\theta \in \Theta$.

In sum,

$$MC_y - \alpha\gamma\phi_{y*} + (1-\beta)\frac{1-F}{f}c_2 < 0 < MC_y \tag{A.34}$$

$$MC_{y^*} - \alpha\gamma^*\phi_y + \beta\frac{1-F}{f}c_2 < 0 < MC_{y^*} \tag{A.35}$$

It is then trivial that the Nash equilibrium with boundary condition (A.26) satisfies $y^{'} > 0$, $y^{*'} > 0$, and (A.4). Since all functions are continuous and have bounded derivatives to the third order, the Lipschitz condition is satisfied uniformly. From Theorem 11 and 12 in Chapter 2 of Hurewicz (1958), there exists a unique solution satisfying (31) and (32) from any initial point $(y, y^*, \theta) \in R_+^2 \times \Theta$ given by boundary condition (A.26). Hence, there exists an implementable Nash equilibrium. The above equilibrium is unique under the boundary condition, $y^{'}(\overline{\theta}) = 0$.

3) Feasibility

Since $\Lambda_\theta = \pi_\theta(1-(1-\beta)\frac{d}{d\theta}(\frac{1-F}{f})) > 0$ and $\Lambda^*_\theta = \pi_\theta(1-\beta\frac{d}{d\theta}(\frac{1-F}{f})) > 0$, $\Lambda(\theta) \geq 0$ if $\Lambda(\underline{\theta}) \geq 0$ and $\Lambda^*(\theta) \geq 0$ if $\Lambda^*(\underline{\theta}) \geq 0$. Following the same arguments as those in the cooperative case, all firms choose to produce in both countries and both governments allow all existing firms to operate.