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Hierarchical Global Pollution Control in Asymmetric Information Environments: A Continuous-type, Three-tier Agency Framework[1]

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Abstract

We construct a continuous-type, three-tier agency model with hidden information and collusion à la Tirole (1986, 1992), thereby providing a framework that can address the problem of the global pollution control. By extensively utilizing the Monotone Comparative Statics method, the First Order (Mirrlees) approach and a graphical explanation, we characterize the nature of the equilibrium contract that the Supra-National Regulator (SNR) can implement under the possibility of collusion by the government and the firm. We compare the two-tier vs. three-tier regulation structures from the SNR's viewpoint, and then obtain a comparative statics result on the accuracy of monitoring and the possibility of collusion. We further examine whether the SNR has an incentive to adopt the dual supervision structure, with reference to "Regulatory Capture".

Key Words: Global Pollution Control, Mechanism Design, Hidden Information, Collusion, Monotone Comparative Statics
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1. Introduction

While there is a common recognition that mechanisms providing for global environmental protection are necessary, the lack of monitoring capabilities by supra-national regulator (SNR),[2] among others, has prevented the successful design and implementation of global pollution control agreements. The SNR cannot observe the firm's private information and nor can he observe the actual abatement action by the polluting firm. Further, the SNR cannot monitor the activities of the government. That is, there is a procession of insider information among the government and the polluting firm in a country, which may result in the inefficiency in the context of global pollution control. However, the SNR can measure air quality. That is, the SNR can observe and verify the production of clean air as the result of abatement activities of the polluting firm.[3]

What kind of pollution abatement patterns can one implement in asymmetric information environments in which an imperfectly informed supra-national regulator (SNR) contracts with governments and polluting firms? Since the government and the firm receive monetary transfers from the SNR for their roles in pollution abatement, there will be circumstances in which there are natural incentives for the government and the firm to collude.[4]

In such hierarchical international environmental contexts, we try to analyze the effect of key informational asymmetries and collusive behaviors on the design of regulatory mechanisms, and characterize the optimal collusion-proof solutions. In order to do so, we construct a continuous-type, three-tier agency model with hidden information and collusion à la Tirole (1986, 1992), thereby providing a framework that can address the problem of the global pollution control. By extensively utilizing the Monotone Comparative Statics method and a graphical explanation, we characterize the nature of the equilibrium contract that the SNR can implement under the possibility of collusion by the government and the firm.

Our model is on an extension line of the problem for the government to regulate a monopolist under asymmetric information on the cost parameter, which was first analyzed by Baron and Myerson (1982). Laffont and Tirole (1993) exhaustively analyzed the asymmetric information models of regulation, whose framework combines both an adverse selection and a moral hazard

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[2]The supra-national regulator (SNR) could be an organization such as the World Bank (specifically in its role as an administrator of the Global Environmental Facility (GEF)), or the United Nations Commission on Sustainable Development (CSD) established in 1992.

[3]The basic structure is the same in water pollution cases. That is, water quality is measurable and so the SNR can observe and verify the production of clean water.

[4]China is often called an environmental "pollution heaven", where collusion between the government and the polluting firm could misreport the information, thereby preventing optimal (global) allocation of the responsibility for cutting pollution emissions. Also for India, collusion between the government and the firm could misreport the information on the pollution abatement technology, in order to pursue the economic growth. Duflo et al. (2012) obtains evidence on the corruption between the pollutant firms and the third party auditors from a randomized field experiment on the environmental regulation in India.

problem. Our paper tries to consider an international regulation problem on the environmental quality in a three-tier agency framework, consisting of Supra-national regulator (Principal), government (Supervisor) and polluting firm (Agent).[5]

Our paper is most related to Batabyal (1997,2000) and Batabyal and Beladi (2002), which applied the Tirole (1986)'s three-tier agency model to the design of hierarchical environmental agreement between the Supra-National Regulator, Sovereign nation government, and the firm with *two types*.[6] However, the structure of his model is a Kuhn-Tucker problem with many IC (Incentive Compatibility) and IR (Individual Rationality) constraints, and the robust comparative statics are difficult to obtain. This mathematical complexity will be a disadvantage. On the other hand, our methodology is based on both the First Order Approach ala Mirelees (1971) in the mechanism design problem and the monotone comparative statics method ala Topkis (1978) and Edlin and Shannon (1998), and we apply them to our three-tier agency model with *a continuum of types*.[7] It will have an advantage in that we can perform a robust (monotone) comparative statics, and the rationale of the results is clearer and more intuitive. Indeed, the series of Batabyal's work (1997,2000,2002) do not make a comparative statics on the accuracy of monitoring and the efficiency of collusion, unlike our paper, and not have a general comparison result on the two-tier vs. three-tier regulation structures. We further examine whether the SNR has an incentive to include another supervisor into the regulation structure and adopt the *dual* supervision structure.

As another related study, Baron and Besanko (1984) introduced ex-post auditing in the Baron and Myerson (1982) model. It employs a *continuous-type* model and applies a large lump sum penalty in case the agent's cheating gets caught (which is a standard way in the literature in the *two-type* models). But then the analysis becomes problematic since the principal's problem does not behave nicely, as Laffont and Martimort (2002) point out in their text book. Our paper gets away with this problem nicely by assuming that the principal can implement the first-best outcome whenever the supervisor's audit (report) reveals the agent's true type.

This paper is constructed as follows. In section 2, we present our continuous-type, three-tier hierarchical framework of Global Pollution Control, which consists of three risk neutral players; the

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[5]Our framework could be also applied to local pollution problems as in US, EU, China and India, where federal (P), state (S) governments, and polluting firms (A) would be involved in a three-tier hierarchical setting.

[6]Suzuki (2011) closely investigated a three-tier agency model with two types, in the context of corporate governance and auditing, including yardstick mechanism in perfectly correlated environments. Kofman and Lawarree (1993) is the pioneering literature which analyzed collusion between Supervisor (Internal Auditor) and Agent (Manager) in the context of corporate governance and auditing in a three-tier agency (P-S-A) model with another Supervisor (External Auditor).

[7]Our methodology is related to the "Envelope Approach" in auction theory, e.g., the analysis of first price auction by the envelope approach. As for it, e.g., see Milgrom (2004). Suzuki (2012) applies this methodology to the analysis of the continuous-type, three-tier hierarchy (Shareholder, Auditor, and Manager) in "Corporate Governance".

Supra-National Regulator (SNR) as the Principal, the Government (G) as the Supervisor, and the Polluting Firm (F) as the Agent. In section 3, we consider a two-tier regime, where the Principal (SNR) communicates only with the Agent (F), and at the same time explain how the structure of the model allows us to use the Mirrlees First-Order approach and a monotone comparative statics method, which allows for clearer comparative static results. In section 4, we analyze a three-tier regime, where the Principal (SNR) communicates not only with the Agent (F), but also the Government (G) of the nation that the Agent (F) belongs to. After introducing the possibility of collusion between the Government (G) and the Agent (F), we characterize the optimal collusion-proof contracts. In section 5, we examine the payoff comparison between the two (two-tier vs. three-tier) regimes, and then provide some comparative statics in the accuracy of monitoring, the possibility of collusion, and the cost of communicating with the Supervisor (G). In section 6, we analyze whether the Principal (SNR) has an incentive to introduce another Supervisor (S') and adopt the dual supervision structure by two supervisors, and refer briefly to the problem of "regulatory capture". Section 7 concludes the paper.

2. Model

We consider a three-tier hierarchical framework of Global Pollution Control, which consists of three risk neutral players; the Supra-National Regulator (SNR) at the top, the Government (G) at the middle, and the Polluting Firm (F) at the bottom.

The firm chooses a level of pollution abatement, and produces clean air, whose output is denoted by $X \in \mathbb{R}_+$. The firm's cost of producing clean air is $C(X,\theta)$, where $\frac{\partial C(X,\theta)}{\partial X} > 0$, $\frac{\partial^2 C(X,\theta)}{\partial X^2} > 0, \forall X \in \mathbb{R}_+$. **The parameter** θ incorporates the uncertainty about **pollution abatement costs**, which has a continuous type space $\Theta = \left[\underline{\theta}, \overline{\theta}\right]$, with the cumulative distribution function $F(\cdot)$ and a strictly positive density $f(\theta) = F'(\theta)$. We refer to θ as **the pollution abatement efficiency state**, and high (low) θ represents the high (low) abatement efficiency state (corresponding to low (high) abatement costs). That is, $\frac{\partial C(X,\theta)}{\partial \theta} < 0$ .The firm has a differentiable payoff $\Pi = T(X) - C(X,\theta)$ from producing clean air X, where $T(X) \in \mathbb{R}$ is the monetary transfer made by the SNR to the firm for producing the clean air X, and we assume that $T(X)$ is differentiable in X.[8]

The government has a payoff function T_G, where $T_G \in \mathbb{R}_+$ is the monetary transfer to the government. The government receives a signal s from the firm regarding its private information θ and then provides a report r to the SNR indicating what it observes about the firm's pollution abatement efficiency parameter θ. Upon receiving r, the SNR offers the government a transfer $T_G \in \mathbb{R}_+$.

The SNR has a payoff function U_P, which takes the form $U_P = B(X) - T_G - T$. X is the quantity of clean air produced by the firm, and $B(X)$ represents the social benefit of clean air X, where $\frac{\partial B(X)}{\partial X} > 0, \frac{\partial^2 B(X)}{\partial X^2} \leq 0, \forall X \in \mathbb{R}_+$[9] The SNR's payoff is the social benefit of the production of clean air <u>less</u> the sum of government and firm monetary transfers. The SNR designs the main contract which he offers to the government and the firm. The main contract can only be conditioned on what the SNR actually observes, i.e., the government's report r and the firm's output X of clean air.

Information Structure

The firm always observes θ before choosing its abatement level. The government on the other hand may or may not observe the firm's private information θ. For each θ, which occurs with probability $f(\theta)$, the government, with probability p, observes θ and can provide a proof (evidence) of the fact, and with probability $1-p$, observes nothing. That is, the government's signal s may or may not be informative. $s \in \{\theta, \phi\}$. If the government's signal is non-informative $s = \phi$, then the corresponding report is $r = \phi$. If the government's signal is informative $s = \theta$, then the corresponding report is $r \in \{\theta, \phi\}$ Proof of θ cannot be falsified, but the evidence can be hidden.

The SNR is unable to monitor the activities of the government and the firm. The SNR can never acquire the firm's private information and must rely on the government's report r to design the optimal contract.

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8 This differentiability assumption is not always necessary. If we resort to a more generalized envelope theorem by Milgrom and Segal (2002), we can also allow non-differentiable contracts.

9 That is, $B(X)$ includes both linear and concave environmental benefit functions.

Government-Firm Collusion

We model **collusion between the government and the firm** as follows. After signing the main contract, i.e., the contract between the SNR, the government and the firm, the firm and the government can sign **a side contract** which entails **the offer and the acceptance of a side payment from the firm to the government**. This side contract is unobservable by the SNR. The side payment can only be conditioned on what the firm and the government both observe, i.e., the side payment b is a function of the government report r and the firm's output of clean air X. In addition, we assume the following collusion technology: if the firm offers the government a transfer (side payment) b, the government benefits up to kb, where $k \in [0,1]$. That is, only a fraction, $k \in [0,1]$, of the firm's side payment b ends up in the government's hands. The idea is that transfers of this sort may be hard to organize and subject to resource losses (transaction cost). We follow the literature in assuming that side-contracts of this sort are *enforceable* (See, e.g., Tirole 1992). Thus, with the offer and the receipt of the side payment, the firm's total transfer becomes $T(X,r)-b(X,r)$ and the government's total transfer becomes $T_G(X,r)+k \cdot b(X,r)$.

Timing of the Game between the SNR, the Government and the Firm

First, the firm observes the actual realization of θ. Second, the SNR offers a main contract to the government and the firm. After signing the main contract, the government receives the signal s. Then, the firm and the government can sign a side contract which entails the offer and the acceptance of a side payment from the firm to the government. Next, clean air X is produced by the firm and the government sends its report r to the SNR, indicating what it observed. Finally, the SNR compensates the government and the firm by making monetary transfers $T_G(X,r)$ and $T(X,r)$, and side transfers $b(X,r)$ between the government and the firm are also implemented according to the side contract.

3. When $p=0$: The Analysis of Two-tier Hierarchy

We start from analyzing the case of $p=0$, which means that the firm observes θ but the government observes nothing, i.e., $s=\phi$ with probability 1. In this case, since there is no collusion between the government and the firm and the incentive problem is limited to the firm's truth-telling problem, the government plays a completely passive role.[10] Hence, **the three-tiered structure substantially reduces to the two-tiered one.** Thus, we can substantially consider only two players: Supra-national Regulator (SNR) and Firm (F). Remember that θ is the efficiency state of pollution abatement and $C\left(X,\theta\right)$ is the effort cost for the firm of type θ to attain the output of clean air X. $T\left(X\right)$ is the monetary transfer made by the SNR to the firm depending on the level of clean air X, and so his payoff is $T\left(X\right)-C\left(X,\theta\right)$. We normalize the firm's reservation profit as $\overline{\pi}=0$.

3.1 Preliminary: Single Crossing Property (SCP) and Monotonicity of Agent's Choice

Faced with a monetary transfer scheme $T\left(X\right)$, the firm of type θ will choose

$$X \in \arg\max_{X} T\left(X\right)-C\left(X,\theta\right)$$

We identify when solutions to the parameterized maximization program

$\max_{X} \Pi\left(X,\theta\right) := T\left(X\right)-C\left(X,\theta\right)$ are strictly increasing in the parameter θ. A key property to ensure monotone comparative statics is the following:

Definition1 *A function* $\Pi : X\times\theta \rightarrow \mathbb{R}$ *has the* ***Single Crossing Property (SCP)*** *if the derivative* $\Pi_X\left(X,\theta\right)$ *exists and is strictly increasing in* $\theta\in\Theta$.[11]

$\Pi\left(X,\theta\right)=T\left(X\right)-C\left(X,\theta\right)$ has SCP if $\Pi_X\left(X,\theta\right)= T_X\left(X\right)-C_X\left(X,\theta\right)$ exists and is strictly increasing in θ for all X. In our model, it holds when the marginal cost of output $C_X\left(X,\theta\right)$ is decreasing in type θ. SCP implies that large increases in X are less costly for higher parameters θ.

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10 The government's payment will be binding at the reservation level $T_G\left(X\right)=\overline{u}_G(=0), \forall X$.

11 Edlin and Shannon (1998) introduced this SCP under the name of "increasing marginal returns".

Theorem 1 (Edlin and Shannon 1998)

Let $\theta'' > \theta'$, $X' \in \arg\max_X \Pi(X, \theta')$, *and* $X'' \in \arg\max_X \Pi(X, \theta'')$. *Then, if* Π *has SCP, and either* X' *or* X'' *is in the interior, then* $X'' > X'$.

We apply Theorem 1 to the firm's choice when facing a transfer scheme $T(\cdot)$, assuming that the firm's cost $C(X, \theta)$ satisfies SCP. To ensure full separation of types, we need to assume that the scheme $T(\cdot)$ is *differentiable*. Then, $\Pi(X, \theta)$ will satisfy SCP, and Theorem 1 implies that interior output choices are strictly increasing in type θ, i.e., we have *full separation*.

3.2 The Full Information Benchmark

As a benchmark, we consider the case in which the SNR observes the firm's type θ. Given θ, she offers the bundle (X, T) to solve:

$$\max_{(X, T_G, T)} B(X) - T(X) - T_G(X) \text{ s.t. } T(X) - C(X, \theta) \geq \bar{\pi} = 0 \quad \text{(IR of the firm)}$$

$$T_G(X) \geq \bar{u}_G = 0 \quad \text{(IR of the Government)}$$

The government's and the firm's *Individual Rationality* constraints bind at an optimal solution. Then, the SNR eventually solves $\max_X B(X) - C(X, \theta)$, which is exactly the total surplus maximization.

Let $X^{FB}(\theta)$ denote a solution to this maximization problem, called the First Best (FB) solution.

We can interpret this solution as the simplest demonstration of the *Coase Theorem*, which says that bargaining among parties in the absence of "transaction cost" results in socially efficient (First Best) outcomes. That is, the SNR assigns the first best bundle $(X^{FB}(\theta), T^{FB}(\theta) = C(X^{FB}(\theta), \theta))$ to the firm θ in the full information environment. We will soon see that private information indeed constitutes a "transaction cost", and prevents the parties (the SNR and the firm) from achieving the first best efficiency. Now, we assume that the First Best output levels of clean air $X^{FB}(\theta)$ exist and unique for each type θ. Uniqueness of efficient (First Best) output $X^{FB}(\theta)$ is ensured by assuming that total surplus $TS = B(X) - C(X,\theta)$ is strictly concave in X. Indeed, it is satisfied because

$$\frac{\partial^2 TS}{\partial X^2} = \frac{\partial^2 B(X)}{\partial X^2} - \frac{\partial^2 C(X,\theta)}{\partial X^2} < 0.$$

Then, using Theorem 1, we check whether our assumptions ensure that the First Best output $X^{FB}(\theta)$ is strictly increasing in type θ. If $C(X,\theta)$ satisfies SCP, then total surplus $B(X) - C(X,\theta)$ satisfies SCP, and if $X^{FB}(\theta)$ is in the interior for each θ, we see that $X^{FB}(\theta)$ is strictly increasing in θ.

3.3 The Revelation Principle

Now we consider a different contract from the contract $T : X \to \mathbb{R}$ which we have considered so far, where the firm is asked to announce his type $\hat{\theta}$, and receives payment $T(\hat{\theta})$ in exchange for an output $X(\hat{\theta})$ on the basis of his announcement $\hat{\theta}$. This is called a *Direct Revelation Contract*. According to the *Revelation Principle*, any contract $T : X \to \mathbb{R}$ can be replaced with a *Direct Revelation Contract* that has an equilibrium in which all types receive the same bundles as in the original contract $T : X \to \mathbb{R}$.[12]

3.4 Solution of Two-tiered Hierarchy with a Continuum of Types when $p = 0$

We further assume that $C(X,\theta)$ is continuously differentiable in θ for all X, and $C_\theta(X,\theta)$ is bounded uniformly across (X,θ). Then the SNR's problem is:

12 As for the Revelation Principle, one of the most important principles of mechanism design, see. .e.g., Bolton and Dewatripont (2005), Fudenberg and Tirole (1991), and Myerson (1991).

$$\max_{\langle X(\cdot),T(\cdot)\rangle} \int_{\underline{\theta}}^{\overline{\theta}} \left[B\left(X(\theta)\right) - T_G(\theta) - T(\theta) \right] f(\theta)\, d\theta$$

$$\begin{aligned}
s.t. \quad & T(\theta) - C\left(X(\theta),\theta\right) \geq T\left(\hat{\theta}\right) - C\left(X\left(\hat{\theta}\right),\theta\right) && \left(IC_{\theta\hat{\theta}}\right) \quad \forall \theta, \hat{\theta} \in \Theta \\
& T(\theta) - C\left(X(\theta),\theta\right) \geq \overline{\pi} = 0 && \left(IR_\theta \text{ of the firm}\right) \quad \forall \theta \in \Theta \\
& T_G(\theta) = \overline{u}_G = 0 && \left(IR \text{ of the government is binding}\right) \quad \forall \theta \in \Theta
\end{aligned}$$

Just as in the two-type case, only the lowest type's IR binds out of all the participation constraints.

Lemma1 *At a solution* $\left(X(\cdot), T(\cdot)\right)$, *all* IR_θ with $\theta > \underline{\theta}$ *are not binding, and only* $IR_{\underline{\theta}}$ *is binding.*

As for the analysis of ICs with a continuum of types, Mirrlees (1971) introduced a widely used way to reduce the number of incentive constraints by replacing them with the corresponding First-Order Conditions. The "trick" is as follows.

(IC) can be written as $\theta \in \arg\max_{\hat{\theta}\in\Theta} \Pi\left(\hat{\theta},\theta\right)$,where $\Pi\left(\hat{\theta},\theta\right) = T\left(\hat{\theta}\right) - C\left(X\left(\hat{\theta}\right),\theta\right)$ is the profit that the firm of type θ receives by announcing that his type is $\hat{\theta}$. If $\theta \in \left(\underline{\theta},\overline{\theta}\right)$ and $\Pi\left(\hat{\theta},\theta\right)$ is differentiable in $\hat{\theta}$, then the first order condition $\partial\Pi\left(\hat{\theta},\theta\right)\big/\partial\hat{\theta}\Big|_{\hat{\theta}=\theta} = 0$ is necessary for the above optimality. We define the firm's equilibrium profit (the value):

$$\Pi(\theta) \equiv \Pi(\theta,\theta) = T(\theta) - C\left(X(\theta),\theta\right)$$

Note that this profit depends on θ in two ways – through the firm's true type and through his announcement. Differentiating with respect to θ, we have $\Pi'(\theta) = \Pi_{\hat{\theta}}(\theta,\theta) + \Pi_\theta(\theta,\theta)$, where the first derivative of Π is with respect to the firm's announcement (the first argument) and the second derivative is with respect to the firm's true type (the second argument). Since the first derivative equals zero by $\partial\Pi\left(\hat{\theta},\theta\right)\big/\partial\hat{\theta}\Big|_{\hat{\theta}=\theta} = 0$, we have $\Pi'(\theta) = \Pi_\theta(\theta,\theta)$. This condition is nothing but the well known ***Envelope Theorem***: the full derivative of the value of the firm's maximization problem with respect to the parameter – his type – equals to the partial derivative holding the firm's optimal announcement fixed. More concretely,

$$\frac{d\Pi(\theta)}{d\theta} = \underbrace{T'(\theta) - \frac{\partial C\left(X(\theta),\theta\right)}{\partial X(\theta)}\frac{dX(\theta)}{d\theta}}_{\text{Indirect Effect}} - \underbrace{\frac{\partial C\left(X(\theta),\theta\right)}{\partial\theta}}_{\text{Direct Effect}}$$

Since $T'(\hat{\theta}) - \frac{\partial C\left(X\left(\hat{\theta}\right),\theta\right)}{\partial X\left(\hat{\theta}\right)} \cdot \frac{dX\left(\hat{\theta}\right)}{d\hat{\theta}} = 0$ at $\hat{\theta} = \theta$ (the firm's optimal announcement is *Truth Telling*), we have $T'(\theta) - \frac{\partial C\left(X(\theta),\theta\right)}{\partial X(\theta)}\frac{dX(\theta)}{d\theta} = 0$. That is, the indirect effect equals zero.

Thus, we have the ***envelope condition***:

$$\Pi'(\theta) = \frac{d\Pi(\theta,\theta)}{d\theta} = -\frac{\partial C\left(X(\theta),\theta\right)}{\partial\theta}.$$

By integrating it, we have the important formula[13]:

$$\Pi(\theta) = \Pi(\underline{\theta}) - \int_{\underline{\theta}}^{\theta}\frac{\partial C\left(X(\tau),\tau\right)}{\partial\tau}d\tau \qquad \textbf{(ICFOC)}$$

(ICFOC) demonstrates that with a continuum of types, *incentive compatibility constraints* pin down up to a constant plus all types' profits for a given output rule $X(\cdot)$.

Intuitively, (ICFOC) incorporates local incentive constraints, ensuring that the firm does not gain by slightly misrepresenting θ. By itself, it does not ensure that the firm cannot gain by misrepresenting θ by a large amount. For example, (ICFOC) is consistent with the truthful announcement $\hat{\theta} = \theta$ being a local maximum, but not a global one. It is even consistent with truthful announcement being a local minimum.

Fortunately, these situations can be ruled out. For this purpose, recall that by SCP, Topkis (1978) and Edlin and Shannon (1998) establish that the firm's output choices from any tariff (and therefore in any incentive compatible contract) are nondecreasing in type. Thus, any piecewise differentiable IC contract must satisfy that $X(\theta)$ is nondecreasing (M). It turns out that under SCP, ICFOC in conjunction with (M) do ensure that truth-telling is a global maximum, i.e., all ICs are satisfied:

13 Value $\Pi(\theta)$ of type θ, which is interpreted as information rent, and its derivative $\Pi'(\theta)$ play a key role as an incentive scheme for information revelation in our analysis. The methodology is closely related to the "Envelope Approach" in auction theory. As for it, e.g., see Milgrom (2004).

Lemma2 $\left(X(\cdot),T(\cdot)\right)$ *is* ***Incentive Compatible*** *if and only if* ***both (ICFOC) and (M) hold****, where*

$\Pi(\theta)=T(\theta)-C\left(X(\theta),\theta\right)$.

Proof See, Appendix 1

Given (ICFOC), we can express transfers: $\underbrace{T(\theta)}_{\text{Monetary Transfer}} = \underbrace{C\left(X(\theta),\theta\right)}_{\text{Effort Cost}} + \underbrace{\Pi(\theta)}_{\substack{\text{Information Rent}\\ \text{given for type } \theta}}$

3.5 Solving the Relaxed Program

Thus, the SNR's optimization problem can be rewritten as

$$\max_{X(.)}\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)-\Pi(\theta)\right]f(\theta)\,d\theta$$

$$\text{s.t.}\qquad dX(\theta)/d\theta\geq 0\quad (M)\quad \forall\theta$$

where $\int_{\underline{\theta}}^{\overline{\theta}}\Pi(\theta)f(\theta)\,d\theta$ can be called the *expected information rents*.

Lemma3: *Expected Information Rent* is transformed as follows.

$$\int_{\underline{\theta}}^{\overline{\theta}}\Pi(\theta)f(\theta)\,d\theta=\Pi(\underline{\theta})-\int_{\underline{\theta}}^{\overline{\theta}}\frac{\partial C\left(X(\theta),\theta\right)}{\partial\theta}\frac{1-F(\theta)}{f(\theta)}f(\theta)\,d\theta$$

Proof See, Appendix 2

Substituting these expected information rents into the SNR's program, and ignoring the constant $\Pi(\underline{\theta})$, the program becomes

$$\max_{X(.)}\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)+\frac{\partial C\left(X(\theta),\theta\right)}{\partial\theta}\frac{1-F(\theta)}{f(\theta)}\right]f(\theta)\,d\theta$$

$$\text{s.t.}\qquad dX(\theta)/d\theta\geq 0\quad (M)\quad \forall\theta$$

We ignore the Monotonicity Constraint (M) and solve the resulting *relaxed program*.[14] Thus, the SNR maximizes the expected value of the expression within the square brackets, which is called the *virtual surplus*, and denoted by $J(X,\theta)$. This expected value is maximized by simultaneously maximizing virtual surplus for (almost) every type θ, i.e.

$$X^{TW}(\theta) \in \arg\max_{X(\cdot)} B(X(\theta)) - C(X(\theta),\theta) + \left[\frac{1-F(\theta)}{f(\theta)}\right]\frac{\partial C(X(\theta),\theta)}{\partial\theta}$$

This defines the optimal output rule $X^{TW}(\cdot)$ for the relaxed program of the "Two-tier" regime.

The SNR's choice of $X^{TW}(\cdot)$ can be understood as a trade-off between maximizing the total surplus for type θ and reducing the information rents of all types above θ, just as in the two-type case.[15] Indeed, **(ICFOC)** says that output choice X for type θ results in additional information rent $-\partial C(X(\theta),\theta)/\partial\theta$ for all types above θ.

In particular, for the highest type $\overline{\theta}$, there are no higher types, i.e., $F(\overline{\theta})=1$ and the SNR just maximizes total surplus, choosing $X^{TW}(\overline{\theta}) = X^{FB}(\overline{\theta})$. In words, we have *efficiency at the top*. For all other types, the SNR will distort output to reduce information rents. To see the direction of distortion, consider the parameterized maximization program

$$\max_X \Psi(X,\gamma) = B(X(\theta)) - C(X(\theta),\theta) + \gamma\left[\frac{1-F(\theta)}{f(\theta)}\right]\frac{\partial C(X(\theta),\theta)}{\partial\theta}$$

where $\gamma = 0$ corresponds to total surplus maximization (first-best), and $\gamma = 1(p=0)$ corresponds to the SNR's (relaxed) second-best program.

Note that $\dfrac{\partial\Psi(X,\gamma)}{\partial X\partial\gamma} = \left[\dfrac{1-F(\theta)}{f(\theta)}\right]\dfrac{\partial^2 C(X(\theta),\theta)}{\partial X\partial\theta} < 0$ for $\theta < \overline{\theta}$ since the firm's profit $\Pi(X,\theta) = T(X) - C(X,\theta)$ has the single crossing property (SCP), that is,

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14 Since the Monotonicity Constraint (M) is the necessary condition for implementability, we present a sufficiency condition for the condition (M) to be satisfied, in the proposition2.

15 For the standard structure of the two-type models, see Bolton and Dewatripont (2005), and Laffont and Martimort (2002).

$\partial^2\Pi(X,\theta)/\partial X\partial\theta = -\partial^2 C(X,\theta)/\partial X\partial\theta > 0$. Therefore, $\Psi(X,\gamma)$ has SCP in $(X,-\gamma)$, and by Theorem 1 (Edlin and Shannon), we have $X^*(\gamma=1) \Leftrightarrow X^{TW}(\theta) < X^{FB}(\theta) \Leftrightarrow X^*(\gamma=0)$ for all $\theta < \overline{\theta}$. In words, the SNR makes all types other than the highest type underproduce the output in order to reduce the information rents of types above them.

<u>Proposition 1</u> *When $p=0$, the SNR-Government-Firm three-tier hierarchy with a continuum of types (substantially) reduces to a two-tier hierarchy. Then, the optimal contract has the property that*

(1) Efficiency at the top (the highest type $\overline{\theta}$) $X^{TW}(\overline{\theta}) = X^{FB}(\overline{\theta})$

(2) Downward distortion for all other types $\theta \in [\underline{\theta}, \overline{\theta})$*, that is,* $X^{TW}(\theta) < X^{FB}(\theta)$.

Now, remember that we ignored the monotonicity constraint (M) and solved the *relaxed program*. So, we need to check that the solution $X^{TW}(\theta)$ indeed satisfies the monotonicity constraint (M), that is, the output rule $X^{TW}(\theta)$ is nondecreasing. We can check it using Theorem 1(Edlin and Shannon (1998)). To simplify expressions, define $h(\theta) \equiv f(\theta)/[1-F(\theta)] > 0$, which is called the *hazard rate* of type θ. Then, SNR's program can be rewritten as

$$\max_X J(X,\theta) = B(X) - C(X,\theta) + \frac{1}{h(\theta)}\frac{\partial C(X,\theta)}{\partial\theta}$$

By Topkis (1978) and Theorem 1, assuming that $C(X,\theta)$ is sufficiently smooth, a sufficient condition for $X^{TW}(\theta)$ to be nondecreasing in θ is for the following derivative to be strictly increasing in θ:

$$\frac{\partial J(X,\theta)}{\partial X} = \frac{\partial B(X)}{\partial X} - \frac{\partial C(X,\theta)}{\partial X} + \frac{1}{h(\theta)}\frac{\partial^2 C(X,\theta)}{\partial X\partial\theta} \qquad (*)$$

Since $-C(X,\theta)$ satisfies SCP, the second term is strictly increasing in θ, and the first term does not depend on θ. The only problematic term, therefore, is the third term. Our result is ensured when the third term is nondecreasing in θ. Since $1/h(\theta)$ is positive and $\partial^2 C(X,\theta)/\partial X \partial\theta$ is negative, this is ensured when $\partial^2 C(X,\theta)/\partial X \partial\theta$ is nondecreasing. That is, we have

<u>Proposition 2</u> *A sufficiency condition for the optimal solution $X^{TW}(\theta)$ to satisfy the monotonicity constraint (M) is that the following conditions hold.*

1. $\partial^2 C(X,\theta)/\partial X \partial\theta$ *is nondecreasing in* θ.

2. *The hazard rate* $h(\theta)$ *is nondecreasing.*

Example: The first assumption is satisfied e.g., in the following cost function forms:

$$C(X,\theta) = (X-\theta)^{\alpha} \text{ and } C(X,\theta) = (X/\theta)^{\alpha}, \quad \alpha \geq 2$$

The second condition is called the "Monotone Hazard Rate Condition" and satisfied by many familiar probability distributions.

Graphical Explanation

Proposition 1 can be understood by using the Figure 1, which shows that the optimal solution $X^{TW}(\theta)$ is determined such that the marginal benefit 1 equals the marginal *virtual cost* (the marginal cost $\frac{\partial C(X,\theta)}{\partial X}$ plus the marginal information rent $-\frac{1}{h(\theta)}\frac{\partial^2 C(X,\theta)}{\partial X \partial\theta}$). The result of $X^{TW}(\theta) \leq X^{FB}(\theta)$.The condition 1 of Proposition2 means that the marginal information rent $-\frac{\partial^2 C(X,\theta)}{\partial X \partial\theta}$ is decreasing in θ, that is, shifts downwards as θ increases. Since the marginal cost $\frac{\partial C(X,\theta)}{\partial X}$ is also decreasing in θ, the proposition 2 as a whole refers to a sufficient condition for the virtual marginal cost to decrease in θ, that is, for $X^{TW}(\theta)$ to increase in θ.

Figure 1

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4. When $p > 0$: Generalization to Three-tier Hierarchy

4.1 The Collusion-proof Problem

Now, we consider the three-tier hierarchy, where the SNR can have access to the government at a cost Z.[16] In that case, the Government can, for each θ, provide a proof of this fact with probability p, and with $1-p$, is unable to obtain any information. We assume that proofs of θ cannot be falsified. That is, θ is hard information.[17] On the other hand, the firm can potentially benefit from a failure by the government to truthfully report that his type is θ when the government observed the signal θ. The government may collude with the firm if he benefits from such behavior. Remember the following collusion technology: if the firm offers the government a transfer (side payment) t, he benefits up to kt, where $k \in [0,1]$. That is, only a fraction, $k \in [0,1]$, of the firm's side payment ends up in the government's hands. The idea is that transfers of this sort may be subject to transaction costs. We assume that side-contracts of this sort are *enforceable* (See, e.g., Tirole 1992).

Now, the government can choose a report $r \in \{\phi, \theta\}$, where ϕ means that he did not obtain any information. If the SNR receives the report from the government that the type information is θ, the SNR will have an incentive to modify the original contract. The SNR can raise her payoff by *eliminating the downward distortions in all other types* than the highest one $\overline{\theta}$. Namely, instead of $\{X(\theta), T(\theta)\}$, she will offer the efficient (first best) contract $\{X^{FB}(\theta), T^{FB}(\theta)\}$, and the information rent $\Pi(\theta)$ will be exploited by the SNR. In summary, the SNR commits herself to the reward scheme for the government, but does not commit to the one for the firm. Thus, she is tempted to modify the initial contract (or the outcome $\{X(\theta), T(\theta)\}$) unilaterally, using the information

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16 Z is the cost for the SNR to communicate with the Supervisor (Government), which includes a cost for verification of the Supervisor (Government)'s report with proof (evidence).

17 We assume that the firm correctly knows whether the government is informed of his type information θ or not. This is the same assumption as the early literature, e.g., Tirole (1986).

revealed by the government.[18]

If the firm of type θ anticipates this modification, since the firm can benefit from a failure by the government to report his type θ truthfully, it will offer the government the transfer (side payment) $t = \Pi(\theta)$,the amount equivalent to his information rent, of which the government benefits up to kt, where $k \in [0,1]$. Thus, the SNR must pay $T_G(\theta) = k\Pi(\theta)$ to the government in opposition to the collusive offer by the firm, in order to elicit true information.[19]

In other words, in order to avoid collusion between the government and the firm, the SNR will have to offer the government a reward $T_G(\theta)$ for providing θ, such that the *coalition incentive compatibility constraint* $T_G(\theta) \geq k\Pi(\theta)$ is satisfied, from which the optimal transfer $T_G(\theta) = k\Pi(\theta)$ is derived.

In summary, the SNR can strictly improve his payoff ex-post by changing $X(\theta)$ into $X^{FB}(\theta)$, but must bear the ex-ante incentive cost $k\Pi(\theta)$. This is the trade-off for the SNR when the government obtains the proof of true information, with probability p.

Only when the government cannot obtain any information for θ with probability $1-p$, does the SNR commit herself to the initial scheme $\{X(\theta), T(\theta)\}\ \forall\theta$, and the same trade-off between the total surplus and the information rent emerges, just like in the two-tiered hierarchy.

Substituting $X(\theta) = X^{FB}(\theta)$, $T_G(\theta) = k\Pi(\theta)$ and $T(\theta) = C(X^{FB}(\theta), \theta)$ with probability p, and $X(\theta) = X(\theta)$, $T_G(\theta) = \bar{u}_G = 0$ and $T(\theta) = C(X(\theta), \theta) + \Pi(\theta)$ with probability $1-p$, into the Principal's objective function $B(X(\theta)) - T_G(\theta) - T(\theta)$, the expected total surplus minus the information rent for type θ in this regime is written as

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[18]This idea is analogous to the ratchet effect and the renegotiation problem caused by lack of a principal's commitment in the dynamics of incentive contracts. See, Laffont-Tirole (1988) and Dewatripont (1988).

[19] We see that the increase in k increases the information rent the SNR must pay to the Government.

$$(1-p)\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)\right]+\underbrace{p}_{\theta \text{ is revealed}}\times\left[\underbrace{B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)}_{\text{(Ex post) First Best Allocative Efficiency}}\right]-\left[(1-p)+pk\right]\Pi(\theta)$$

Hence, the SNR's optimization problem is as follows.

$$\max_{X(.),\Pi(.)}\int_{\underline{\theta}}^{\overline{\theta}}\left[\begin{array}{r}(1-p)\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)\right]+p\left[B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)\right]\\ -\left[(1-p)+pk\right]\Pi(\theta)\end{array}\right]f(\theta)d\theta-Z$$

s.t. $\quad dX(\theta)/d\theta\geq 0$: $X(\theta)$ is nondecreasing (M)

$$\Pi(\theta)=\Pi(\underline{\theta})-\int_{\underline{\theta}}^{\theta}\frac{\partial C\left(X(\tau),\tau\right)}{\partial\tau}d\tau \qquad \text{(ICFOC)}$$

$$\Pi(\underline{\theta})=\Pi(\underline{\theta})-C\left(X(\underline{\theta}),\underline{\theta}\right)\geq\overline{\pi} \quad \text{(Const.)} \quad (\text{IR}_{\underline{\theta}})$$

Eventually, in this regime, the SNR maximizes the *virtual surplus* $J(X,\theta)$,

$$\max_{X} J(X,\theta)=(1-p)\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)\right]+\frac{\left[(1-p)+pk\right]}{h(\theta)}\frac{\partial C(X,\theta)}{\partial\theta}$$

The first order condition for the optimum is,

$$\frac{\partial J(X,\theta)}{\partial X}=(1-p)\left[\frac{\partial B(X)}{\partial X}-\frac{\partial C(X,\theta)}{\partial X}\right]+\frac{\left[(1-p)+pk\right]}{h(\theta)}\frac{\partial^2 C(X,\theta)}{\partial X\partial\theta}=0$$

$$\Leftrightarrow\underbrace{\frac{\partial B(X)}{\partial X}-\frac{\partial C(X,\theta)}{\partial X}}_{\text{Marginal Total Surplus}}+\underbrace{\frac{\left[1+\frac{p}{1-p}k\right]}{h(\theta)}\frac{\partial^2 C(X,\theta)}{\partial X\partial\theta}}_{\text{Marginal Information Rent}}=0 \qquad (**)$$

Noting that the marginal information rent for each $\theta\in\left[\underline{\theta},\overline{\theta}\right)$ effectively becomes larger than the former regime, we have the following proposition on the comparison of equilibrium incentives.

Proposition 3 *Supposing that* $X^{NC}(\theta)$ *is the solution (in the no-information phase* $\varnothing$*) of this 'No-Commitment' (Three-tier)regime, we obtain:*

$$X^{NC}(\theta)\leq X^{TW}(\theta)\leq X^{FB}(\theta) \quad \textit{for all}\ \theta\in\left[\underline{\theta},\overline{\theta}\right]$$

In words, the optimal collusion-proof solution in the Three-tier regulatory structure is as follows. When the *SNR* learns the true state of the world θ through the Government's report $r=\theta$, it will implement the first best solution $X^{FB}(\theta)$. When the *SNR* does not learn the true state of the world θ from the Government, but induces the firm to reveal the information θ, it implements a somewhat stricter policy than was optimal in the Two-tier structure, i.e. $X^{NC}(\theta)\leq X^{TW}(\theta)$.

Graphical Explanation

$X^{NC}(\theta)\leq X^{TW}(\theta)$ in Proposition **3** comes from the effective increase in the virtual cost, i.e., the information rent in the Three-tier regime. Virtual marginal cost increases by $pk/(1-p)$, compared with the standard no-government case. The below figure 2 clearly shows this point.

Figure 2

Now, we can perform a comparative statics on the optimal solution $X^{NC}(\theta)$.

<u>Proposition 4</u> Comparative statics on $X^{NC}(\theta)$

The optimal output $X^{NC}(\theta)$ in this 'No-Commitment' (Three-tier) regime is nonincreasing in the parameter p, and nonincreasing in the parameter k.

Proof:

The coefficient of the marginal information rent $1+(pk)/(1-p)$ increases as the parameter p increases. Hence, the marginal information rent (and so the marginal virtual cost) $-\frac{\left[1+(pk)/(1-p)\right]}{h(\theta)}\frac{\partial^2 C(X,\theta)}{\partial X\partial\theta}$ increases as p increases. This brings about the decrease in the optimal output $X^{NC}(\theta)\downarrow$. Similarly, the coefficient of the marginal information rent

$1+(pk)/(1-p)$ increases as the parameter k increases. Hence, the marginal information rent (and so the marginal virtual cost) increases as k increases. This brings about the decrease in the optimal output $X^{NC}(\theta)\downarrow$. ■

5. Payoff Comparison between Two Regimes

We compare the payoffs between two regimes, that is, 'No-Commitment' (three-tier) regime (NC) and 'No-Supervisor' (two-tier) regime (NS).

The expected payoff for the SNR in the 'No-Commitment' (three-tier) regime (NC) is

$$(1-p)\int_{\underline{\theta}}^{\bar{\theta}}\left[B\left(X^{NC}(\theta)\right)-C\left(X^{NC}(\theta),\theta\right)\right]f(\theta)d\theta+p\times\int_{\underline{\theta}}^{\bar{\theta}}\left[B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)\right]f(\theta)d\theta$$
$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\bar{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^{NC}(\theta),\theta\right)}{\partial\theta}f(\theta)d\theta-Z$$

The expected payoff for the SNR in the No-Supervisor (two-tier) regime (NS), which is the standard second best regime and corresponds to $p=0$ in the SNR-Government-Firm regime, is

$$\int_{\underline{\theta}}^{\bar{\theta}}\left[B\left(X^{TW}(\theta)\right)-C\left(X^{TW}(\theta),\theta\right)+\frac{1}{h(\theta)}\frac{\partial C\left(X^{TW}(\theta),\theta\right)}{\partial\theta}\right]f(\theta)d\theta$$

We first consider the comparison when $Z=0$ (The cost for the SNR to communicate with the Supervisor (Government) is zero). Then, we have the following proposition.

<u>Proposition 5</u>

Suppose Z=0. The SNR prefers the 'Three-tier' regime with government supervision (NC) to the 'Two-tier' regime with no government supervision (NS) in terms of her expected payoff. That is,

$$(1-p)\int_{\underline{\theta}}^{\bar{\theta}}\left[B\left(X^{NC}(\theta)\right)-C\left(X^{NC}(\theta),\theta\right)\right]f(\theta)d\theta+p\int_{\underline{\theta}}^{\bar{\theta}}\left[B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)\right]f(\theta)d\theta$$
$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\bar{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^{NC}(\theta),\theta\right)}{\partial\theta}f(\theta)d\theta$$
$$\geq\int_{\underline{\theta}}^{\bar{\theta}}\left[B\left(X^{TW}(\theta)\right)-C\left(X^{TW}(\theta),\theta\right)+\frac{1}{h(\theta)}\frac{\partial C\left(X^{TW}(\theta),\theta\right)}{\partial\theta}\right]f(\theta)d\theta$$

Proof See, Appendix 3

Rationale

First, the SNR compares the 'No Commitment' three-tier regime (NC) with the Commitment regime (S) where the SNR commits herself to the output rule $X^{S}(\theta)$. In the 'No Commitment' three-tier regime (NC), the SNR designs a "more state-contingent" contract for more efficient use of government's report $r \in \{\theta, \phi\}$, that is, she sets $X^{FB}(\theta)$ for the states $\{\theta, s=\theta\}$ where the agent type is θ and the government's signal is $s=\theta$, and sets $X^{NC}(\theta)$ for the states $\{\theta, s=\phi\}$ where the agent type is θ and the government's signal is $s=\phi$. On the other hand, in the Commitment regime $X^{S}(\theta)$, the SNR does not use the government's report $r \in \{\theta, \phi\}$ in a state-dependent way, but unanimously imposes the pooling output $X^{S}(\theta)$ for both states $\{\theta, s=\theta\}$ and $\{\theta, s=\phi\}$, which would not be efficient.

If we use the terminology in Weitzman's paper (1974) "Prices vs. Quantities", the "Commitment" regime (S) is the regime where the SNR adjusts only the price rule $T(\theta)$ under the commitment to the output (quantity) rule $X^{S}(\theta)$, in the form that she does not pay the information rent $\Pi(\theta)$ to the polluting firm of type θ when the government's report is $r=\theta$.[20] On the other hand, "No Commitment" regime (NC) is the regime where the SNR can<u>not</u> commit herself <u>not</u> to adjust the output (quantity) rule $X(\theta)$ as well as the price rule $T(\theta)$, that is, the SNR optimally adjusts both of them contingent on the government's report $r \in \{\theta, \phi\}$. As shown in Section 4, when the true type information θ is revealed from the supervisor (Government) with probability p, the principal (SNR) implements the first-best outcome $\{X^{FB}(\theta), T^{FB}(\theta)\}$ based on its hard evidence. Otherwise, the downward distorted outcome $\{X^{NC}(\theta), T^{NC}(\theta)\}$ is implemented. These

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20 As for the detailed analysis of this "Commitment" regime, see Suzuki (2008). In contrast, in this paper, it is just a <u>hypothetical</u> regime used for the proof on the payoff comparison between two regimes (Three-tier vs. Two-tier regimes).

arrangements are optimally created as the collusion-proof contract by the principal (SNR).

Next, when the SNR compares the Commitment regime $X^{S}(\theta)$ with the 'No Supervisor' two-tier regimes $X^{TW}(\theta)$, the virtual surplus for type θ is more increased in the former regime through the effective reduction of information rent due to $(1-p)+pk \le 1$, that is,

$$B(X(\theta))-C(X(\theta),\theta)+\underbrace{[(1-p)+pk]}_{\le 1}\underbrace{\frac{\partial C(X(\theta),\theta)}{\partial \theta}}_{-}\frac{1}{h(\theta)}$$

$$\ge B(X(\theta))-C(X(\theta),\theta)+\underbrace{\frac{\partial C(X(\theta),\theta)}{\partial \theta}}_{-}\frac{1}{h(\theta)}$$

Combining these two comparison results, we find that the SNR always prefers the "No Commitment" three-tier regime (NC) to the "No Supervisor" two-tier regime (NS) when $Z=0$.

The Choice of Regulatory Structure

Now define $Z^{*}(p,k)$ be the payoff difference between the 'Three-tier' regime (NC) and the 'Two-tier' regime (NS) when $Z=0$. That is,

$$\begin{aligned} Z^{*}(p,k) := \Big\{ &(1-p)\int_{\underline{\theta}}^{\overline{\theta}}\left[B(X^{NC}(\theta))-C(X^{NC}(\theta),\theta)\right]f(\theta)\,d\theta \\ &+p\int_{\underline{\theta}}^{\overline{\theta}}\left[B(X^{FB}(\theta))-C(X^{FB}(\theta),\theta)\right]f(\theta)\,d\theta+[(1-p)+pk]\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C(X^{NC}(\theta),\theta)}{\partial \theta}f(\theta)\,d\theta\Big\} \\ &-\int_{\underline{\theta}}^{\overline{\theta}}\left[B(X^{TW}(\theta))-C(X^{TW}(\theta),\theta)+\frac{\partial C(X^{TW}(\theta),\theta)}{\partial \theta}\frac{1}{h(\theta)}\right]f(\theta)\,d\theta \end{aligned}$$

$Z^{*}(p,k)$ is the relative importance of the three-tier structure with government supervision, and could be rephrased as the "comparative (relative) advantage" a la Weitzman (1974).

Then, we have the following corollary for $Z>0$.

Corollary

The optimal regulation structure R^{*} *is determined based on the following rule:*

$$R^*\left(p,k,Z\right)=\begin{cases} NC: \text{Three-tier structure} & if\ \ Z\leq Z^*\left(p,k\right) \\ NS: \text{Two-tier structure} & if\ \ Z>Z^*\left(p,k\right) \end{cases}$$

That is to say, the SNR's optimal strategy is to choose the three-tier structure with government supervision (NC) if $Z\leq Z^*\left(p,k\right)$, and to choose the two-tier structure with no supervision (NS) if $Z>Z^*\left(p,k\right)$, for $0\leq p,k\leq 1$.

From the simple comparative statics, we have

$$\frac{\partial Z^*\left(p,k\right)}{\partial p}=\int_{\underline{\theta}}^{\bar{\theta}}\underbrace{\left\{\left[B\left(X^{FB}\left(\theta\right)\right)-C\left(X^{FB}\left(\theta\right),\theta\right)\right]-\left[B\left(X^{NC}\left(\theta\right)\right)-C\left(X^{NC}\left(\theta\right),\theta\right)\right]\right\}}_{\geq 0}f\left(\theta\right)d\theta$$

$$+\underbrace{\left(k-1\right)}_{\leq 0}\int_{\underline{\theta}}^{\bar{\theta}}\frac{1}{h\left(\theta\right)}\underbrace{\frac{\partial C\left(X^{NC}\left(\theta\right),\theta\right)}{\partial\theta}}_{<0}f\left(\theta\right)d\theta\geq 0$$

$$\frac{\partial Z^*\left(p,k\right)}{\partial k}=p\int_{\underline{\theta}}^{\bar{\theta}}\frac{1}{h\left(\theta\right)}\frac{\partial C\left(X^{NC}\left(\theta\right),\theta\right)}{\partial\theta}f\left(\theta\right)d\theta\leq 0\qquad\forall\left(p,k\right)\in\left[0,1\right]^2$$

As p (the accuracy of supervision/monitoring) increases, the relative importance $Z^*\left(p,k\right)$ of the three-tier structure with government supervision increases. On the other hand, as k (the efficiency of collusion, the easiness of collusion) increases, it decreases, since the increase in k increases the expected information rent the SNR needs to pay to the government (S)[21].

6. The Possibility of Improvement by Adding Another Supervisor

We introduce another supervisor (second supervisor), who is honest (not strategic), but only with a smaller probability $p'\left(\leq p\right)$ can observe the signal θ. We assume for simplicity that the states which he can observe are included in the ones which the government (main supervisor) can observe, and that it is a common knowledge. In this setting, when the government (main supervisor) tries to

[21] Conversely, as k decreases, the "comparative (relative) advantage" of the three-tier structure increases. The size of k will be related to the quality of the government (See, Shleifer et al (2012)) The lower (higher) k implies the possibility of less (more) collusion between the government and the pollutant firm, and so the higher (lower) quality government. Our result would be consistent with it.

tell a lie (hides information θ) collusively, the second supervisor observes the signal θ with probability $p'(\leq p)$, and reports it to the SNR *at no incentive cost*, since he is honest (not strategic). Then, the government (main supervisor) cannot obtain any positive information rent. Thus, the expected gain for the government (main supervisor) when he observes the signal θ will be reduced to $(p-p')k\Pi(\theta)$. Bringing in an additional supervisor can help, even if it costs Z', provided he is honest. The second supervisor can work as a checking device for collusion and reduce the information rent of the government (main supervisor). Due to the reduction of the expected information rent, the marginal incentive of the polluting firm will also be increased in equilibrium.

Let us formally check this argument. The SNR maximizes the virtual surplus $J(X,\theta)$,

$$\max_X J(X,\theta)=(1-p)\big[B\big(X(\theta)\big)-C\big(X(\theta),\theta\big)\big]+\frac{\big[(1-p)+(p-p')k\big]}{h(\theta)}\frac{\partial C(X,\theta)}{\partial\theta}$$

The first order condition for the optimum is,

$$\frac{\partial J(X,\theta)}{\partial X}=\frac{\partial B(X)}{\partial X}-\frac{\partial C(X,\theta)}{\partial X}+\frac{\left[1+\dfrac{p-p'}{1-p}k\right]}{h(\theta)}\frac{\partial^2 C(X,\theta)}{\partial X\partial\theta}=0$$

Since $p'\in[0,p]$, we have the proposition on the comparison of the equilibrium incentives.

<u>Proposition 6</u>

Supposing that $X^{S'}(\theta)$ *is the solution of this regime, we have:*

$$X^{NC}(\theta)\leq X^{S'}(\theta)\leq X^{TW}(\theta)\leq X^{FB}(\theta)\quad \textit{for all}\ \theta\in\big[\underline{\theta},\overline{\theta}\big]$$

That is, another supervisor can serve as an incentive mechanism not only for the government (main supervisor) but also for the polluting firm. Introduction of another supervisor brings about two positive effects, which consist of the benefits due to both the increase in the marginal incentive $X^{S'}(\theta)\geq X^{NC}(\theta)$ and the expected reduction in the information rent $p'k\Pi(\theta)$. This means the marginal improvement in efficiency ("marginal contribution") due to adding the second supervisor S' into the original principal-supervisor-agent hierarchy. The below figure 3 clearly shows the point. When it is greater than the resource cost Z' of introducing the sub-supervisor, the SNR has indeed an incentive to introduce him into the regulation structure and adopt the *dual* supervision structure.[22]

Figure 3

6.1 Remark on "Regulatory Capture"

We could interpret the analysis of this section such that the "regulatory capture" by the polluting firm, that is, the collusion between the polluting firm and the government (a corruptive, lenient supervisor) could be broken or weakened by the introduction of another honest (tough) supervisor S'. Laffont and Tirole (1991) analyze the "regulatory capture" and its deterrence through the collusion-proof mechanism in a three-tier agency framework which consists of Congress-Regulatory Agency- Interest Groups with *two* types. Tai (2012) discusses a political economy model of the regulatory process where media scrutiny can combat regulatory capture (an interest group aims for capturing a regulator) through media reports. In his framework, media scrutiny and reports can play a similar incentive role to our additional supervisor. Agarwal et al (2012) empirically investigate whether inconsistent regulation between (softer, more lenient) state regulators and (tougher) federal regulators in the US banking industry leads to the "regulatory capture" where state supervisors may be captured by the constituents (commercial banks) they oversee. But they do not analyze the effectiveness of dual structure of supervision from a theoretical viewpoint.

7. Conclusion

Recently, mechanisms for global environmental protection have rapidly been increasing in importance all over the world. Given this trend, we were motivated to build a theoretical model to examine what kind of pollution abatement patterns one can implement in simple economic environments in which an imperfectly informed supra-national regulator (SNR) contracts with governments and polluting firms. We introduced the outcomes of "Monotone Comparative Statics" à la Topkis (1978), Edlin and Shannon (1998), and Milgrom and Segal (2002) into a familiar screening

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22 If we allow some possibility of collusion with the second supervisor $k' \in (0, k)$, the government (main supervisor) will try to collude with the second supervisor, where the government (S)'s maximum willingness to collude is his information rent $k\Pi(\theta)$, and so the SNR must pay an additional information rent $k'k\Pi(\theta)$ to the second supervisor with probability p', in order to induce truth reporting from him. Hence, the additional expected information rent $p'k'k\Pi(\theta)$ would be required for the SNR. In the current model, we assumed $k' = 0$, which has the maximum incentive effect, for simplification.

(self selection) model with a continuum of types, and constructed a three-tier agency model with a mathematically tractable structure, whose solution has the property that (1) *Efficiency at the top* (the highest type) and (2) *Downward distortion* for all other types. We interpreted the results in the context of clean air production, potentially an important topic in environmental economics.

We then showed what happens when the SNR cannot fully commit to the regulation mechanism and the renegotiation is unavoidable. When the SNR commits herself to the reward scheme for the government, but does not commit to the one for the polluting firm, the SNR is tempted to modify the initial contract (or the outcome) unilaterally, using the information revealed by the government. The idea is similar to the ratchet problem and the renegotiation problem caused by lack of the SNR's commitment in the dynamics of incentive contracts, studied early by Laffont-Tirole (1988), and Dewatripont (1988) etc. If the polluting firm anticipates such a modification, since the polluting firm can benefit from a failure by the government to report his type truthfully, he will offer the government the transfer (side payment) equivalent to his information rent. Thus, the SNR must pay the government in opposition to the collusive offer by the polluting firm. Thus, the SNR can strictly improve his payoff ex-post, but must bear the ex-ante incentive cost. We characterized the optimal solutions of this regime, and gave a graphical explanation.

The optimal collusion-proof regulatory contract in the SNR-Government-Firm three-tier hierarchy structure has the property whereby (1) *Efficiency at the top* (the highest type) and (2) *Downward distortion* for all other types, and the downward distortion is *deteriorated* at the optimum, in comparison with the Principal-Agent two-tier hierarchy.[23] In this point, our model could be interpreted as *a continuous type formulation* of Tirole (1986, 1992) model. The optimal solution allows a robust (monotone) comparative statics, which shows that downward distortions from the first best increase when the accuracy of monitoring increases and the efficiency of collusion increases. This will be a specific contribution to the literature.

In summary, the overall contribution of our paper is to have applied the monotone comparative statics method to the continuous-type, three-tier agency model with hidden information and collusion à la Tirole (1986, 1992), thereby providing a framework that can address the problem of the global pollution control. By extensively utilizing the Monotone Comparative Statics method, the First Order (Mirrlees) approach and a graphical explanation, we characterized the nature of the equilibrium contract that can be implemented under the possibility of collusion by the government

[23] In the former version (Suzuki (2013)), we also analyzed the effect of contractual procedure, i.e., *ex ante* versus *ex post* contracting on the nature of optimal output (clean air) patterns, and showed that in *ex ante* contracting regimes, where contracting occurs *before* the resolution of the uncertainty regarding the type information θ, and so all parties share *imperfect but symmetric* information about θ, the first best solutions are implementable in equilibrium, in contrast with *ex post* contracting regimes (in this paper).

and the firm. In addition, we obtained a general comparison result on the two-tier vs. three-tier international environmental regulation structures, and rationalized it from the view point of cost vs. benefit of monitoring (supervision).

APPENDICES

Appendix1 Proof of Lemma2

Proof: The "$\Rightarrow$" part was established above. It remains to show that **(ICFOC)** and monotonicity **(M)** imply that $\Pi\left(\hat{\theta},\theta\right)\le\Pi\left(\theta\right)$ for all $\hat{\theta},\theta$. For $\hat{\theta}>\theta$, we can write

$$\Pi\left(\hat{\theta},\theta\right)-\Pi\left(\theta\right)=T\left(\hat{\theta}\right)-C\left(X\left(\hat{\theta}\right),\theta\right)-\Pi\left(\theta\right)$$

$$=\Pi\left(\hat{\theta}\right)+C\left(X\left(\hat{\theta}\right),\hat{\theta}\right)-C\left(X\left(\hat{\theta}\right),\theta\right)-\Pi\left(\theta\right)$$

$$=\left[C\left(X\left(\hat{\theta}\right),\hat{\theta}\right)-C\left(X\left(\hat{\theta}\right),\theta\right)\right]+\left[\Pi\left(\hat{\theta}\right)-\Pi\left(\theta\right)\right]$$

$$=\int_{\theta}^{\hat{\theta}}\frac{\partial C\left(X\left(\hat{\theta}\right),\tau\right)}{\partial\tau}d\tau+\int_{\theta}^{\hat{\theta}}\left[-\frac{\partial C\left(X\left(\tau\right),\tau\right)}{\partial\tau}\right]d\tau \qquad (*)$$

$$=\int_{\theta}^{\hat{\theta}}\left[\frac{\partial C\left(X\left(\hat{\theta}\right),\tau\right)}{\partial\tau}-\frac{\partial C\left(X\left(\tau\right),\tau\right)}{\partial\tau}\right]d\tau\le 0 \qquad (**)$$

In $(*)$, we used the following fact by **(ICFOC)** and Envelope theorem

$$\Pi\left(\hat{\theta}\right)-\Pi\left(\theta\right)=\int_{\theta}^{\hat{\theta}}\frac{d\Pi}{d\tau}\left(\tau\right)d\tau=\int_{\theta}^{\hat{\theta}}-\frac{\partial C\left(X\left(\tau\right),\tau\right)}{\partial\tau}d\tau$$

In $(**)$, the last inequality is obtained by **SCP** and the fact that $X\left(\hat{\theta}\right)\ge X\left(\theta\right)$ by **(M)**. As explained just below the Definition 1, **SCP** implies that the marginal cost of output $\frac{\partial C\left(X,\theta\right)}{\partial X}$ is decreasing in type θ in our model. That is $\frac{\partial^2 C\left(X,\theta\right)}{\partial X\partial\theta}<0$. This condition implies that $\frac{\partial C\left(X\left(\hat{\theta}\right),\theta\right)}{\partial\theta}-\frac{\partial C\left(X\left(\theta\right),\theta\right)}{\partial\theta}\le 0$ for $X\left(\hat{\theta}\right)\ge X\left(\theta\right)$ due to **(M).** So, we obtain the last inequality. The proof for $\theta > \hat{\theta}$ is similar. **Q.E.D**

<u>Appendix2</u> Proof of Lemma3

Proof: We transform the *expected information rents* by exploiting "Integration by Parts".

Now, remember that

$$\int_{\underline{\theta}}^{\overline{\theta}} \left[\Pi(\underline{\theta}) - \int_{\underline{\theta}}^{\theta} \frac{\partial C(X(\tau),\tau)}{\partial \tau} d\tau \right] f(\theta) d\theta = \int_{\underline{\theta}}^{\overline{\theta}} \Pi(\theta) f(\theta) d\theta$$

Because $\left[\Pi(\theta)F(\theta)\right]' = \Pi(\theta) f(\theta) + \underbrace{\frac{d\Pi(\theta)}{d\theta}} F(\theta) = \Pi(\theta) f(\theta) - \underbrace{\frac{\partial C(X(\theta),\theta)}{\partial \theta}}_{\text{(Due to Envelope Theorem)}} F(\theta),$

and so $\Pi(\theta) f(\theta) = \left[\Pi(\theta)F(\theta)\right]' + \frac{\partial C(X(\theta),\theta)}{\partial \theta} F(\theta)$, we have

$$\int_{\underline{\theta}}^{\overline{\theta}} \Pi(\theta) f(\theta) d\theta = \left[\Pi(\theta)F(\theta)\right]_{\underline{\theta}}^{\overline{\theta}} + \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} F(\theta) d\theta$$

$$= \Pi(\overline{\theta}) + \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} F(\theta) d\theta = \Pi(\underline{\theta}) - \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} d\theta + \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} F(\theta) d\theta$$

$$\left(\because \Pi(\overline{\theta}) = \Pi(\underline{\theta}) - \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} d\theta \right)$$

$$= \Pi(\underline{\theta}) - \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} \left(1 - F(\theta)\right) d\theta = \Pi(\underline{\theta}) - \int_{\underline{\theta}}^{\overline{\theta}} \frac{\partial C(X(\theta),\theta)}{\partial \theta} \frac{1 - F(\theta)}{f(\theta)} f(\theta) d\theta$$

Q.E.D

<u>Appendix3</u> Proof of Proposition 5

First, by definition, $X^{NC}(\theta)$ is the optimal decision over the problem

$$\max_{X(.)} (1-p) \int_{\underline{\theta}}^{\overline{\theta}} \left[B(X(\theta)) - C(X(\theta),\theta) \right] f(\theta) d\theta + \left[(1-p) + pk \right] \int_{\underline{\theta}}^{\overline{\theta}} \frac{1}{h(\theta)} \frac{\partial C(X(\theta),\theta)}{\partial \theta} f(\theta) d\theta$$

Similarly, by definition, $X^{TW}(\theta)$ is the optimal decision over the problem

$$\max_{X(.)}\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)+\frac{\partial C\left(X(\theta),\theta\right)}{\partial\theta}\frac{1}{h(\theta)}\right]f(\theta)d\theta$$

We also set the following payoff function

$$\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X(\theta)\right)-C\left(X(\theta),\theta\right)+\underbrace{\left[(1-p)+pk\right]}_{\leq 1}\frac{1}{h(\theta)}\frac{\partial C\left(X(\theta),\theta\right)}{\partial\theta}\right]f(\theta)d\theta$$

and let $X^S(\theta)$ be the optimal decision over this "Commitment" regime. So, the equilibrium payoff of the problem is,

$$\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^S(\theta)\right)-C\left(X^S(\theta),\theta\right)+\left[(1-p)+pk\right]\frac{1}{h(\theta)}\frac{\partial C\left(X^S(\theta),\theta\right)}{\partial\theta}\right]f(\theta)d\theta$$

From the *revealed preference* argument, the following two inequalities hold.

$$(1-p)\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{NC}(\theta)\right)-C\left(X^{NC}(\theta),\theta\right)\right]f(\theta)d\theta$$
$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^{NC}(\theta),\theta\right)}{\partial\theta}f(\theta)d\theta$$
$$\geq(1-p)\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^S(\theta)\right)-C\left(X^S(\theta),\theta\right)\right]f(\theta)d\theta$$
$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^S(\theta),\theta\right)}{\partial\theta}f(\theta)d\theta$$

$$\underbrace{p\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)\right]f(\theta)d\theta}_{\text{First Best Expected Total Surplus}}\geq p\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^S(\theta)\right)-C\left(X^S(\theta),\theta\right)\right]f(\theta)d\theta$$

Adding them up, we obtain <u>the first comparison</u> result:

$$(1-p)\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{NC}(\theta)\right)-C\left(X^{NC}(\theta),\theta\right)\right]f(\theta)d\theta+\underbrace{p\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)\right]f(\theta)d\theta}_{\text{First Best Expected Total Surplus}}$$
$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^{NC}(\theta),\theta\right)}{\partial\theta}f(\theta)d\theta$$
$$\geq(1-p)\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^S(\theta)\right)-C\left(X^S(\theta),\theta\right)\right]f(\theta)d\theta+p\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^S(\theta)\right)-C\left(X^S(\theta),\theta\right)\right]f(\theta)d\theta$$
$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^S(\theta),\theta\right)}{\partial\theta}f(\theta)d\theta$$

$$=\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{S}(\theta)\right)-C\left(X^{S}(\theta),\theta\right)+\left[(1-p)+pk\right]\frac{1}{h(\theta)}\frac{\partial C\left(X^{S}(\theta),\theta\right)}{\partial\theta}\right]f(\theta)\,d\theta$$

Next, from the *revealed preference* argument, the second comparison holds.

$$\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{S}(\theta)\right)-C\left(X^{S}(\theta),\theta\right)+\left[(1-p)+pk\right]\frac{\partial C\left(X^{S}(\theta),\theta\right)}{\partial\theta}\frac{1}{h(\theta)}\right]f(\theta)\,d\theta$$

$$\geq\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{TW}(\theta)\right)-C\left(X^{TW}(\theta),\theta\right)+\left[(1-p)+pk\right]\frac{\partial C\left(X^{TW}(\theta),\theta\right)}{\partial\theta}\frac{1}{h(\theta)}\right]f(\theta)\,d\theta$$

$$+\underbrace{p(1-k)}_{\geq 0}\underbrace{\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^{TW}(\theta),\theta\right)}{\partial\theta}f(\theta)\,d\theta}_{-}$$

$$=\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{TW}(\theta)\right)-C\left(X^{TW}(\theta),\theta\right)+\frac{1}{h(\theta)}\frac{\partial C\left(X^{TW}(\theta),\theta\right)}{\partial\theta}\right]f(\theta)\,d\theta$$

Combining these two comparison results, we obtain

$$(1-p)\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{NC}(\theta)\right)-C\left(X^{NC}(\theta),\theta\right)\right]f(\theta)\,d\theta+p\underbrace{\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{FB}(\theta)\right)-C\left(X^{FB}(\theta),\theta\right)\right]f(\theta)\,d\theta}_{\text{First Best Expected Total Surplus}}$$

$$+\left[(1-p)+pk\right]\int_{\underline{\theta}}^{\overline{\theta}}\frac{1}{h(\theta)}\frac{\partial C\left(X^{NC}(\theta),\theta\right)}{\partial\theta}f(\theta)\,d\theta$$

$$\geq\int_{\underline{\theta}}^{\overline{\theta}}\left[B\left(X^{TW}(\theta)\right)-C\left(X^{TW}(\theta),\theta\right)+\frac{1}{h(\theta)}\frac{\partial C\left(X^{TW}(\theta),\theta\right)}{\partial\theta}\right]f(\theta)\,d\theta$$

Q.E.D

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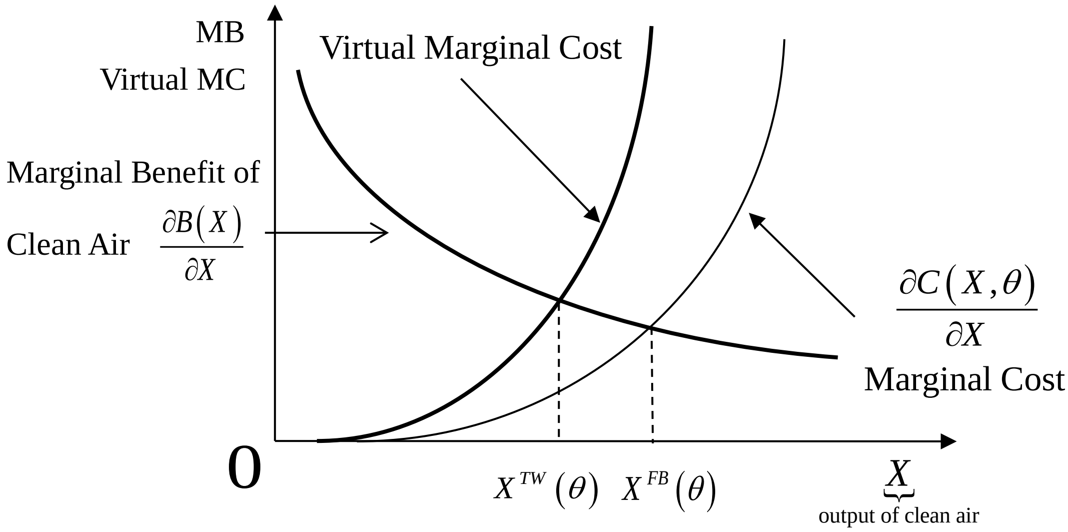
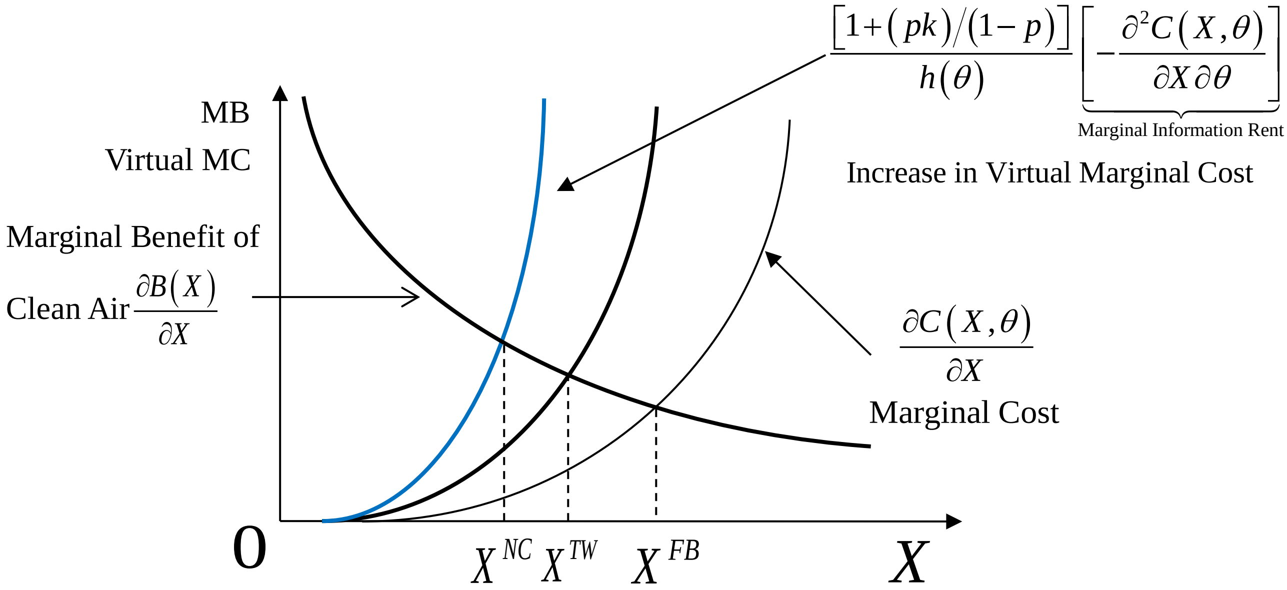
Figure 1



Equilibrium Output (of Clean Air) in the No-Supervisor (Two-tier) Regime：

Downward Distortion $X^{TW}(\theta) < X^{FB}(\theta)$ for $\theta \in \left[\underline{\theta}, \overline{\theta}\right)$

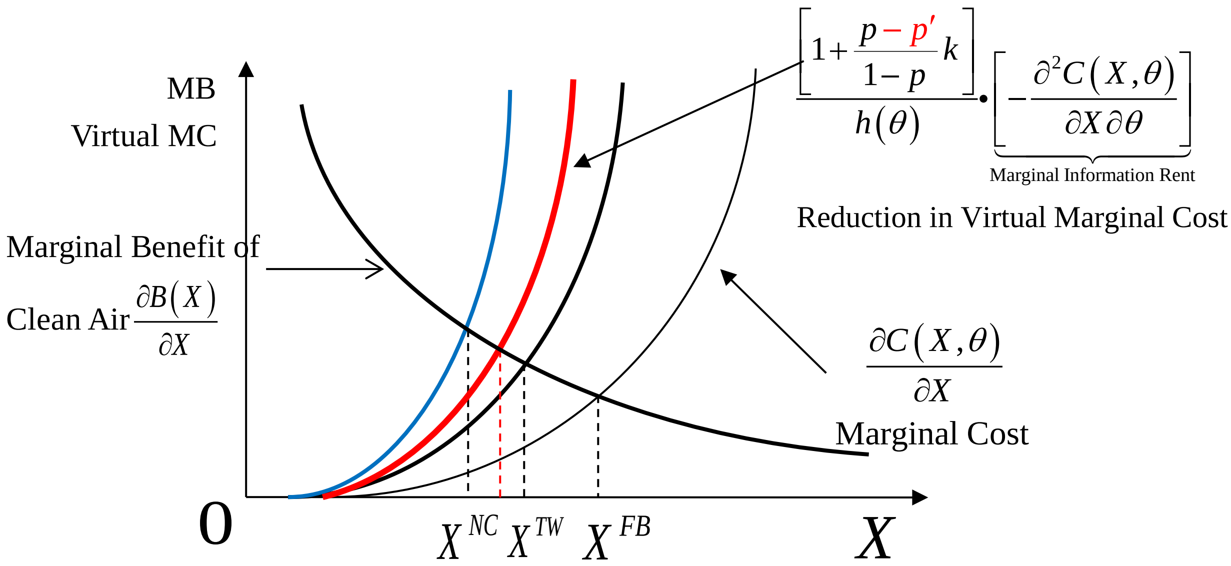
Figure2



Equilibrium Output (of Clean Air) in the No-Commitment (Three-tier) Regime

$X^{NC}(\theta)$ w.p $1-p$ **and** $X^{FB}(\theta)$ w.p p for $\theta \in \left[\underline{\theta}, \overline{\theta}\right)$

Figure3



Incentive Effect of introducing Another Supervisor (Dual Supervision)