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Optimal Control of Upstream Pollution under Asymmetric Information

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Abstract. This paper derives optimal bribes to reduce upstream transfrontier emissions in the presence of asymmetric information on the polluter's concern for the environment. In a model in which the starting point for the negotiations on emission reduction is a Cournot-Nash equilibrium, it is shown that transfers from the victim induce the polluting country to exaggerate its concern for the environment. As a consequence, in the second best solution, abatement of all but the least caring type is distorted downward and optimal bribes may be such that more caring types turn them down. These results are in sharp contrast to earlier policy proposals derived for a non-equilibrium starting point. They indicate that under asymmetric information the binding incentive problem is to prevent the polluting country from claiming not to care about the environment and that optimal bribes from the victim should be restricted to sufficiently environmentally concerned polluters.

Key words: asymmetric information, downstream pollution, transboundary emissions, type-dependent reservation utility

JEL classification: D62, D82, F42, Q25, (C71, H23)

1. Introduction

The transboundary dimension of many important examples of pollution arises from the fact that emissions in one country also damage the environment in other countries. Obvious examples include global warming, damage to the stratospheric ozone layer, acid rain, and pollution of transnational waters, as e.g. the North Sea, the River Rhine, or the Niger.

A crucial distinguishing feature of *transboundary pollution* is the lack of a supra-national authority empowered to impose any particular course of action. Thus, voluntary agreements among sovereign countries are needed to deal with these problems. An obvious difficulty with any such agreement is the tendency for countries to seek a free ride, in other words, to get the benefits of reduced pollution without spending resources on cutting their own emissions. A further problem is that the reduction of emissions to efficient levels may involve some countries making losses relative to the status quo. This is especially true for extreme examples of non-uniform mixing[1] or non-uniform damages,[2] where moving towards an efficient solution without paying compensation to polluters inevitably violates individual rationality. As a consequence, financial transfers from the victim(s) to the polluter(s) have been advocated, both in the theoretical and empirical literature (cf., for example, Mäler 1989, 1990; Barrett 1990; Newberry 1990; Chander and Tulkens 1992, 1995, 1997; Amann et al. 1992; Kaitala et al. 1992; Tahvonen et al. 1993) and by politicians (as in the follow-up of the Montreal Protocol, in the Framework Convention on Climate Change, or, more recently, in Kyoto).[3]

Most compensation-proposals in the academic literature are based on the assumption that information on each country's marginal benefit and marginal cost of pollution control is perfect and symmetric. This is clearly a strong assumption, especially with respect to the benefits of pollution control, as several authors have admitted (cf., for example, Mäler 1989; Chander and Tulkens 1992; Carraro and Siniscalco 1993).

The present paper derives optimal compensation for transboundary emission-reduction in the presence of asymmetric information on the polluter's concern for the environment. To do so we formulate a simple downstream pollution model consisting of two countries located along a river. Each country benefits from using the river as a drip-pan for emissions but, at the same time, suffers from pollution. While the benefit of each country depends on domestic emissions only, the cost in terms of pollution depends on domestic and upstream emissions. This implies that the downstream country, country d, cannot efficiently control its exposure to pollution through its own action but only through negotiations with the upstream country, country u. Negotiations are assumed to take the form of a take-it-or-leave-it-offer from country d to country u, specifying a desired emission-reduction to be reached by u, combined with d's offer to pay a compensation. The benchmark against which the benefits of cooperation are judged is the status quo. This is assumed to be given by a Nash equilibrium in which each country chooses its own emissions taking the emissions of the other country as given.

Perfect observations of equilibrium emissions would allow the victim (country d) to disclose the polluter's (country u's) private information on his concern for the environment. In our set-up, this revelation is suppressed by the interplay of two modeling details. First, the assumption that immissions in each country can be measured at relatively low (in the model, at no) cost whereas measuring a country's emissions is prohibitively costly for an external observer. And second, the supposition that immissions in country u are the result of current emissions by u and pollution stemming from elsewhere (from natural sources, from irreversibly contaminated sites in country u, etc.). In this situation the victim is unable to infer the polluter's equilibrium emissions from observing immissions: The immissions might be high because pollution stemming from elsewhere is high; or they might be high because the polluting country u does not care much about the environment.

In this set-up, financial transfers (bribes) from the victim for emission-reductions by the polluter generate counter-vailing incentives for the polluter: (i) incentives to understate the concern for the environment in order to suggest a higher status quo utility; and (ii) incentives to exaggerate the concern for the environment to suggest higher reduction costs. We show that at an optimum the latter incentive dominates the former. Consequently, the optimal abatement of all but the least caring type is distorted downward, and optimal bribes may induce more caring types to turn them down.

The issue of asymmetric information has rarely been studied in the optimal bribes literature before. Indeed, to our knowledge, there are only two previous contributions analyzing that topic. The earlier one is Mäler (1990). He studies a 2-country downstream-pollution model in which the upstream country has private information on abatement- and the downstream country private information on damage-costs. Mäler shows that the outcome of bargaining among the two countries on pollution control and side payments is efficient relative to the true cost and benefit functions. Crucial for this result is Mäler's assumption that the two countries have equal bargaining power in their negotiations on emission-reductions.[4] To understand the power of this assumption, first note that if there only were asymmetric information on the upstream county's abatement cost, then the first best (f.b.) solution would prevail, if that country had all the bargaining power. Moreover, the f.b. would still prevail, if a small enough portion of the bargaining power were lost to the second country. Symmetrically, if there only were asymmetric information on the downstream county's damage cost, then the f.b. solution would be maintained if that country were the residual claimant in the negotiations. It would still be maintained if a small enough part of the cake were lost to the second country. Looking now at a set-up with two-sided asymmetric information, the mechanisms at work are clear: With equal bargaining power, each county's share in the bargaining gain *might be* large enough for the outcome of negotiations on pollution control to be efficient. Whether the shares *are really* large enough, depends on the details of the model considered. In the Mäler (1990) model the details are such that the outcome is indeed efficient.

The question arises what happens if we leave Mäler's special framework? The simplest way to study this is to consider a set-up where the less informed party has all the bargaining power. This has previously been done in the second contribution considering asymmetric information, the semi-empirical paper by Huber and Wirl (1996). These authors study a 2-country downwind pollution model in the presence of asymmetric information on damage-costs. As in the present paper, it is assumed that the benefits of cooperation go to the victim country. Huber and Wirl show that the binding incentive problem is to prevent the polluting country from claiming not to care about the environment in hope of solicitating greater compensation from the victim. Then, they derive a subsidy scheme from the victim (Austria) to the polluter (the former Czechoslovakia) under which the compensation from the victim increases with respect to the polluter's appreciation of environmental benefits. If the polluter doesn't care sufficiently about the environment, he gets nothing.

There is one critical detail in the Huber-and-Wirl model. To make sure that observed pollution allows for no inference on the environmental concern of the polluter, the authors (implicitly) assume that the situation that prevails before the victim offers financial support for emission-reduction in the polluting country, is not an equilibrium situation.[5] While this assumption is quite plausible in their context (the situation prevailing in in former Czechoslovakia at that time was to a large degree the result of fifty years of socialist planning), it is questionable in other settings. An important question therefore is, whether the Huber-and-Wirl results are robust in that respect. The present paper tackles this question. It shows that by explicitly considering the Cournot-Nash equilibrium as the starting point for the negotiations on emission reduction, the Huber-and-Wirl results are turned upside down. Indeed, as mentioned before, in our model the binding incentive problem is to prevent the polluting country from exaggerating its concern for the environment, and optimal bribes might be such that more caring types turn them down. As will become clear in the paper, there is a convincing intuition for this rather startling difference in results.

From a technical point of view, the present paper is also related to the work on optimal contracts with type-dependent reservation utility as presented, among others, by Lewis and Sappington (1989), Champsaur and Rochet (1989), and Maggi and Rodriguez-Clair (1995) on the one, and by Laffont and Tirole (1990), Caillaud, Jullien and Picard (1990), and Kerschbamer and Maderner (1997) on the other hand. On an analytical level, a major difference to the first group of papers is that they derive their results from a model with a continuous type-set while our type-set is discrete. A difference to the second group of papers is that they restrict attention to settings with a binary type-set (the unique exception is Kerschbamer and Maderner 1997) while we allow for arbitrarily many types.

The rest of the paper is organized as follows. Section 2 describes the basic model and derives the status quo solution and the optimal bribes under symmetric information. Section 3 introduces asymmetric information and presents the main results. Conclusions are drawn in Section 4.

2. Symmetric Information

2.1. The Basic Model

We consider a simple transfrontier pollution model consisting of 2 countries, indexed by $i = d, u$. Each country derives utility from consuming a private good X and suffers from pollution Q. Under the assumption that labor, capital and other input factors are optimally employed, country i's production of the private good depends only on its emissions, $p^i \geq 0$. This dependence is represented by the smooth, strictly increasing and strictly concave production function $y^i = f(p^i)$, which is assumed to satisfy the regularity condition $f'''(p^i) \geq 0$ for all $p^i > 0$.[6]

Consumption of the private good by country d (and country u, respectively) is given by $x^d = y^d - t$ (and $x^u = y^u + t$, respectively), where t is a transfer from d to u (or a transfer from u to d whenever $t < 0$) measured in units of X. Country i's preferences over consumption of the private good and pollution are represented by the quasi-linear utility function $U^i(x^i, q^i) = x^i - v^i(q^i)$, where q^i denotes the immission of pollution in this country and where $v^i(\cdot)$ is a smooth, strictly increasing, strictly convex function, so that $v^{i'}(\cdot) > 0$ and $v^{i''}(\cdot) > 0$. Borrowing from Mäler (1989) we assume that immission in country i $(= d, u)$ is given by a weighted sum of the emission levels p^d and p^u in the two countries and pollution p^e stemming from elsewhere (from natural sources, from irreversibly contaminated sites, etc.). The weights in the summation are commonly known transmission coefficients indicating what proportion of emission from a given source $j(= d, u, e)$ is ultimately deposited in country i. Since we are interested in an extreme instance of non-uniform mixing where the upstream (or upwind) country u pollutes a downstream (or downwind) country d we represent this weighted sum by[7]

$$\begin{aligned} q^d &= p^d + a^u(p^u + p^e) = p^d + a^u q^u \\ q^u &= p^u + p^e. \end{aligned} \tag{1}$$

The variables q^d and q^u are assumed to be observable and verifiable. Emission by country i, on the other hand, is i's private information. For later use, it is convenient to express county i's utility before transfer in terms of p^i and q^u, both being observable by country i:

$$\begin{aligned} u^d(p^d, q^u) &:= f(p^d) - v^d(p^d + a^u q^u) \\ u^u(p^u, q^u) &:= f(p^u) - v^u(q^u). \end{aligned} \tag{2}$$

2.2. The status quo solution

The status quo is given by a non-cooperative equilibrium of the Nash type. In a Nash equilibrium each country i chooses its emission p^i so as to maximize its own utility, taking the emission of the other country and pollution stemming from elsewhere as given. In a Nash equilibrium we must have

$$f'(\bar{p}^i) = v^{i'}(\bar{q}^i) \qquad \text{for } i = d, u, \tag{3}$$

where the upper bars denote the status quo solution. Here, notice that if the disutility of pollution functions (and technologies) were common knowledge among both players, country d could deduce country u's status quo emissions from knowing $\bar{q}^u$.

2.3. Optimal bribes under symmetric information

It is obvious that the status quo solution is not efficient: In choosing its emission the upstream country ignores the negative externality its activity imposes on the downstream country. In this situation, an agreement between the two countries specifying a desired emission reduction Δp to be reached by the polluter combined with the victim's offer to pay t as compensation could lead to a Pareto improvement. Assume, for the moment, that each country has complete information on the other's preferences and technology. Then the agreement $(\Delta p, t)$ that maximizes the victim's utility solves

$$\begin{aligned} &\max_{p^d,\Delta p,t}\{u^d(p^d, \bar{q}^u - \Delta p) - t\} \qquad \text{s.t.} \\ &\quad u^u(\bar{p}^u - \Delta p, \bar{q}^u - \Delta p) + t \geq \bar{u}^u, \end{aligned} \tag{4}$$

where $\bar{u}^u := u^u(\bar{p}^u, \bar{q}^u)$ is the polluter's status quo utility level.[8] The solution to this problem (marked by an asterisk) is usefully characterized by the FOCs[9]

$$\begin{aligned} f'(p^{d*}) &= v^{d'}(p^{d*} + a^u(\bar{q}^u - \Delta p^*)) \\ f'(\bar{p}^u - \Delta p^*) &= a^u v^{d'}(p^{d*} + a^u(\bar{q}^u - \Delta p^*)) + v^{u'}(\bar{q}^u - \Delta p^*) \end{aligned} \tag{5}$$

and by

$$t^* = \bar{u}^u - u^{u*} > 0, \tag{6}$$

where $u^{u*} := u^u(\bar{p}^u - \Delta p^*, \bar{q}^u - \Delta p^*)$. Obviously, $u^{d*} - t^* := u^d(p^{d*}, \bar{q}^u - \Delta p^*) - t^* > \bar{u}^d$ and $\Delta p^* > 0$. Furthermore, $p^{d*} > \bar{p}^d$.[10]

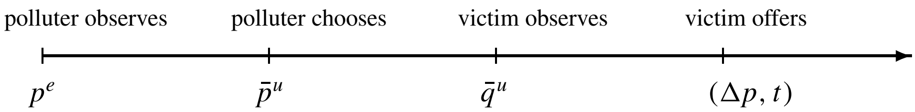

Figure 1. Time Line.

3. Asymmetric Information

3.1. "Caring" and "non-caring" countries

The bribes solution derived in Section 2.3 requires perfect information on the polluter's preferences and technology. We now drop this assumption and assume instead that the preferences of any country are known only to that country. In this situation the victim is unable to infer the polluter's status quo emissions from observing $\bar{q}^u$: $\bar{q}^u$ might be high because pollution stemming from elsewhere is high; or it might be high because the polluting country does not care much about the environment so that its pollutant discharges $\bar{p}^u$ are high. The victim simply does not know which of these cases prevails. Given its observation of $\bar{q}^u$ (and, might be, some additional information on pollution stemming from elsewhere) it will, however, have beliefs about the polluter's attitude towards the environment. In the sequel we assume that these beliefs are represented by the victim's subjective conditional probability distribution over a set of possible disutility-of-pollution functions for the polluting country. Specifically, we assume that – conditional on its (perfect) information on $\bar{q}^u$ and its (imperfect) information on p^e – country d expects u's disutility-of-pollution function $v^u(\cdot)$ to have n different realizations v_l^u, $l \in I := \{1, \ldots, n\}$, each occurring with strictly positive probability according to the marginal distribution $(\pi_1, \ldots, \pi_n)$, with cumulative distribution $\Pi_l = \sum_{k=1}^{l} \pi_k$. A higher realization is assumed to imply higher total and marginal disutility of pollution ("a higher type cares more about the environment"), and the difference in disutilities between two different types is assumed to be increasing at an increasing rate with pollution. Formally we have

$$\begin{aligned} v_k^u(q) &< v_l^u(q) && \text{for } k < l \text{ and } q > 0 \\ v_k^{u\prime}(q) &< v_l^{u\prime}(q) && \text{for } k < l \text{ and } q > 0 \\ v_k^{u\prime\prime}(q) &< v_l^{u\prime\prime}(q) && \text{for } k < l \text{ and } q > 0. \end{aligned} \tag{7}$$

3.2. The Status Quo Solution

Given a status quo immission level $\bar{q}^u$ and the associated set of possible disutility of pollution functions for the polluting country u, country d can calculate the status quo emissions associated with any type of the polluter. Obviously, the polluter's status quo emissions are lower for more caring types, and more caring types have lower status quo utilities. This is confirmed by Lemma 3.1.

LEMMA 3.1. *Let $\bar{p}_l^u$ be country u's status quo emission-, and $\bar{u}_l^u$ its status quo utility-level given that u is of type $l \in I$. Then $\bar{p}_k^u > \bar{p}_l^u$ and $\bar{u}_k^u > \bar{u}_l^u$ for $k < l$ with $k, l \in I$.*

Proof: Follows immediately from $f'(\cdot) > 0$ and $f''(\cdot) < 0$. □

3.3. A Benchmark Solution

The victim country can also calculate what emission reduction by the polluter it would strive for if it knew his type. Since more caring types have already lower status quo emissions, a given reduction in discharges increases the polluter's marginal cost (in terms of lost production) by more for these types than for less caring ones. At the same time, a given reduction in immissions decreases the polluter's marginal benefit (in terms of reduced disutility of pollution) by more for more caring types. Thus, for a given reduction in emissions, Δp, the gap between the polluter's marginal cost and his marginal benefit is larger for more caring types. Moreover, the difference in gaps is increasing at an increasing rate with the reduction in emission. We record this preliminary result as Lemma 3.2.

LEMMA 3.2. *For $l \in I \setminus \{n\}$ let*

$$W_l(\Delta p) := u_l^u(\bar{p}_l^u - \Delta p, \bar{q}^u - \Delta p) - u_{l+1}^u(\bar{p}_{l+1}^u - \Delta p, \bar{q}^u - \Delta p). \quad (8)$$

$W_l(\cdot)$ is strictly positive, strictly increasing and strictly convex on $\mathbb{R}_+$.

Proof: By (7) $W_l(\cdot)$ is strictly positive. That it is strictly convex and strictly increasing for $\Delta p > 0$ follows from $W_l'(\Delta p) = -\{f'(\bar{p}_l^u - \Delta p) - v_l^{u\prime}(\bar{q}^u - \Delta p) - (f'(\bar{p}_{l+1}^u - \Delta p) - v_{l+1}^{u}{}'(\bar{q}^u - \Delta p))\}$ being zero for $\Delta p = 0$ (by (3)) and (by (7) and since $f'''(\cdot) \geq 0$) from $W_l''(\Delta p) = f''(\bar{p}_l^u - \Delta p) - f''(\bar{p}_{l+1}^u - \Delta p) - v_l^{u\prime\prime}(\bar{q}^u - \Delta p) + v_{l+1}^{u}{}''(\bar{q}^u - \Delta p) > 0$. □

Together with (5) Lemma 3.2 implies that the desired emission reduction in a first best setting with symmetric information is lower for higher (i.e., more caring) types. We record this as Lemma 3.3:

LEMMA 3.3. *Let Δp_l^* be the desired emission reduction for type $l \in I$ under symmetric information. Then $\Delta p_k^* > \Delta p_l^*$ for $k < l$ with $k, l \in I$.*

Proof: By the FOCs of the first best problem, and since $\Delta p_k^* > 0$ for all $k \in I$ implying $W_l'(\Delta p_k^*) > 0$ for all $k \in I$, we have

$$\begin{aligned}
0 &= a^u v^{d\prime}(p_l^{1*} + a^u(\bar{q}^u - \Delta p_l^*)) + v_l^{u\prime}(\bar{q}^u - \Delta p_l^*) - f'(\bar{p}_l^u - \Delta p_l^*) \\
&< W_l'(\Delta p_{l+1}^*) \\
&= v_l^{u\prime}(\bar{q}^u - \Delta p_{l+1}^*) - f'(\bar{p}_l^u - \Delta p_{l+1}^*) \\
&\quad - v_{l+1}^{u}{}'(\bar{q}^u - \Delta p_{l+1}^*) + f'(\bar{p}_{l+1}^u - \Delta p_{l+1}^*) \\
&= a^u v^{d\prime}(p_{l+1}^{1*} + a^u(\bar{q}^u - \Delta p_{l+1}^*)) + v_l^{u\prime}(\bar{q}^u - \Delta p_{l+1}^*) - f'(\bar{p}_l^u - \Delta p_{l+1}^*).
\end{aligned}$$

Using the fact that the derivative of this expression with respect to Δp is strictly negative,[11] we conclude that $\Delta p_l^* > \Delta p_{l+1}^*$ for all $l \in I \setminus \{n\}$ and therefore $\Delta p_k^* > \Delta p_l^*$ for $k < l$ with $k, l \in I$. □

To compensate the polluter for his reduction in emissions, the victim country has to pay a transfer, guaranteeing him (at least) his status quo utility level. From (6) we know that in a first best setting with symmetric information this transfer would satisfy

$$t_l^* = u_l^u(\bar{p}_l^u, \bar{q}^u) - u_l^u(\bar{p}_l^u - \Delta p_l^*, \bar{q}^u - \Delta p_l^*),$$

where l indicates the type for which the transfer is intended.

3.4. Optimal bribes under asymmetric information

In the present setting with asymmetric information the first best solution from the victim's point of view is not a feasible allocation as Lemma 3.5 below shows. Nevertheless there are attainable gains from cooperation. What is in this setting with asymmetric information the optimal agreement to be offered by the victim? By the revelation principle (cf., e.g., Dasgupta et al. 1979; Myerson 1979) the victim can restrict attention, without loss of generality, to direct mechanisms of the form $(\boldsymbol{\Delta p}, \boldsymbol{t})$=$((\Delta p_l, t_l)|l \in I)$, where Δp_l is the reduction in emission designated for the polluter if he reveals to be of type l and t_l is the associated transfer paid by the victim, provided the polluter implements Δp_l.[12] Consider an agreement $(\boldsymbol{\Delta p}, \boldsymbol{t})$. For type l of country u to choose the emission reduction designated for him the agreement must be incentive compatible, i.e., satisfy the condition

$$u_l^u(\bar{p}_l^u - \Delta p_l, \bar{q}^u - \Delta p_l) + t_l \geq u_l^u(\bar{p}_l^u - \Delta p_k, \bar{q}^u - \Delta p_k) + t_k \qquad (IC_{lk})$$

for any $k \neq l$. If type l of country u breaks the agreement the status quo solution prevails. Hence, type l will obey the agreement only if it is individual rational, i.e., if it satisfies the condition

$$u_l^u(\bar{p}_l^u - \Delta p_l, \bar{q}^u - \Delta p_l) + t_l \geq u_l^u(\bar{p}_l^u, \bar{q}^u). \qquad (IR_l)$$

The agreement $(\boldsymbol{\Delta p}, \boldsymbol{t})$ that maximizes the victim's utility therefore solves

$$\max_{\boldsymbol{p^d}, \boldsymbol{\Delta p}, \boldsymbol{t}} \quad E\{u^d(p_l^d, \bar{q}^u - \Delta p_l) - t_l\} \qquad (M)$$

subject to (IR_l) and (IC_{lk}) hold for all $l, k \in I$. We name the solution to this problem the second best solution and denote it by $(\boldsymbol{\hat{p}^d}, \boldsymbol{\Delta \hat{p}}, \boldsymbol{\hat{t}})$= $((\hat{p}_l^d, \Delta \hat{p}_l, \hat{t}_l)|l \in I)$. Our first result shows that both, second best emission-reductions and second best transfers, are non-increasing in type:

LEMMA 3.4. *Let* $(\boldsymbol{\hat{p}^d}, \boldsymbol{\Delta \hat{p}}, \boldsymbol{\hat{t}})$ *be the second best solution. Then* $\Delta \hat{p}_k \geq \Delta \hat{p}_l$ *and* $\hat{t}_k \geq \hat{t}_l$ *for* $k < l$ *with* $k, l \in I$.

Proof: Using the function $W_l(\Delta p)$ as defined in (8), the two i.c. constraints $(IC_{l+1,l})$ and $(IC_{l,l+1})$ can for all $l \in I \setminus \{n\}$ be rewritten as

$$\begin{aligned} W_l(\Delta p_l) &\geq (t_l - t_{l+1}) + u_l^u(\bar{p}_l^u - \Delta p_l, \bar{q}^u - \Delta p_l) \\ &-u_{l+1}^u(\bar{p}_{l+1}^u - \Delta p_{l+1}, \bar{q}^u - \Delta p_{l+1}) \geq W_l(\Delta p_{l+1}). \end{aligned} \qquad (9)$$

Since for any $l \in I \setminus \{n\}$ $W_l'(\cdot) > 0$ for all $\Delta p > 0$ these constraints can only be met if $\Delta p_l \geq \Delta p_{l+1}$ and hence the first part of the claim follows. Using $(IC_{l,l+1})$ and the fact that $\partial u_k^u / \partial \Delta p \leq 0$ for all $\Delta p \geq 0$ and all $k \in I$ we get $0 \leq u_l^u(\bar{p}_l^u - \Delta p_{l+1}, \bar{q}^u - \Delta p_{l+1}) - u_l^u(\bar{p}_l^u - \Delta p_l, \bar{q}^u - \Delta p_l) \leq t_l - t_{l+1}$ for all $l \in I \setminus \{n\}$ and therefore $\hat{t}_k \geq \hat{t}_l$ for $k < l$, which confirms the second part of the claim. □

Next, we show that the first best solution from the victim's point of view, that is, the unique maximizer of (M) subject to (IR_l) holds for all $l \in I$, is not feasible in the considered situation with asymmetric information:

LEMMA 3.5. *The second best solution* $(\hat{\boldsymbol{p}}^d, \boldsymbol{\Delta}\hat{\boldsymbol{p}}, \hat{\boldsymbol{t}})$ *is different from the first best solution* $(\boldsymbol{p}^{d*}, \boldsymbol{\Delta p}^*, \boldsymbol{t}^*)$.

Proof: Inserting the respective first best values in (9) and using that $t_k^* = u_k^u(\bar{p}_k^u, \bar{q}^u) - u_k^u(\bar{p}_k^u - \Delta p_k^*, \bar{q}^u - \Delta p_k^*)$ we get $W_l(\Delta p_{l+1}^*) \leq W_l(0) \leq W_l(\Delta p_l^*)$, which contradicts $W'(\cdot) > 0$. □

The problem with the first best solution is that the incentive compatibility constraints $(IC_{l,l+1})$ for $l \in I \setminus \{n\}$ are violated. Thus, the agreement $(\boldsymbol{\Delta p}^*, \boldsymbol{t}^*)$ would induce lower types to pretend to care more about the environment than they actually do. On first sight, this seems to be counterintuitive, since by doing so they suggest a lower status quo utility so that a low transfer is needed to induce them to accept the victim's offer. However, there is also a countervailing effect: By posing as higher types, lower types also suggest that their cost (net of private benefits) of implementing a given emission reduction is high, so that a high transfer is required to compensate them for their abatement efforts. With the first best offer this latter incentive unambiguously dominates the former; in other words, the agreement $(\boldsymbol{\Delta p}^*, \boldsymbol{t}^*)$ unambiguously induces the polluter to *exaggerate his concern for the environment* in an attempt to convince the victim that his emissions are already low while the pollution inherited from elsewhere is high. Proposition 3.1 below shows that the temptation to overstate the type remains the binding incentive problem in the second best solution. To introduce this result we need another lemma. In this lemma reference is made to the term "adjacent incentive compatibility constraint". For all $l \in I \setminus \{n\}$ the adjacent incentive compatibility constraints are defined to be $(IC_{l,l+1})$ and $(IC_{l+1,l})$.

LEMMA 3.6. *In the second best solution only adjacent incentive compatibility constraints matter.*

Proof: Assume that all adjacent incentive compatibility constraints are satisfied. Take any pair of types $k, l \in I$ with $k < l - 1$. Adding constraints $(IC_{k,k+1})$, $(IC_{k+1,k+2}), \ldots, (IC_{l-1,l})$ and using $\Delta p_k \geq \ldots \geq \Delta p_{l-1} \geq \Delta p_l$ shows that (IC_{kl}) is satisfied. The argument for the converse case is similar. □

PROPOSITION 3.1. *In the second best solution there exists an* $l_0 \leq n$ *such that (i) the adjacent incentive compatibility constraint* $(IC_{l,l+1})$ *is binding (with a strictly positive multiplier) and the individual rationality constraint* (IR_l) *is slack for all* $l < l_0$*; (ii) the individual rationality constraint* (IR_l) *is binding for* $l = l_0$*; and (iii)* $\Delta\hat{p}_l = \hat{t}_l = 0$ *for all* $l > l_0$.

Proof: Let μ_l denote the Lagrange multiplier for (IR_l) and $\lambda_{l,l+1}$ (resp. $(\nu_{l+1,l})$) that for $(IC_{l,l+1})$ (resp. $(IC_{l+1,l})$). The FOCs with respect to t_l are

$$\begin{aligned}
&\pi_1 = \mu_1 + \lambda_{12} - \nu_{21} \\
&\pi_l = \mu_l + \lambda_{l,l+1} - \lambda_{l-1,l} - \nu_{l+1,l} + \nu_{l,l-1} \qquad \text{for } 2 \le l \le n-1 \\
&\pi_n = \mu_n - \lambda_{n-1,n} + \nu_{n,n-1}.
\end{aligned}$$

Summing up these conditions leads to $1 = \sum_{l=1}^{n} \pi_l = \sum_{l=1}^{n} \mu_l$. Hence, there exists at least one $l \in I$ for which (IR_l) is binding. From the upward incentive compatibility constraints $(IC_{l,l+1})$ we deduce that the information rent given by $\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u := u_l^u(\bar{p}_l^u - \Delta\hat{p}_l, \bar{q}^u - \Delta\hat{p}_l) + \hat{t}_l - \bar{u}_l^u$ is non-increasing in type:

$$\begin{aligned}
\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u &\ge \hat{u}_{l+1}^u + \hat{t}_{l+1} \\
&\quad - \bar{u}_{l+1}^u + W_l(\Delta\hat{p}_{l+1}) - W_l(0) \ge \hat{u}_{l+1}^u + \hat{t}_{l+1} - \bar{u}_{l+1}^u,
\end{aligned}$$

since $W_l(\Delta p)$ is minimal at $\Delta p = 0$. Hence, there must exist an $l_0 \le n$ such that (IR_l) is binding for $l \ge l_0$ and slack otherwise. Consider any $l \ge l_0$. Using (9), the incentive compatibility constraints $(IC_{l,l+1})$ and $(IC_{l+1,l})$ can be rewritten as

$$W_l(\Delta\hat{p}_{l+1}) \le \bar{u}_l^u - \bar{u}_{l+1}^u = W_l(0) \le W_l(\Delta\hat{p}_l),$$

which can only be met if $\Delta\hat{p}_{l+1} = 0$. Since (IR_{l+1}) is binding, $\hat{t}_{l+1} = 0$, too. Consider now any $l < l_0$ and define $\gamma_l := \lambda_{l,l+1} - \nu_{l+1,l}$. Using the fact that $\mu_l = 0$ for $l < l_0$ the FOCs with respect to t_l simplify to $\pi_l = \gamma_l - \gamma_{l-1}$ for $l > 1$ and $\pi_1 = \gamma_1$. Summing the first l of these conditions up leads to $\gamma_l = \Pi_l > 0$. Consequently, $\lambda_{l,l+1} > 0$ for all $l < l_0$ and thus $(IC_{l,l+1})$ is binding. □

Under complete information the victim country d would strive for strictly positive emission reductions for all types of the polluter, i.e., $\Delta p_l^* > 0$ for all $l \in I$. Proposition 3.1. tells us that this might no longer be the case in the present setting with asymmetric information. Here the *binding incentive problem is to prevent lower types from exaggerating their concern for the environment* by choosing abatement levels intended for higher ones. It may therefore be worthwhile for country d to design an agreement that is unattractive for types that have the highest valuation for the environment since this reduces the mimicking potential for lower types. The following proposition contains a more accurate description of the second best solution:

PROPOSITION 3.2. *The second best emissions by country d* $\hat{\boldsymbol{p}}^{\boldsymbol{d}} = (\hat{p}_1^d, \ldots, \hat{p}_n^d)$ *and the second best abatements by country u* $\boldsymbol{\Delta\hat{p}} = (\Delta\hat{p}_1, \ldots, \Delta\hat{p}_n)$ *solve*

$$\begin{aligned}
&\max_{\boldsymbol{p^d},\, \boldsymbol{\Delta p}} \sum_{l=1}^{n} \pi_l [u^d(p_l^d, \bar{q}^u - \Delta p_l) + u_l^u(\bar{p}_l^u - \Delta p_l, \bar{q}^u - \Delta p_l) \\
&\qquad\qquad - \tfrac{\Pi_{l-1}}{\pi_l}(W_{l-1}(\Delta p_l) - W_{l-1}(0))] \qquad (10) \\
&\text{s.t. } \Delta p_1 \ge \ldots \ge \Delta p_n,
\end{aligned}$$

where $W_0 \equiv 0$ *and* $\Pi_0 \equiv 0$. *The second best transfers are given by* $\hat{t}_l = \bar{u}_l^u - \hat{u}_l^u + \sum_{k=l}^{n-1}(W_k(\Delta p_{k+1}) - W_k(0))$ *for* $l < n$ *and* $\hat{t}_l = \bar{u}_l^u - \hat{u}_l^u$ *for* $l = n$.

Proof: It is sufficient to show that the solution to (M) subject to (IR_l) and (IC_{lk}) for $k, l \in I$ satisfies $\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u = \sum_{k=l}^{n-1}(W_k(\Delta p_{k+1}) - W_k(0))$ for $l < n$ and $\bar{u}_l^u + \hat{t}_l - \hat{u}_l^u = 0$ for $l = n$ and hence

$$\begin{aligned}\sum_{l=1}^{n}\pi_l(\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u) &= \sum_{l=1}^{n-1}\pi_l(\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u)\\ &= \sum_{l=1}^{n-1}\pi_l(\sum_{k=l}^{n-1}(W_k(\Delta p_{k+1}) - W_k(0)))\\ &= \sum_{l=1}^{n-1}\Pi_l(W_l(\Delta p_{l+1}) - W_l(0)).\end{aligned}$$

For $l \geq l_0$ this trivially holds since $\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u = 0 = \sum_{k=l}^{n-1}(W_k(\Delta p_{k+1}) - W_k(0))$ for $\Delta p_{k+1} = 0$. Suppose therefore $l < l_0$. As shown in the proof of Proposition 3.1, $(IC_{l,l+1})$ is binding in this case. Therefore,

$$\begin{aligned}\hat{u}_l^u + \hat{t}_l - \bar{u}_l^u &= \hat{u}_{l+1}^u + \hat{t}_{l+1} - \bar{u}_{l+1}^u + (W_l(\Delta p_{l+1}) - W_l(0))\\ &= \hat{u}_{l_0}^u + \hat{t}_{l_0} - \bar{u}_{l_0}^u + \sum_{k=l}^{l_0-1}(W_k(\Delta p_{k+1}) - W_k(0))\\ &= \sum_{k=l}^{n-1}(W_k(\Delta p_{k+1}) - W_k(0))\end{aligned}$$

which finishes the proof. □

Proposition 3.2 tells us that the second best emission reductions $(\Delta\hat{p}_1, \ldots, \Delta\hat{p}_n)$ are determined by trading off *distortions in the abatements of more caring types* against *rents to be left to less caring ones.* To see this, first notice that maximizing only the first (upper) part of (10) yields first best abatements. Next, notice that the term $W_{l-1}(\Delta p_l) - W_{l-1}(0)$ measures the extra rent type $l - 1$ must get for not mimicking his more caring neighbor, type l – extra in the sense of "in addition to the rent already conceded to l". So the required emission reduction intended for type l maximizes the welfare gain from l's abatement activity under symmetric information minus an amount that corresponds to the sum of increments in informational rents that the victim must concede to those types of the polluting country that care less about the environment than l does in order to prevent them from posing as type l. An immediate implication of this rent effect is:

COROLLARY 3.2. *The second best abatements by country u $\boldsymbol{\Delta\hat{p}} = (\Delta\hat{p}_1, \ldots, \Delta\hat{p}_n)$ satisfy $\Delta\hat{p}_l = \Delta p_l^*$ for $l = 1$ and $\Delta\hat{p}_l < \Delta p_l^*$ for $1 < l \leq n$.*

Proof: We have already shown that $\Delta\hat{p}_l = 0$ for $l_0 < l \leq n$. Employing the same technique as in the proof of Proposition 3.1 we see that the FOCs with respect to Δp_l for $1 < l \leq l_0$ are

$$\pi_l(a^u v^{d\prime}(p_l^d + a^u(\bar{q}^u - \Delta p_l)) + v_l{}^{u\prime}(\bar{q}^u - \Delta p_l) - f'(\bar{p}_l^u - \Delta p_l)) = \lambda_{l-1,l} W'_{l-1}(\Delta p_l) - \nu_{l+1,l} W'_l(\Delta p_l). \quad (11)$$

The FOC for $l = 1$ is

$$\pi_1(a^u v^{d\prime}(p_1^d + a^u(\bar{q}^u - \Delta p_1)) + v_1{}^{u\prime}(\bar{q}^u - \Delta p_1) - f'(\bar{p}_1^u - \Delta p_1)) = -\nu_{21} W'_1(\Delta p_1).$$

The left hand side of both of these equations is decreasing in Δp_l and equals zero iff $\Delta p_l = \Delta p_l^*$. Hence, for $1 \leq l \leq l_0$ there is downward distortion in country u's abatement level iff the right hand side of the respective equation is positive.

We start by showing that $\Delta\hat{p}_{l_0} < \Delta p_{l_0}^*$. Assume first that $l_0 < n$ and $\nu_{l_0+1,l_0} > 0$ so that (IC_{l_0+1,l_0}) is binding. From Proposition 3.1 we know that (IR_{l_0}) is binding and $\Delta\hat{p}_{l_0+1} = \hat{t}_{l_0+1} = 0$. By (9) this means that $\bar{u}_{l_0}^u - \bar{u}_{l_0+1}^u = W_{l_0}(0) = W_{l_0}(\Delta p_{l_0})$ and hence, $\Delta\hat{p}_{l_0} = 0$. If, on the other side, $\nu_{l_0+1,l_0} = 0$ or $l_0 = n$ then $\Delta\hat{p}_{l_0} < \Delta p_{l_0}^*$ follows from (11).

Assume now that $\nu_{21} > 0$ and thus $\Delta\hat{p}_1 > \Delta p_1^*$. We define $k_0 := \max\{k \leq l_0 | \nu_{l+1,l} > 0 \text{ for all } l < k_0\}$. Then either $\nu_{l+1,l} = 0$ for $l = k_0$ or $l_0 = k_0$. In any case it follows from the binding incentive compatibility constraints that $\Delta\hat{p}_1 = \Delta\hat{p}_l$ for any $l \leq k_0$. We have already shown that $\Delta\hat{p}_{l_0} < \Delta p_{l_0}^*$. Assume therefore that $k_0 < l_0$. The FOC with respect to Δp_{k_0} is (left hand side of equation (11) for $l = k_0) = \lambda_{k_0-1,k_0} W'_{k_0-1}(\Delta p_{k_0}) > 0$. Hence, $\Delta\hat{p}_{k_0} < \Delta p_{k_0}^*$. But this contradicts $\Delta p_1^* > \Delta p_{k_0}^*$. Hence, $\nu_{21} = 0$ and $\Delta\hat{p}_1 = \Delta p_1^*$.

It remains to be shown that $\Delta\hat{p}_l \leq \Delta p_l^*$ for $1 < l < l_0$. To see this, first notice that for these types there exists an $\underline{l} > 1$ and $\bar{l} \leq l_0$ such that (i) $\underline{l} \leq l \leq \bar{l}$ and (ii) $\nu_{k+1,k} > 0$ for $\underline{l} \leq k < \bar{l}$. Furthermore, $\nu_{k,k-1} = 0$ for $k = \underline{l}$ and $\nu_{k+1,k} = 0$ or $k = l_0$ for $k = \bar{l}$. By the same arguments as above it follows that $\Delta\hat{p}_{\underline{l}} = \Delta\hat{p}_l = \Delta\hat{p}_{\bar{l}}$ and $0 < \Delta\hat{p}_l = \Delta\hat{p}_{\bar{l}} < \Delta p_{\bar{l}}^* < \Delta p_l^*$. □

This result is easily understood: The least caring type, type 1, is not jeopardized by any other type. So the required emission reduction for this realization corresponds to its first best level. All other types are jeopardized by less caring ones. Distorting their abatement levels downward mitigates the binding incentive problem because the cost (net of private benefits) of implementing a given emission reduction is higher for more caring types; so demanding a lower abatement level from them allows the victim to reduce the associated transfer in a way that makes it less attractive for less caring realizations to misrepresent their private information.

Notice that nothing in the present analysis guarantees that the second best solution is separating. Pooling (different types are induced to choose the same – strictly positive – abatement level) occurs if the solution to (10) obtained by ignoring the monotonicity constraint $\Delta \hat{p}_1 \geq \ldots \geq \Delta \hat{p}_n$ violates monotonicity. Kerschbamer and Maderner (1998) distinguish two basic forces potentially leading to an incompatibility with monotonicity. First, an incompatibility might arise with more than 2 types even in absence of countervailing incentives because with incentive compatibility constraints binding in a single direction only, second best production levels moving in the same direction might try to "overhaul" each other. Kerschbamer and Maderner refer to this as "classical- or overtake-pooling".[13] Specific to settings with countervailing incentives is the second kind of pooling which they call "centripetal- or crash-pooling". Centripetal-pooling arises if incentive compatibility constraints binding towards the centre cause potential violations of monotonicity. Corollary 3.2 implies that if pooling occurs in the present setting with countervailing incentives, it is necessarily of the classical variety. Moreover, by Corollary 3.2 (and Lemma 3.3), the abatement level chosen by all types within the pooling region necessarily falls short of the first best level of the most caring among them.

4. Concluding Remarks

The present paper has studied optimal bribes to reduce upstream transfrontier emissions in the presence of asymmetric information on the polluter's concern for the environment. In a model in which the starting point for the negotiations on emission reduction is a Cournot-Nash equilibrium, we have shown that bribes from the victim generate counter-vailing incentives for the polluter: (i) incentives to understate the concern for the environment in order to suggest a higher status quo utility so that a higher transfer is warranted to induce participation; and (ii) incentives to exaggerate the concern for the environment in order to convince the victim that a relatively high environmental standard has already been implemented so that a high compensating transfer is required for further emission-reductions.

We have shown that in the optimum the incentive to exaggerate the concern for the environment unambiguously dominates the incentive to understate it. Consequently, the solution is determined by trading off distortions in the abatements of more caring types against rents to be left to less caring ones. The least caring type is not jeopardized by any other type. So the required emission-reduction for this realization corresponds with its first best level. All other types are jeopardized by less caring ones. Their abatements are therefore distorted below efficient levels. This mitigates the binding incentive problem because the cost (net of private benefits) of implementing a given emission-reduction is higher for more caring types; so requiring a lower abatement level from them allows the victim to reduce the associated compensation in a way that makes it less attractive for less caring realizations to misrepresent their private information. To reduce the mimicking potential of less caring polluters further, optimal bribes are designed in such a way that acceptance is unattractive for polluters that have a high valuation for the environment.

Our results are in sharp contrast to earlier policy proposals derived for a non-equilibrium starting point. They indicate that under asymmetric information the binding incentive problem is to prevent the polluter from claiming not to care about environment, and that optimal bribes from the victim should be restricted to sufficiently environmentally concerned polluters.

The intuition for the rather startling difference in results is as follows: If the starting point for the negotiations is a Cournot-Nash equilibrium, then more caring types have already implemented a relatively high environmental standard. In this situation, bringing more caring types to reduce their emissions further requires a *higher* compensating transfer than bringing less caring ones because their cost (net of private benefits) of further reductions is higher. This, in turn, seduces less caring types to exaggerate their concern for the environment. By contrast, if the starting point for the negotiations is some non-equilibrium situation, then bringing more caring types to implement a given emission-reduction requires a *lower* compensating transfer than bringing less caring ones. The reason is that the private benefit of implementing this reduction is higher for more caring types while the cost is the same as for less caring ones.

Our work suggests several avenues for future research: The present paper has focused on a very simple downstream pollution problem involving only one up- and one downstream country. Extending the model to two or more up- or/and downstream countries and studying the interactions among them, is a first potentially fruitful research agenda. Also, in the present paper the externality is purely unilateral and bribes are used exclusively to deal with what Botteon and Carraro (1996) have called the "profitability problem", i.e. the problem that moving towards an efficient solution without paying compensation may yield negative net benefits for some countries. Studying optimal bribes to mitigate the free-rider or "stability" problem in a model where the externality is reciprocal, is another promising research agenda. A third potentially fruitful avenue for future research is asymmetric information in an issue linkage model (see Footnote 3 above for references). Finally, considering a setting where the asymmetric information involves two dimensions – costs and benefits of emission reduction – would allow to study the problems of multidimensional screening and incentive design with type dependent reservation utility jointly. This could yield interesting insights from a viewpoint of design.

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Notes

1. Non-uniform mixing refers to the phenomenon that immissions in a given country are dependent not just on the total amount of emissions, but also on the emitting country's spatial location. Extreme examples of non-uniform mixing are down-stream pollution (as, for example, pollution of the river Rhine, where emissions of France and Germany adversely affect the Netherlands but not vice versa) and down-wind pollution (because of prevailing westerly winds, much of the UK's production of acid rain precursors is deposited in Scandinavia; similarly, a considerable part of the US production of these gases is deposited in Canada).
2. Non-uniform damages refers to the fact that different countries suffer differently from pollution. This may be due to physical factors (e.g., acid rain causes more damage on more acidic than on less acidic soils) or to economical factors (as, for example, the fact that the valuation of environmental quality or the structure of economic activity varies across countries).
3. Nonmonetary alternatives to financial transfers have recently been studied in the so-called "issue-linkage literature" (see, e.g., Whalley 1991; Folmer et al. 1993; Barett 1994; Carraro and Siniscalco 1994; Botteon and Carraro 1996).
4. Mäler uses the Harsanyi-Selten extension of the Nash bargaining solution to derive the efficient outcome of the negotiations.
5. As one of the referees has pointed out, the Huber-and-Wirl framework is still applicable if the polluter's environmental concerns change randomly so that past information on emissions is useless.
6. Notice that if $f'(p^i) > 0$ and $f''(p^i) < 0$ for all $p^i > 0$ it cannot be the case that $f'''(p^i) < 0$ for all $p^i > 0$. So a strictly increasing and strictly concave (production) function can violate our regularity condition at most locally, never globally.
7. The same results can be obtained from a more general downstream pollution model where immission in country $i(= d, u)$ is given by $q^i = \sum_{j\in\{d,u,e\}} a^{ij} p^j$ with $a^{ud} = 0$.
8. Here, notice that it is important for our analysis that p^e remains fixed for the contracting period, since otherwise $\bar{q}^u$ would change, too. One of the referees criticizes this modeling detail. We do not regard this assumption as implausible. The variable p^e only needs to be fixed in the very short run, that is for the contracting period. If the contract is made contingent on $\bar{q}^u$ – and our formal set-up allows that interpretation – then it suffices for p^e to remain constant for the time needed by the polluter to choose an offer out of the menue. And even if measured p^e varied, we wouldn't regard this as problematic. In reality, pollution abatement requires irreversible investments and measured pollution is subject to daily and seasonal variations and to measurement failures. In such a situation, the decision-relevant $\bar{q}^u$ (and p^e, respectively) is an average value in any case, and single observations wouldn't influence that value provided they are within a reasonable range.
9. The SOCs are trivially satisfied since $f''(\cdot) < 0$ and $v^{i''}(\cdot) > 0$.
10. To see this, note that $(v^{d''}(p^{d*}+a^u(\bar{q}^u-\Delta p^*))-f''(p^{d*}))\partial p^d/\partial\Delta p = a^u v^{d''}(p^{d*}+a^u(\bar{q}^u-\Delta p^*)) > 0$.
11. To see this define $p^d(\Delta p)$ as country d's emission level satisfying the corresponding FOC: $f'(p^d(\Delta p)) \equiv v^{d'}(p^d(\Delta p) + a^u(\bar{q}^u - \Delta p))$. Its derivative is given by $(\partial p^d(\Delta p))/(\partial\Delta p)(v^{d''}(p^d(\Delta p) + a^u(\bar{q}^u - \Delta p)) - f''(p^d(\Delta p))) = a^u v^{d''}(p^d(\Delta p) + a^u(\bar{q}^u - \Delta p))$ and therefore clearly positive. It follows that the derivative of the above expression equals $a^u f''(p^d(\Delta p))(\partial p^d(\Delta p)/(\partial\Delta p) - v_l^{u''}(\bar{q}^u - \Delta p) + f''(\bar{p}_l^u - \Delta p) < 0$.
12. If a direct mechanism satisfies the incentive-compatibility (IC) and individual-rationality (IR) constraints to be defined below, then it is *de facto* equivalent to an indirect mechanism, in which the victim elicits the polluter's private information by having him choose an offer $(\Delta p_l, t_l)$ that varies with his type, rather than an announcement of his type that implements the same allocation. Also, with direct mechanisms in general the phrases "type k of the polluter pretends

to be of type *l*" and "type *k* of the polluter chooses the offer intended for type *l*" can be used interchangeably.

13. In models with a continuous type space special regularity conditions on the probability distribution over the set of types (referred to as monotone hazard rate conditions) are often imposed to avoid this kind of pooling (cf, for example, Guesnerie and Laffont 1984; Champsauer and Rochet 1989; Lewis and Sappington 1989).

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