ENVIRONMENTAL AND RESOURCE ECONOMICS
Vol. 3 No. 3 June 1993

SPECIAL ISSUE

MARKET INCENTIVES AND ENVIRONMENTAL REGULATION:
THEORETICAL ISSUES, CASE STUDIES and POLICY CONSIDERATIONS

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Economic Instruments for Emission Abatement Under Appreciable Technological Indivisibilities

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Abstract. The paper explores the performance of decentralized incentives when abatement involves technological indivisibilities. Technologically, pollution abatement is often carried out as a discrete process, if pollution reduction involves relatively large-scale investments in emission abatement equipment. Consequently, the firm's response to decentralized economic incentives for pollution abatement is affected by the indivisible property of the technology. It can be shown that in such cases efficiency may not be realized. Installing an abatement device may entail "too much" or "too little" investment compared with the efficient solution.

To partially remedy this problem, an incentive scheme which incorporates a fine (penalty) on pollution-induced damages is proposed in this paper. Essentially, as in the case of the command and control approach, the mechanism imposes a fine when firms do not meet an aggregate (e.g., a "bubble") emission level. The fine is set as a proportion of the polluting firm's share of the total excess damage inflicted when the standard has been violated. The paper explores alternative outcomes under this scheme in the framework of a non-cooperative game.

The outcomes under command and control (uniform percentage reductions), taxes, pollution permits and the fine scheme are illustrated with data from the Haifa area in northern Israel. They are compared with the social planner solution in terms of efficiency (achieving a given standard at minimum cost) and the volume of transfer cost.

1. Introduction

It is well known that effluent taxes and tradeable pollution permits are decentralized, cost-effective market mechanisms for achieving desirable environmental standards (Baumol and Oates, 1988). Emission abatement, however, is often characterized by non-convexities, and in particular, by indivisibility of the abatement technology, e.g., the construction of abatement devices such as scrubbers. Once an abatement device is installed, it would normally be planned to operate at full capacity in order to achieve scale economies. Therefore, the firm's response to decentralized incentives, such as emission taxes and permits would be affected by the indivisible property of the technology. It can be shown that under these conditions efficiency may not be realized: Installing an abatement device may entail "too much" or "too little" investment vis-a-vis the target level, if full capacity happens to correspond to an emission level below or above the standard.

Attempting to achieve the cost-effective outcome through decentralized economic incentives under conditions of indivisibility might yield either too little or too much abatement. Investment may thus fail the cost-benefit test, since the taxes or permits will not yield the desired outcome: installing the device will involve "too much" investment, if the device is capable of reducing emission levels beyond those mandated by the standard, or vice versa, there may be too little abatement. In this case, as in similar instances involving non-convexities, a decentralized market incentive system involving emission taxes or permits will not necessarily generate the desired social optimum. Specifically, there could therefore exist a range of tax rates and permit prices which would fail to induce the expected response by the polluting firms, i.e., the firms will end up merely paying the tax, without changing emission levels. If taxes are neither paid back to polluters nor used to compensate pollutees (as required on efficiency grounds), that outcome will surely generate a good deal of opposition from all parties concerned, and rightly so. In such situations, some form of administrative ("command-and-control") approach (see below) might yet turn out to be a preferred alternative.

This point is depicted in Fig. 1. In reducing pollution (P), a firm moves towards the origin, and it needs to install, say, two devices, I and II, in succession, in order to reach the pollution level at the origin of the graph. Assume that variable costs are relatively negligible. Average total abatement cost (AAC) is given by $AAC_I$ and $AAC_{II}$, with $C_I$ and $C_{II}$ indicating average cost at full capacity. In this case, marginal abatement cost (MAC) is first equal to the vertical part of the curve (= total investment) and then coincides with the horizontal axis.

Let MD in Fig. 1 be the marginal damage function. Will the firm operate at the point where marginal cost equals marginal damage (point $P'$)? The firm must consider two equilibria: one at point $P_I$, which implies no abatement is undertaken; the other at point $P_{II}$, which implies that device II is installed. Consequently, there may be either too little or too much investment in abatement relative to the efficient solution at point $P'$. A cost-benefit calculation can of course resolve the issue by comparing benefits forgone at $P_I$ (given by area $P_IAP'$), and the cost of the device (given by the height of the curve $AAC_{II}$ at $P_{II}$). A Pigouvian emission tax — which should be set at zero marginal net damage — will not induce the firm to the right solution.

The problem is exacerbated in markets where strategic behavior is possible, e.g., when only a small number of firms are involved. Thus, in order to meet a given standard it may be sufficient, as well as economically efficient, for only a subset of the firms involved to install abatement devices. However, in a decentralized, non-cooperative environment, some free riding may take place. Less efficient firms may end up installing abatement devices if it so happens that they are responsible for a large share of the emission, and would have otherwise been required to spend an even larger sum on emission taxes (or for the purchase of permits). Other firms may turn free-riders, and the outcome may be less efficient than the one which would have resulted from a command and control approach.

Is it possible to devise some kind of a decentralized incentive scheme which would achieve compliance at the desired level (or as close as possible) in an efficient manner? The paper proposes such a scheme, referred to as the Fine Incentive Scheme (denoted as FIS). It involves paying fines only on emissions which exceed a given (preferably the socially optimal) standard, with the fine corresponding to the monetized damage associated with the excess emission.

Section 2 of the paper presents the various approaches to pollution abatement for cases characterized by indivisibilities. In section 3 the problem is analyzed through an empirical example which deals with the situation in the Haifa bay area in Israel. The results of two economic incentive schemes — emission taxes and tradable permits — are contrasted with the social planner's solution and with those obtained under a command-and-control approach (uniform reduction across plants) under present conditions. Section 4 deals with the Fine Incentive System, and compares its performance with that of the other approaches.
2. Abatement Control in the Presence of Indivisibilities

2.1. Economic Efficiency: The "Social Planner" Solution

The control authority, acting as a social planner, is assumed to know the social damage function as well as the abatement technology and cost functions of the various polluting plants. Abatement cost is made of discrete components, \( PAC_i \) — the cost of abatement device \( j \) in firm \( i \). The control authority wishes of course to minimize aggregate regional social costs, consisting of the firms outlays on abatement plus the monetary value of the damages inflicted by the firms (i.e., the externality), e.g., health damages:

\[
\text{Min } D \left( \bar{E} - \sum_i AE_i \right) + \sum_j \sum PAC_j \delta_j,
\]

subject to: \( \sum_i E_i \leq E^* \),

\[ (1) \]

where

- \( D(\cdot) \) is the social damage function, \( D' > 0, D^* > 0 \);
- \( \bar{E} \) is current (benchmark) total regional emissions;
- \( E_i \) is current (benchmark) emission of firm \( i \);
- \( E^* \) is the level of the emission standard;
- \( AE_i \) is the emission abated by firm \( i \);
- \( \delta_j = 1 \) if device \( j \) has been installed by firm \( i \), \( 0 \) otherwise;

Acting as a social planner, the solution to (1) would guide the planner how to optimally allocate emission abatement among firms, depending of course on their respective costs.1

2.2. The Command and Control Approach

Command and control (CAC) approach is the most common method in reducing pollution levels, since it is relatively easy to administer. The control authority determines a regional emission level, and requires all firms to reduce emissions in a pre-specified manner, whether as a uniform percentage reduction, where all firms reduce their current respective emissions by a given, identical percentage, or through the specification of a mandatory (or, alternatively, the “best available”) abatement technology, or variations thereof. Contrary to economic instruments, it is well known that CAC is not an economically efficient way for achieving a given emission reduction (Baumol and Oats, 1988). This, however, is not necessarily the case when indivisibilities are present, as the result of the present analysis show. In addition, it may be worth mentioning that — in a different context — reservations have been recently voiced regarding the claim for universal inferiority of CAC. It has been demonstrated (Oats et al., 1989) that when ambient levels at different receptors are taken into account, and if no safe threshold concentrations can be assumed, then — compared with economic incentives — CAC may lead to concentrations below the required standard at some of these receptors, thereby generating additional benefits, which may outweigh the cost differential between CAC and economic incentives.

Under CAC, the firm’s objective is to minimize costs:

\[
\text{Min } \sum_i PAC_i \delta_i,
\]

s.t.: \( AE_i \geq \alpha \bar{E}_i \),

where \( \alpha \) is the required (uniform) percentage reduction, such that \( \sum_i (1 - \alpha)E_i \leq E^* \) holds.

2.3. Decentralized Economic Incentives: Emission Taxes

An emission tax is normally a cost effective mechanism. In the case of indivisibilities, however, it may fail the efficiency test, as we show below. The control authority imposes an emission charge at a rate of \( t \) per unit of emission, which would reduce aggregate regional emission to the desired level, \( E^* \). Following the imposition of the tax, each firm’s outlay consists of actual abatement (control) cost plus the tax payment ("transfer cost") on the unabated emissions, \( E_i \). The firm’s objective is to minimize:

\[
\text{Min } (\bar{E}_i - AE_i) + \sum_j PAC_j \delta_j.
\]

As long as the total tax payment is lower than the cost of investing in abatement, i.e.,

\[
\sum_j PAC_j \delta_j > tE_i \text{ for any } j,
\]

the firm will not install devices or substitute into low sulfur fuel. As \( t \) increases, total tax payment increases and the firm reaches a point where the tax payment is larger than the abatement cost, and it will begin to invest in abatement devices.

2.4. Decentralized Economic Incentives: Tradeable Emission Permits

The failure of economic incentive to produce a pre-specified level of emis-
sion is evident again in the case of tradable emission permits. Let us assume that the authority would issue a total of \( E^* \) tradable permits, allocating \( E^*_i \) to each firm, on say, a grand fathering basis (other initial allocations are possible, of course; for instance, auctioning them off, but these need not concern us here, as they would not modify the basic conclusion regarding indivisibilities).

A firm will sell permits if it installed an abatement device and has consequently found itself with a surplus of permits, or it can purchase permits if this were less costly than controlling emissions. Firms would exchange permits as long as there is an excess supply or demand. The firm's objective now is to minimize its outlay on abatement plus permits or, alternatively, minimize the outlay on abatement fixing the receipts from selling permits:

\[
\begin{align*}
\text{Min } & \sum_j PAC_j \delta_j + p^*[E_i - AE_E(\cdot) - E^*_i], \\
\text{s.t. } & \sum_i [E_i - AE_E(\cdot) - E^*_i] = 0, \\
& \sum_i E^*_i = E^*, \\
\end{align*}
\]

where \( p^* \) is the market clearing (equilibrium) price per traded permit. The firm will purchase extra permits (i.e., will be a net buyer) as long as

\[
\sum_j PAC_j \delta_j > p^*[E_i - AE_E(\cdot) - E^*_i] \text{ for any } j,
\]

and will be a net seller otherwise.

3. The Empirical Setting

The problem of controlling air pollution when abatement technology is characterized by indivisibilities is examined using real data for \( \text{SO}_2 \) reduction in the Haifa metropolitan area in Israel. Haifa is a highly polluted area, with a relatively small number of polluters. The different policy instruments (taxes, tradable permits, command and control, FIS) are analyzed using the TELMA model (Baron and Shechter, 1991). TELMA (an acronym for the Hebrew “A Computer Package for the Management of Air Resources”) is a PC software which optimally allocates the air shed of a region among polluting industries, for any given level of total permissible emissions. Alternatively, if ambient air standard is given (in terms of the permissible concentration of \( \text{SO}_2 \)), TELMA allocates appropriate emission levels among the pollution sources. The package was designed especially for the complicated terrain which characterizes the Haifa area.

The problem is illustrated by a series of abatement scenarios involving only two firms: a power utility (denoted by EL) with a capacity of 430 MW, generated by four units, and a large refinery complex, with a refining capacity of 5 mill. tons/year (denoted by R). Together these two firms contribute about 85% of \( \text{SO}_2 \) emissions. Abatement may be achieved by either fuel substitution, an option which is disregarded in this paper, or by installing scrubbers. Scrubbers are currently not installed at any of the country’s power plants.

Table I shows the costs and plant efficiency of various abatement devices applicable in the present case. As noted, the devices are associated with different production lines (R, B, and C); each line is connected to a single emission source — a stack. Thus, in the case of the refinery, two types of scrubbers are considered — \( R_1, R_2 \), each with a different abatement capacity (indicated in column 3, “percent emission reduction”), and a different cost (column 2). Note also that for various technological reasons, 50% of the refinery’s emissions (9900 tons/yr) cannot be abated. The power utility operates four generating units in two separate production lines. Average abatement costs — when devices are operated at full capacity — are given in column 4. These correspond to the troughs of the average cost curve depicted in Fig. 2. Note that although the two devices, \( B \) and \( C \) are identical, production line \( C \) involves higher emission outputs and its average abatement cost lower.

The outcome under the various control schemes — administrative and incentive-based — are given in Table II, for successive reductions in regional emissions. The columns of Table II show the emission standard, \( E^* \), in terms of percentage reduction from current levels, \( E \) (column 1); the actual reduction in emission levels (“Reduction”), again as a percentage of benchmark emissions (column 3); abatement devices costs (“Cost”, column 4);

<table>
<thead>
<tr>
<th>Production Line</th>
<th>Abatement Cost ($1000)</th>
<th>Percent Emission Reduced*</th>
<th>Average Abatement Cost*</th>
<th>Current Pollution Ton/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refinery R1</td>
<td>7,589</td>
<td>90%</td>
<td>851.7</td>
<td>9900</td>
</tr>
<tr>
<td>Refinery R2</td>
<td>4,094</td>
<td>80%</td>
<td>517.0</td>
<td>9900</td>
</tr>
<tr>
<td>Refinery**</td>
<td></td>
<td></td>
<td></td>
<td>9900</td>
</tr>
<tr>
<td>Electric B1</td>
<td>4,579</td>
<td>45%</td>
<td>1027.9</td>
<td>9900</td>
</tr>
<tr>
<td>Electric B2</td>
<td>9,159</td>
<td>90%</td>
<td>1027.9</td>
<td>9900</td>
</tr>
<tr>
<td>Electric C1</td>
<td>4,579</td>
<td>45%</td>
<td>481.8</td>
<td>21120</td>
</tr>
<tr>
<td>Electric C2</td>
<td>9,159</td>
<td>90%</td>
<td>481.8</td>
<td>21120</td>
</tr>
</tbody>
</table>

* At full capacity.
** No device can be installed at this production line.
transfer costs ("T. Gov.", column 5); inter-firm transfers for the purchase and sale of permits ("T.B.F.", column 6); and the associated tax rate or equilibrium permit price ("Tax/P. Price"), depending on the policy employed (column 7). The rows denoted "penalty" in each reduction category refer to the EIS scheme, and will be explained later.

3.1. EMISSION TAXES

The results of the imposition of an efficient tax structure, that is, one which is predicated on an omniscient control authority, are given in Table II. However, in the real world, the control authority does not necessarily know the firms' cost functions, and therefore will fail to reach the desired emission level, $E^*$. The region will reach a level which is either too low (too much abatement), or too high (too little abatement). The reason for this can be seen in Fig. 3, which depicts the results of Table II for successive tax rates.

The step functions show successive "switching points", corresponding to the points where firms find it cheaper to invest in abatement devices, given the increasing levels of the tax rate. Thus, for certain ranges, as the tax rate is increased, the amount of emission abated will remain unchanged until the next device becomes profitable relative to the tax payment. However, unless a given emission reduction happens to coincide with the switching point, it will not be achieved at this tax rate, or there will be an "overshoot" and an

![graph](image-url)

**Fig. 2. Average cost of SO₂ abatement.**

<table>
<thead>
<tr>
<th>Reduction Level</th>
<th>Policies</th>
<th>Regional Outcome</th>
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<tbody>
<tr>
<td></td>
<td>Reduction</td>
<td>R. Cost</td>
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<tr>
<td>10%</td>
<td>Uniform (CAC)</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>Social</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Tax</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>Permits</td>
<td>15%</td>
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<td></td>
<td>Penalty #1</td>
<td>18%</td>
</tr>
<tr>
<td></td>
<td>Penalty #2</td>
<td>15%</td>
</tr>
<tr>
<td>15%</td>
<td>Uniform (CAC)</td>
<td>34%</td>
</tr>
<tr>
<td></td>
<td>Social</td>
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<td></td>
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<td>Uniform (CAC)</td>
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<td></td>
<td>Permits</td>
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<tr>
<td></td>
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### Table II (Continued)

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<th>Reduction Level</th>
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<th>T. F</th>
<th>Tax/P. Price</th>
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<td>Uniform (CAC)</td>
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<td></td>
<td>Permits</td>
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<td>53%</td>
<td>13,254</td>
<td>(1,329)</td>
<td>0</td>
<td>517</td>
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<td>Uniform (CAC)</td>
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<td>15,401</td>
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<td>15,401</td>
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<td>1028</td>
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<td>15%</td>
<td>4,095</td>
<td>18,430</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

R. Cost — Reduction Cost; T. Gov — Transfer to/from Government; T. F — Transfer between Firms; Permits trading.

---

**FIG. 4.** Tax payment and abatement costs vs. tax rates.

The excess amount of emission abatement will occur (relative to the specified level). The envelope curve depicted in Fig. 3 can also be interpreted as the long-run regional supply function of clean air.

Moreover, the emission tax might result in substantial transfer cost without necessarily yielding the desired emission level. Since efficiency requires that tax receipts not be returned to the plants (except as lump-sum transfers), one can imagine that that is likely to raise objections on the part of firms, and maybe the public if higher costs are shifted through higher prices. This point is depicted in Fig. 4, which shows that at low tax rates most of the firms outlays constitute merely cash transfers to the control authority, with relatively little abatement.

### 3.2. Tradeable Emission Permits

The various outcomes for successive emission reductions are given in Table II. Note that the table includes non-round divisions as well, viz., the 37% and 53% reductions. These are "corner" solutions, where the reduction can be achieved exactly by employing a certain mix of devices. As was pointed above, these are the points where the two decentralized incentive schemes — tax and tradeable permits — would yield the efficient solution.

Figure 5 illustrates the case where the control authority wishes to achieve a 50% reduction in regional emission. The figure indicates that there is an
excess demand for permits at relatively low prices, because then firms would prefer to purchase the cheap permits rather than abate. This is indicated in the graph by the region left to the equilibrium point, denoted by 0 on the horizontal axis. As the price of permits rises, abatement becomes a more profitable option for an increasing number of firms, and they switch from being net demanders to net suppliers, until the price reaches the range of values for which supply equals demand (in the range of $512 to $640). However, there is no guarantee that there exists such a price which would support any given level $E^*$, unless the number of permits associated with this level just happened to coincide with a “switching” point in a firm’s cost curve (cf., e.g., Fig. 3). In other words, it must coincide with a point where the marginal abating firm operates a device at full capacity, just prior to the installation of the next device (by the same or another firm). If the prescribed amount (e.g., 50% reduction in Fig. 5) does not coincide with such a switching point, the desired abatement will not be achieved through a tradeable permit market.

As seen from Table II a true market equilibrium is reached for 37% and 53% reductions. At these points a transfer of permits valued at $3.5 mil. and $1.1 mil. respective, is taking place among the firms. An equilibrium between demand and supply for permits is possible for unit permit prices of $48.2 and $51.7 respectively. These prices also correspond to the minimum average cost of the respective marginal devices. At all other points, either part or all of the outstanding permits are purchased by the government (indicated by a negative sum under the “T. Gov.” column), effectively enabling, or supporting, the indicated equilibrium price. Without this contrived intervention, no equilibrium exists. Note that at the true equilibrium points, the permit price always equals the tax rate, as is well known.

4. The Fine Incentive Scheme (FIS)

In order to overcome the problem raised by indivisibilities, whether with respect to command and control or the usual decentralized, economic incentive schemes, an alternative incentive scheme is proposed here. It is shown that this scheme is capable of overcoming at least part of the inefficiency caused by indivisibilities as well as by strategic behavior. Specifically, using the Haifa example, it is shown that in the presence of indivisibilities, FIS may involve lower total abatement and tax outlays, than under command and control (CAC) or “conventional” emission tax scheme. The scheme may be characterized by three main features:

(a) A charge is imposed only on emissions which exceed the pre-specified standard, $E^*$; no emission standard is set for the individual firm (i.e., no $E_t$). Any time the standard is not met, the authority imposes a fine, $\tau$, equal or proportional to the benefits foregone because the standard had been exceeded (due to the actions of any firm).

(b) The charge, $\tau$, is equal (or proportional) to the additional damage due to emission levels above the standard: $\tau = D(E - E^*)$; it is assumed that the control authority possesses some information regarding the damages which would be avoided as a result of reducing emissions from $E$ down to $E^*$.

(c) The charge paid by the individual firm, $\tau$, is determined on the basis of its benchmark pollution levels: $\tau = (E/E)\tau$.

The scheme therefore presupposes that the monitoring authority has some information on the benefits associated with reducing emission from current levels down to the given standard. Depending on their cost functions, firms may be able to reduce abatement cost by paying a fine on the amount of excess emissions by all firms.

The firm’s problem, then, is to minimize the sum of penalty plus abatement costs:

$$\text{Min } \tau + \sum_i PAC_i \delta_{pi}$$

where $\tau = D(E - E^*)$ and $\tau = (E/E)\tau$.

Note that unlike the regular emission tax scheme, the firm pays the fine only on the amount of emissions above the standard, and not on total unabated emissions. Consequently, total abatement and tax outlays should
usually be much lower, while still achieving the desired emission reduction. Since under FIS the control authority need not know which firm(s) is responsible for violating the standard in order to impose the fine, nor who did not install an abatement device, individual plant inspection is not required. All the information can be obtained from monitoring stations.

Basically, the fine incentive scheme is a decentralized, incentive compatible scheme which may be thought of as imposing an imaginary "bubble" over all the relevant firms, inducing firms to enter into negotiations with the others in order to reduce their emission charge burden, while trying to arrive at an allocation which will minimize their abatement costs. FIS thus allows foregoing the achievement of E∗ in return for the payment of a fine. This feature imparts a measure of continuity to the decision problem, and thus reduces the obstacles raised by indistinguishability in attempting to reach efficient solutions. The reason will become clearer when we analyze the empirical results below.

However, that FIS could conceivably invite free-rider behavior. The reduction in cost obviously can be obtained only if abatement were carried out by the firm with the lowest abatement costs. Whether and under what conditions such cooperation will take place, and how the costs will be shared among the firms, are of course crucial issues, and will be addressed below. Moreover, it should be emphasized that since the number of participants is small, strategic behavior is very likely, and it is appropriate to analyze the problem in a game theoretic framework.

Under FIS a firm's abatement decision generates an externality vis-à-vis the other firms in the "bubble." This resembles the case of the Clarke tax (Clarke, 1971; Tideman and Tullock, 1976). Under that scheme, those responsible for generating a negative externality must pay a fine which would have been sufficient to compensate the affected individuals, i.e., equal to their loss. As with pollution taxes, actual compensation need not be made (cf. Oates, 1983; Shibata and Winrich, 1983); this holds also for FIS. However, unlike the Clarke tax where each individual faces the consequences of his or her own actions, under FIS the charges imposed on each polluting firm is a function of its own actions and those of all other firms.

An essential feature of FIS obviously is the assumption that the monitoring authority has some notion regarding the benefits associated with reduction in emissions (from Ē to E∗). This kind of knowledge involves information on damages avoided — which is usually assembled in connection with the preparation of support documents for the standard, and the associated monetary valuation of those damages. The latter is not so readily available, unless the standard was based on a comprehensive cost-benefit analysis, which has seldom been the case so far. However, order of magnitude estimate of monetary damages are not an impossible task for the authority (see, e.g., Shechter, 1991).

4.1. SOLUTIONS FOR NON-COOPERATIVE-GAME SCENARIOS

Under FIS, firms would have incentives either to cooperate or not to cooperate among them in the manner they respond to the imposition of the fine scheme. In the present case each firm faces two cost components: abatement and penalty, the penalty being a function of the damage caused by excess pollution. The damage function used here is based on health damage estimates for the Haifa region (Shechter, 1991). Each firm decides whether to install the device it would install to meet its own best interests, and the analysis attempts to identify the game's saddle-points which are likely to emerge in each emission reduction scenario. In what follows we consider only pure strategy equilibria because mixed strategies do not make much sense here; it is not a repeated game, where strategies can be changed in every game.

The various possible outcomes of the two-firm, non-cooperative game are presented in Table III, where the four cells give the cost matrix for the two players. Each player has two strategies: (a) "Install" — installing an abatement device, which would reduce everyone's fine, or (b) "Not Install" — not installing devices. D(·) is the pollution damage function. Since here we are only interested in what happens if pollution levels exceed the allowable level (say, standard) the function is specified as follows: D(·) > 0 if ∑Ei − ∑jAEj > E∗, and D(·) = 0 otherwise.

<table>
<thead>
<tr>
<th></th>
<th>Not Install</th>
<th>Install</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Install</td>
<td>S1 + S1[D(E) - D(E*)]</td>
<td>C1 + S1[D(E − AE1) − D(E)]</td>
</tr>
<tr>
<td>Install</td>
<td>S2 + S2[D(E) - D(E*)]</td>
<td>S2[D(E − AE1) − D(E)]</td>
</tr>
</tbody>
</table>

A "Not Install" strategy for firm 1 would be its dominant strategy if the following two conditions were satisfied. These conditions imply that no matter what the other player does, the firm will always be better off by not installing a device. Define S1 to be player i’s share in total (regional) benchmark emissions, and C1 its abatement cost.

\[
S_1[D(E) - D(E^*)] < C_1 + S_1[D(E - AE_1) - D(E^*)]
\]

(6)

\[
S_1[D(E - AE_2) - D(E^*)] < C_1 + S_1[D(E - AE_1 - AE_2) - D(E^*)]
\]

(7)
Eq. (6) applies to the case when firm 2 does not install any device, and eq. (7) to the case where it does.

In a similar fashion, for firm 2:

\[
S_2[D(E - AE_1) - D(E^*)] < C_1 + \\
+ S_2[D(E - AE_1 - AE_2) - D(E^*)] 
\]

\(8\)

\[
S_2[D(E) - D(E^*)] < C_1 + S_2[D(E - AE_1)]
\]

\(9\)

Equations (6) and (7) together imply, after some manipulation,

\[
C_1 > \max \{ S_1[D(E) - D(E - AE)], \\
S_1[D(E - AE_2) - D(E - AE_1 - AE_2)] \}
\]

\(10\)

and similarly for equations (8) and (9):

\[
C_2 > \max \{ S_2[D(E - AE_1) - D(E - AE_1 - AE_2)], \\
S_2[D(E) - D(E - AE_2)] \}
\]

\(11\)

When these two inequalities are reversed (i.e., \( C_i < \min \{ \cdot \} \)), the outcome will be efficient. If only one of the inequalities reversed sign, we obtain an equilibrium with only one major player “cooperating”, while the other firm is a free rider. This could be the case where the firm threatens its rival with “non-cooperation”, although in doing so it would actually worsen its situation (“The Non-Credible Threat Case”). Finally, there is the case where \( \min \{ \cdot \} < C_i < \max \{ \cdot \} \); here the firm has no dominant strategy and multiple equilibria could arise. Bargaining among the firms could be one way out of this impasse (but we ignore this case for now). Altogether, seven such games were investigated and described below; their respective saddle point (or points) solutions are given in Table IV.10 These outcomes correspond to the “Penalty” rows in Table II. Column 3 of Table IV lists the installed devices (cf. Table I) under each reduction scenario, for the electric utility (EL) and the refinery (R). Columns 4, 5 and 6 show the associated device costs, fine payment, and their combined sum, respectively. The last column shows the actual reduction for each firm and for the region.

Take, first, the 10% reduction. Unless bargaining is possible, both solutions could emerge. One solution involves the installation of a device in firm E, while in the other solution the device is installed in firm R, with a cost figure of $4.58 and $4.09 mil., respectively. Since in either case the stated reduction objective is met, no penalty would be paid. Note that the social planner and permit market solutions reduce 15% of the benchmark emissions, whereas the required reduction is only 10%. In the CAC case emissions are reduced even more, by 34%, since here each firm must install a relatively expensive device, while in fact it would have been sufficient for only one of them to do so (as evident from the social planner case).

<table>
<thead>
<tr>
<th>Reduction Level</th>
<th>Devices</th>
<th>Reduction Cost</th>
<th>Penalty Cost</th>
<th>Total Cost</th>
<th>Emission Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EL R</td>
<td>EL R</td>
<td>EL R</td>
<td>EL R</td>
<td>EL R Total</td>
</tr>
<tr>
<td>10%</td>
<td>C1</td>
<td>4.58</td>
<td>4.58</td>
<td>9.06</td>
<td>9.06</td>
</tr>
<tr>
<td>20%</td>
<td>C1</td>
<td>4.58</td>
<td>0.37</td>
<td>0.25</td>
<td>4.93</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>4.99</td>
<td>1.51</td>
<td>0.87</td>
<td>6.57</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.54</td>
</tr>
<tr>
<td>50%</td>
<td>C1</td>
<td>4.58</td>
<td>2.88</td>
<td>1.92</td>
<td>7.46</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>4.99</td>
<td>3.83</td>
<td>2.35</td>
<td>6.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>9.54</td>
</tr>
<tr>
<td>60%</td>
<td>C2</td>
<td>9.16</td>
<td>4.08</td>
<td>2.72</td>
<td>13.24</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>4.09</td>
<td>7.82</td>
<td>5.21</td>
<td>16.16</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.00</td>
</tr>
<tr>
<td>70%</td>
<td>C2</td>
<td>9.16</td>
<td>4.09</td>
<td>7.37</td>
<td>11.06</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>4.09</td>
<td>11.06</td>
<td>4.16</td>
<td>19.27</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>19.27</td>
</tr>
</tbody>
</table>

In this scenario the tax scheme fails the efficiency test, too, reducing emissions by 37%, because the wrong signals are sent to the firms with indivisible choices. The tax must be set at $482 per ton for some reduction to take place, using the least costly abatement device (with AAC equal to $482). However, this device has quite a large capacity, and its costs accordingly, hence the very high abatement cost ($9.16 mil.), and a very large sum as transfer cost ($15.33 mil.). The FIS would achieve 15% (as in the social planner solution) or 18% reduction in emissions, and would be cheaper. In this case only the cost of abatement devices $4.09 or $4.58 mil. is involved. From Table IV one should note, however, that all of the costs are incurred by one plant (depending on the equilibrium point), leaving of course open the question of sharing these costs between the firms.

As a further illustration of the working of the FIS, examine the 20% reduction. From Table IV we see that, again, the two previous equilibria emerge. Compare these results to Table II. The social planner solution, as well as uniform reduction (i.e., CAC) involve a higher outlay, because both firms must now install a device in order to meet the specified reduction, for a total outlay of $8.67 mil., although this results in over-abatement (34% instead of 20%). The tax solution performs exactly as in the previous scenario. Regarding FIS, note from Table IV that if a device is installed in firm EL (device C1), total cost to both firms amounts to $5.2 mil. (4.58 + 0.37 + 0.25), while if the device is installed at firm R (device R2), total cost would be $6.27 mil. As explained above, both equilibria are possible, but both result in lower total outlays. Although FIS fails to reach the stated
reduction (achieving a reduction of only 15% or 18%), this is characteristic of FIS, as will become evident from succeeding scenarios: it trades reduction for compensation through the proceeds from the fine, precisely because this is the more socially efficient option. Thus, on efficiency grounds, FIS emerged as a superior instrument in this scenario.

In the 30% scenario, CAC turns out to be the least costly instrument, yielding identical results to those of the social planner. The emission tax produces exactly the same solution as in the previous two scenarios (and would remain so as long as the tax is set at its minimal effective level of $482). For FIS total costs (inclusive of the fine), associated with the (same) two equilibria, are $9.38 and $10.47 mil. In this scenario it happens that one of the firms (E) is capable of reducing its own emissions by exactly 30%. This gives an advantage to CAC — which indeed requires it to do so — over FIS. Under the latter, its costs become a function of the other firm’s actions, which in this case results in higher abatement plus penalty costs to firm E.

A similar outcome is observed in the case of a 40% reduction, although here the CAC, social planner and tax options deviate much more from the specified reduction (53% vs. 40%). The tax and CAC schemes produce the social planner’s outcome, although when transfer cost associated with the tax are added, it becomes a much more expensive proposition. FIS is slightly more costly than CAC ($14.01 vs. $13.25 mil).

From the 50% reduction onwards, CAC is excluded from the analyses because it is technologically impossible for firm R to realize a 50% reduction using only its own devices (unless it curtails production). Therefore the corresponding entries in Table II are left blank. Now, total cost for FIS is $17.12 mil., which is higher than in the social planner’s solution ($13.25 mil.), but less than the tax solution ($25.60 mil., including transfer cost).

The 60% case gives rise to a total cost of $17.8 mil. under the social planner, while the tax solution involves an outlay of $22.41 mil. without transfer cost, and $37.82 mil. with it. In comparison, FIS — which now produces a 37% reduction in emissions — involves a much lower outlay of $15.96 mil., lower as well than the social planner’s solution.14 In the 70% case, total cost for FIS is $22.52 mil., slightly more than the social planner’s outcome, but again much lower than the tax solution ($37.82 mil., inclusive to transfer cost).

To summarize: at least for the (real life) example used here to illustrate the scheme, and even for a non-cooperative setting (where, unlike a cooperative setting, each firm looks after its own “narrow” interests), FIS has largely succeeded in overcoming the indivisibility problem, scoring rather well compared with the other two economic incentive schemes. Excluding the switching points of 15, 37, and 53 percent, which normally would not in any case be known to the authority, in three out of ten outcomes (equilibrium #2 under 10%, 20% and 60%) FIS has performed cost-wise as well or even better than the social planner solution. In two cases (40% and 70%) it has come quite close to it. This is remarkable, because it means that FIS has been capable of producing in this situation an efficient solution, which cannot be said of any of the other methods except, ironically, CAC. Of course, one may question the desirability of over-abatement exhibited in some scenarios, in relation to the additional benefits vs. the additional costs of the extra reduction. This, however, is precisely the major reason for seeking a substitute mechanism when indivisibilities are present, since then the authority would often fail to reach the desired emission target with incentive-based instruments.

5. Concluding Remarks

The empirical results presented in the paper strongly suggest that pervasive non-convexities in the abatement technology may severely handicap the cost-effectiveness of decentralized economic incentives. Moreover, they may fail to achieve the desired emission reduction targets, usually overshooting them — which could well be a questionable outcome on efficiency grounds.

It is of course possible to argue that the analysis is flawed because only two firms are involved, and this is not representative of situations where taxes and tradable permits would be relevant. A control authority would certainly not bother to explore the use of these tools in such circumstances. It is believed, however, that the problems investigated here characterize situations involving either a small group of different firms (in terms of their cost structure), or a relatively large number of firms, each belonging to one of a small number of group-types (again in terms of their cost structure), with the firms in each group being more-or-less identical.

An alternative incentive scheme has therefore been proposed, the Fine Incentive System, which involves paying fines only on excess regional emissions, prorated according to the corresponding monetized damage. In a certain sense, the fine scheme imparts the decision problem a measure of continuity, and generates signals which implicitly apply marginal benefit-cost type considerations in solving the problem. The outcomes under the suggested fine scheme, emission tax, permit markets and uniform percentage reduction were compared with the efficient, “social planner” solution, namely, achieving a given standard at minimum cost.

Although the FIS cannot (and need not, by its very nature) guarantee the attainment of the given standard, it may be perceived as an exact embodiment of the Polluter Pays Principle (PPP). With the regular emission tax, unless the standard was derived through a benefit-cost analysis, and the charge therefore represents a true Pigouvian tax, transfer costs do not necessarily correspond to the externality perpetrated by the polluters. If for one reason or another the standard was determined on a basis different from benefit-cost (which is true in almost all cases), then it would be the proceeds of FIS, rather than the tax, which would represent proper compensation by the polluters in the spirit of PPP. Furthermore, the FIS incorporates the
efficiency principle guiding benefit-cost analysis: if it is socially cheaper to compensate than to abate, then abatement is indeed the less preferred option.

Interestingly, it turns out that some existing tax schemes resemble the FIS (Tietenberg, 1990; Opschoor and Vos, 1989). In Germany, dischargers are required to meet minimum standards of waste water treatment, and a fee is levied on every unit of untreated discharge. However, discharges meeting or exceeding efficient standards have to pay only half the normal tax rate. In Italy, the charge is nine times higher for firms that do not meet prescribed standards for waste water than for firms that meet them. In Japan an air pollution emission charge has been imposed specifically to raise revenue to compensate the victims of air pollution, and the charge is determined by the cost of the compensation program. That is, in the Japanese case, like under FIS, excess damage serves to determine the fine.

It would certainly be wrong, on the basis of basically an empirical analysis, to generalize and unequivocally conclude which is the best scheme in all cases involving indivisibilities. More research is required in order to establish the generality of the approach proposed here, as well as its policy implications. The analysis of the various scenarios may nevertheless suggest some preliminary, tentative conclusions. For one, indivisibilities do indeed render the customary market incentives inefficient. Furthermore, using a real-life example, the paper has further shown that FIS has out-performed the emission taxes, or installing one device and to level and paying the fine on the rest, or not installing any device, and so on. In order to simplify the analysis, we present only the 2 × 2 case. In fact, it turns out that in the empirical situation analyzed below, it is possible to install at most two devices, one for each firm. Only from a reduction of 61% onwards, an option to install two devices by one of the firms becomes relevant, and is considered there.

A complete description of the game payoffs is given in Becker, Baron and Shechter (1992).

1 It should be noted that the social planner's solution aims to reach at least the target emission level, while the FIS does not require that.

It may be noted that if policy selection were viewed as an endogenous process (e.g., firms can "vote" or lobby for the most advantageous from their point of view), different firms may prefer different incentive schemes, and the game setting analysis can indicate which schemes different firms would prefer in different scenarios.

References


Notes

1 Note that only emissions are considered here, and not ambient levels. Carrying out the analysis with ambient levels should obviously become much more complicated and cumbersome (see Baron and Shechter, 1991).

2 Clearly, it will attain this level only if it knows the cost functions of each polluter. Note also that $E^*$ is not necessarily the socially optimal level. If it were, the associated tax rate would also be socially optimal. Otherwise, it is only the cost-effective tax rate.

3 A detailed analysis of the efficient allocation of emissions between the two firms is given in Becker et al. (1992).

4 Note that the relevant cost is average cost at full capacity, and not marginal cost.

5 It may be of some interest to know that Domar (1974), Freisinger and Vogelsang (1981), Baron and Myerson (1982), Laffont and Tirole (1986), among others, have dealt with a similar problem with respect to the control of monopolies, where the welfare losses caused by the monopoly are known to the regulator but not their cost structure.

6 Even if routine plant inspection were undertaken, the authority would usually not be able to ascertain (nor should it care to for that matter) whether a firm violated the standard because it is a free rider, or because it was cheaper to pay the fine.

7 A distinction should be made between being able to compute a global optimal level of the externality and having information about marginal benefits in the neighborhood of any pre-specified standard. The latter is assumed here; not the former. This justifies exploring how the various instruments perform at successive emission reductions (i.e., different levels of emission standards). A similar rationale was offered by Oates et al. (1989).

8 The original estimates in Shechter (1991), derived under alternative valuation methods (direct and indirect), were for a 50% reduction in present pollution levels. Most of the health damages in the Haifa area are attributable to SO2 emissions, 85% of which are generated by the two plants considered in this paper. Linear interpolations and extrapolations were used in calculating fine schedules for the scenarios involving reductions other than 50%.

9 Note that, in general, the payoff matrix in Table II would be of a higher order than 2 by 2, since a firm would be faced with mixed combinations of "install" and "not install". For example, when required to abate 10% of benchmark emissions, it may have only one choice — install a device to reduce 10%, or not install and pay the fine. When faced with a 20% reduction, however, it may be possible to meet this requirement by either installing, say, two devices, or installing one device and paying the fine on the rest, or not installing any device, and so on. In order to simplify the analysis, we present only the 2 × 2 case. In fact, it turns out that in the empirical situation analyzed below, it is possible to install at most two devices, one for each firm. Only from a reduction of 61% onwards, an option to install two devices by one of the firms becomes relevant, and is considered there.