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Incentives for Firms to Share Abatement Technology under a Proportional Liability Rule

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We analyze in this paper the technology diffusion decisions of two polluting firms. Firm 1, armed with superior pollution abatement technology, must decide on how much technology to share with firm 2. Meanwhile, firm 2 must determine how much of the available technology to adopt. Though inspired by Endres and Friehe (2011), which investigates a related issue under environmental laws of strict liability and negligence rules, this paper differs crucially in two fundamental aspects: we consider a proportional liability rule and costly technology diffusion. We find that the decision to release or adopt more advanced technology hinges on the form of external damage as well as the existence of diffusion costs. Only when external damage is linear and technology diffusion is free will the market equilibrium be efficient.

Keywords: pollution emission, technology transfer, proportional liability
JEL classification: K13, Q52, Q55

1 Introduction

Polluting firms in an industry usually have different pollution abatement technologies at their disposal. The technology state of a firm depends naturally on changes in technology and the time the firm makes purchases of technology. Milliman and Prince (1989) pioneered the analysis of a firm's incentives to promote changes in technology, and was followed by Jaffe and

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Stavins (1995), Requate and Unold (2003), and Coria (2009). These authors considered various policy instruments, including taxes, subsidies and permits, and compared their welfare effects. However, no victim compensation requirements are included in any of this analysis. An up-to-date survey of this literature is provided by Allan, Jaffe, and Sin (2014).

Endres and Friehe (2011) were the first to embody environmental liability laws in their model. They compared firm diffusion decisions under strict liability, which requires polluting firms to compensate harm irrespective of their behavior, and a negligence rule, which holds firms liable for harm only when they breach certain behavioral norms (for example, excess emission beyond an announced pre-set level). They argued that firm diffusion incentives are socially optimal under strict liability, but suboptimal under negligence, if advancement in technology lowers marginal abatement costs for all levels of abatement.

The problem we consider here differs from that of Endres and Friehe (2011) in two important aspects. Firstly, they assumed an exogenous split of compensation responsibility for their strict liability scenario, but offer no explanation or justification as to how the split ratio is determined. We assume instead that firms' payments are proportional to their emission levels. A firm discharging twice the pollutants of another firm will accordingly face a compensation fine double that of the other.

Secondly, Endres and Friehe (2011) did not take transfer costs of technology into account. There is thus no cost for the leading firm to diffuse its superior technology, and there is similarly no cost for the sluggish firm to upgrade its technology. This is certainly un-realistic. We incorporate technology diffusion costs in our model, and find that the extent of technology sharing by firms depends critically on these costs.

This paper follows the literature on voluntary technology diffusion (e.g., Endres and Friehe (2011), Coria (2009), and Requate and Unold (2003)) and rules out the possibility of side-payments by firms to acquire superior technology from other firms. We acknowledge that there is indeed a substantial literature on technology licensing (e.g., Fosfuri (2006), Arora and Ceccagnoli (2006), Lach and Schankerman (2004), Sine, Shane, and Gregorio (2003), and Arora (1996)) that focuses on paid technology transfer. It would be interesting to compare the market outcomes of these two scenarios, but this is outside the scope of the current paper and will be dealt with in follow-up work.

This paper is organized as follows: The analytical framework is first laid out in section 2. In the third section we analyze the socially efficient levels of technology diffusion with and without diffusion costs as benchmark cases for comparison. The fourth section then focuses on market interaction between the firms. Two dimensions are considered: constant versus increasing marginal damage, and the presence/absence of diffusion costs. We compare market outcomes in these settings with corresponding social optima to check on their efficiency. The final section concludes and summarizes our findings.

2 The Model

Consider two polluting firms (1 and 2) generating identical pollutants in a metropolitan area. Assume that firm 1 possesses a more advanced pollution abatement technology than firm 2. Let their emission levels be denoted by:

$$(x_1, x_2), \quad 0 \leq x_i \leq \bar{x}_i,$$

with $\bar{x}_i$ being firm i's natural uncontrolled emission level. The external pollution damage caused by the two firms depends on the aggregate level:

$$D(X), \quad X \equiv x_1 + x_2,$$

which may exhibit constant or increasing marginal damage (MD):

$$D'(X) > 0, \quad D''(X) \geq 0.$$

To reduce the emission of pollution below its initial unregulated level $\bar{x}_i$, firm i has to incur a cost:

$$C^i\,(x_i, T_i)$$

for installing the end-of-pipe emission control equipment, $T_i (\in [0, 1])$ denoting firm i's state of technology. The abatement cost function has the usual properties of increasing marginal cost and diminishing returns to technology:

$$C^i_x < 0, \quad C^i_{xx} > 0, \quad \forall x_i \in (0, \bar{x}_i)\,,$$

$$C^i_T < 0, \quad C^i_{TT} > 0, \quad \forall T_i \in (0, 1).$$

It is also plausible that an advancement in technology will imply a downward shift in the marginal abatement cost (MAC) for all firm emission levels:

$$-C^i_{xT} < 0. \tag{1}$$

Further, for notational simplicity, we normalize firm 1's superior technology state to 1:

$$T_1 \equiv 1.$$

Firm 2's level of technology depends on how much technology is actually transferred from firm 1:

$$T_2 = t_1 \cdot t_2$$

with $t_1 \in [0, 1]$ representing firm 1's rate of technology sharing, and $t_2 \in [0, 1]$ being firm 2's rate of adoption.

3 Socially Efficient Technology Diffusion

We first derive the necessary conditions for the efficient diffusion of technology when there are no costs associated with sharing or adopting technologies. In this case, the EPA aims to minimize the total social cost:

$$\min_{T_2, x_1, x_2} \ \mathrm{TSC}^0 \equiv C^1(x_1, 1) + C^2(x_2, T_2) + D(X).$$

It is obvious that the total social cost can always be reduced if firm 2 possesses a better technology for abatement:

$$\frac{\partial \mathrm{TSC}^0}{\partial T_2} = C_T^2(x_2, T_2) < 0.$$

As such, free diffusion of technology prescribes total technology diffusion:

$$T_2^* = t_1^* = t_2^* = 1,$$

and firm 2 should always embrace the best available technology. This requirement for full transfer comes as no surprise because improved technology can lower firms' marginal abatement costs for all emission levels, and hence is necessary for social cost-effectiveness. Meanwhile, the interior abatement choice $x_i^* \in (0, \bar{x}_i)$ must satisfy:

$$\begin{aligned} &(x_1^*) \quad C_x^1(x_1, 1) + D'(X) = 0, \\ &(x_2^*) \quad C_x^2(x_2, 1) + D'(X) = 0, \end{aligned} \tag{2}$$

which has the intuitive interpretation of the marginal abatement cost being equal to the marginal social damage.

If, instead, diffusion costs have to be incurred by both firms to bring about the transfer of technology, complete diffusion may no longer be socially desirable. Let c_i be the constant marginal cost that firm i has to expend to share (or adopt) a superior technology. The EPA goal, after incorporating these diffusion costs, becomes:

$$\min_{t_1,t_2,x_1,x_2} \quad \mathrm{TSC}^c \equiv C^1(x_1, 1) + C^2(x_2, t_1 t_2) + D(X) + c_1 t_1 + c_2 t_2.$$

The first-order necessary conditions thus become:

$$\begin{aligned}
&(t_1) \quad -t_2 \cdot C_T^2(x_2, t_1 t_2) = c_1,\\
&(t_2) \quad -t_1 \cdot C_T^2(x_2, t_1 t_2) = c_2,\\
&(x_1) \quad C_x^1(x_1, 1) + D'(X) = 0,\\
&(x_2) \quad C_x^2(x_2, t_1 t_2) + D'(X) = 0.
\end{aligned} \tag{3}$$

Apparently, unless c_i is extremely low, only partial diffusion $t_i^{**} \in (0, 1)$ is desired in an interior solution. The EPA now has to balance the costs of transferring technology with the abatement costs saved due to the improvement in firm 2's technology. To understand how the diffusion of technology affects the firms' emissions, we totally differentiate the two equations

$$\begin{aligned}
C_x^1(x_1, 1) + D'(x_1 + x_2) = 0,\\
C_x^2(x_2, T_2) + D'(x_1 + x_2) = 0,
\end{aligned}$$

with respect to three variables (x_1, x_2, T_2), and find that:

$$\frac{dx_1}{dT_2} > 0, \quad \frac{dx_2}{dT2} < 0, \quad \frac{d[x_1 + x_2]}{dT2} < 0. \tag{4}$$

The intuition behind the comparative statics results (4) runs as follows: since firm 2 possesses better abatement technology, its marginal cleanup cost $(-C_x^2(x_2, T_2))$ declines (by assumption (1)), and hence it should cause less pollution, leading to lower x_2. Meanwhile, as x_2 goes down, firm 1 faces a lower marginal damage $D'(X)$ for all levels of x_1, and hence should increase its pollution emission x_1. In aggregate, however, a better technology owned by firm 2 still leads to a reduction in total emission.

Further, total differentiation of the complete set of first-order conditions (3) yields:

$$\frac{dt_i}{dc_j} < 0, \quad i, j = 1, 2,$$

which indicates that higher diffusion costs for either firm will lower the efficient rate of diffusion, and ultimately lead to a higher aggregate level of pollution X. Therefore, the government is advised to provide platforms to facilitate inter-firm sharing of technology.

4 The Two-stage Decentralized Market Equilibrium

We next analyze the market interaction between the firms under a proportional liability rule. Contrary to the strict liability rule with the exogenous responsibility split as in Endres and Friehe (2011), we assume a more equitable rule, which dictates that polluting firms be obligated to compensate victims an amount proportional to their emission share:

$$\eta_i \equiv \frac{x_i}{x_1 + x_2}, \quad i = 1, 2.$$

In this case, the individual firm's liability will be:

$$F^i\left(x_1, x_2\right) = \eta_i \cdot D(X).$$

First proposed by John Makdisi in Makdisi (1988), the proportional liability rule has been much discussed in the past two decades by legal scholars (for example, Fischer (1993), Boyd and Ingberman (1996), and Green (2004)) as a way to incorporate 'causation' in tort case judgements. In Makdisi's words, "damage should be allocated in proportion to the probability of causation." Simply put, the idea is to make liability depend on the cause of the damage. In reality, proportional liability laws have already been adopted in many countries. For example, in Taiwan, parties involved in traffic accidents will be held responsible according to the level of their negligent behavior.

The interaction between firms can be modeled as a two-stage game. In Stage 1, both firms set their individual diffusion rate

$$(t_1, t_2)$$

simultaneously and independently. Subsequently in Stage 2, given (t_1, t_2), each firm chooses its emission level to minimize costs, including the costs of pollution abatement and victim compensation, again simultaneously and independently:

$$\min_{x_1} \; C^1(x_1, 1) + F^1(x_1, x_2) = C^1(x_1, 1) + \frac{x_1}{x_1 + x_2} \cdot D(x_1 + x_2), \tag{5}$$

$$\min_{x_2} \; C^2(x_1, T_2) + F^2(x_1, x_2) = C^2(x_2, t_1 t_2) + \frac{x_2}{x_1 + x_2} \cdot D(x_1 + x_2). \tag{6}$$

The reason for a Nash setting in Stage 2 is pure symmetry: both firms generate the same pollutants and jointly cause environmental damage, so there is no particular reason to employ a sequential setting.[1]

To solve for the subgame-perfect Stackelberg equilibrium backwards, we begin with the second stage. The interior stage-2 firm choices of emission $x_i(t_1, t_2)$ are implicitly defined by the first-order conditions:

$$(x_1) \quad C_x^1(x_1, 1) + \left[\frac{x_1}{x_1 + x_2} \cdot D'(X) + \frac{x_2}{[x_1 + x_2]^2} \cdot D(X) \right] = 0, \tag{7}$$

$$(x_2) \quad C_x^2(x_2, t_1 t_2) + \left[\frac{x_2}{x_1 + x_2} \cdot D'(X) + \frac{x_1}{[x_1 + x_2]^2} \cdot D(X) \right] = 0. \tag{8}$$

Back in Stage 1, firm choices (t_1, t_2) apparently will depend on the cost of technology diffusion.

With *costless* technology adoption, firm 2 will certainly set the maximal rate of adoption to reduce its abatement costs:

$$t_2 = 1.$$

As for firm 1, it would simply like to choose t_1 to

$$\min_{t_1} \; \mathrm{TC}^1 \equiv C^1(x_1(t_1, 1), 1) + \frac{x_1(t_1, 1)}{x_1(t_1, 1) + x_2(t_1, 1)} \times D(x_1(t_1, 1) + x_2(t_1, 1)). \tag{9}$$

If instead the diffusion of technology is *costly* with marginal diffusion cost c_i, the firms will now engage in a Nash game in Stage 1 to minimize respective

[1] For a sequential emission game in stage 2, firm 1 would have to pollute before firm 2, and not after firm 2. This scenario does not seem very plausible or appealing.

costs:

$$\min_{t_1} \ \mathrm{TC}_c^1 \equiv C^1\left(x_1\left(t_1,t_2\right),1\right)+\frac{x_1\left(t_1,t_2\right)}{X\left(t_1,t_2\right)}\times D\left(X\left(t_1,t_2\right)\right)+c_1t_1, \tag{10}$$

$$\min_{t_2} \ \mathrm{TC}_c^2 \equiv C^2\left(x_2\left(t_1,t_2\right),t_1t_2\right)+\frac{x_2\left(t_1,t_2\right)}{X\left(t_1,t_2\right)}\times D\left(X\left(t_1,t_2\right)\right)+c_2t_2. \tag{11}$$

Solving first-order conditions (10) and (11) simultaneously, the extent to which the firms are willing to share/adopt new technology can be found.

For concrete results, we consider in the following sub-sections first the standard case of linear pollution damage and then the more complicated case of increasing marginal damage.

4.1 Constant Marginal Damage

In reality, many pollutants, such as SO_2 (sulfur dioxide, the major industrial discharge causing acid rain) and CO_2 (carbon dioxide, the major cause of global warming) demonstrate the property of constant marginal damage to victims, including detrimental health effects as well as material losses. For these pollutants, the damage function is rightfully linear:

$$D(X)=kX, \quad k>0,$$

with k being the constant marginal damage. In what follows in this section, we derive equilibrium conditions for both cases of free and costly diffusion.

4.1.1 Free Diffusion of Technology

In the absence of diffusion costs, firm total costs (5) (6) become simply:

$$C^1\left(x_1,1\right)+\frac{x_1}{x_1+x_2}\cdot kX=C^1\left(x_1,1\right)+kx_1,$$
$$C^2\left(x_2,T_2\right)+\frac{x_2}{x_1+x_2}\cdot kX=C^2\left(x_2,T_2\right)+kx_2.$$

We know already that, when adoption of technology is free, firm 2 will choose the maximal technology adoption rate $t_2=1$. Given this, both firms, in Stage 2, intend to minimize respective costs:

$$\min_{x_1} \; C^1(x_1, 1) + kx_1,$$
$$\min_{x_2} \; C^2(x_2, t_1) + kx_2,$$

which yields the necessary MAC=MD conditions:

$$-C_x^1(x_1, 1) = k,$$
$$-C_x^2(x_2, t_1) = k.$$

It can be easily verified that:

$$\frac{dx_1}{dt_1} = 0,$$
$$\frac{dx_2}{dt_1} = -\frac{C_{xT}^2}{C_{xx}^2} < 0.$$

Therefore, the more firm 1 is willing to share its advanced technology (as manifested by a higher t_1), the better technology firm 2 will have at its disposal (and hence the less pollutants it will generate).

Back in Stage 1, with no diffusion costs, firm 1 is indifferent about its diffusion rate t_1. We might as well suppose good will and assume maximal release of technology:

$$t_1 = 1.$$

Thus, in the current case of free diffusion, the market outcome is efficient with complete technology diffusion:

$$T_2^* = t_1^* = t_2^* = 1.$$

This efficient result is intuitively straightforward, yet interestingly it is the only case in which the market outcome coincides with the social goal.

4.1.2 Costly Diffusion of Technology

Now consider the case in which diffusion of technology is costly for both firms, with marginal cost c_i. Firm 1, trying to minimize

$$\mathrm{TC}_c^1 \equiv C^1(x_1, 1) + kx_1 + c_1 t_1,$$

has no incentive to share its superior technology with firm 2, and will set

$$t_1 = 0,$$

leading to:

$$T_2 = t_1 \cdot t_2 = 0.$$

As a result, with no new technology available, firm 2's goal

$$\min \quad TC_c^2 \equiv C^2(x_2, 0) + kx_2 + c_2 t_2$$

dictates zero adoption efforts:

$$t_2 = 0.$$

Contrary to the efficient no-cost case analyzed in the previous subsection, the market outcome with costly diffusion is utterly inefficient, with absolutely no technology transfer at all. That is, no firm has an incentive to share, and no firm has an incentive to learn.

Note that, when pollution damage is linear, a firm's compensation liability depends only on its own emissions under the proportional liability rule. Consequently firm 1 cares nothing about firm 2's emission level, and has no incentive to share its superior technology as it is costly to do so. It is therefore the government's responsibility to promote the sharing of technology by providing economic incentives such as tax relief or diffusion subsidies to the leading firms.

4.2 Increasing Marginal Damage

We next turn to the situations in which pollution damage grows at increasing rates. Unlike SO_2 or CO_2 that cause linear harm, many pollutants, such as heavy metals, often inflict marginally increasing health hazards on pollution victims:

$$D'(X) > 0, \quad D''(X) > 0.$$

For analytical tractability, we consider the standard quadratic damage case:

$$D(X) = kX + \frac{sX^2}{2}, \quad k, s > 0.$$

In the following subsections, we again consider and compare two possible cases of diffusion cost: free versus costly diffusion.

4.2.1 Free Technology Diffusion

In the absence of diffusion costs, firm 2 has no reason not to adopt more advanced technologies available to it, and hence must set

$$\tilde{t}_2 = 1.$$

Therefore in Stage 2, firm objectives (5) (6) can be simplified as:

$$\min_{x_1} \; C^1(x_1, 1) + \left\{ kx_1 + \frac{sx_1[x_1 + x_2]}{2} \right\}, \tag{12}$$

$$\min_{x_2} \; C^2(x_2, t_1) + \left\{ kx_2 + \frac{sx_2[x_1 + x_2]}{2} \right\}. \tag{13}$$

And the firm-optimal emissions must satisfy the following first-order conditions, given t_1:

$$C_x^1(x_1, 1) + k + sx_1 + \frac{sx_2}{2} = 0, \tag{14}$$

$$C_x^2(x_2, t_1) + k + sx_2 + \frac{sx_1}{2} = 0, \tag{15}$$

from which we can derive some interesting comparative statics:

$$\frac{dx_1}{dt_1} = \frac{\frac{s}{2}C_{xT}^2}{C_{xx}^1 C_{xx}^2 + s\left[C_{xx}^1 + C_{xx}^2\right] + s^2 - \frac{s^2}{4}} > 0,$$

$$\frac{dx_2}{dt_1} = \frac{-\left[C_{xx}^1 + s\right]C_{xT}^2}{C_{xx}^1 C_{xx}^2 + s\left[C_{xx}^1 + C_{xx}^2\right] + s^2 - \frac{s^2}{4}} < 0,$$

$$\frac{dX}{dt_1} = \frac{-\left[C_{xx}^1 + \frac{s}{2}\right]C_{xT}^2}{C_{xx}^1 C_{xx}^2 + s\left[C_{xx}^1 + C_{xx}^2\right] + s^2 - \frac{s^2}{4}} < 0,$$

and

$$\frac{dD(X)}{dt_1} = D'(X) \cdot \frac{dX}{dt_1} < 0.$$

In words, these equations state that, as firm 1 renders more superior technology to firm 2, the latter will be induced to abate more pollution (x_2 goes down). In the mean time, however, firm 1 will find itself polluting more (x_1 goes up). The aggregate emissions X and the external damage $D(X)$ will nevertheless become lower.

As for firm 1's diffusion rate choice $\tilde{t}_1$ in Stage 1, we find that

$$\frac{d\mathrm{TC}^1}{dt_1} = C_x^1 \cdot \frac{dx_1}{dt_1} + \frac{d\left[\eta_i\left(t_1\right) \cdot D\left(X\left(t_1\right)\right)\right]}{dt_1} \gtreqless 0.$$

With a larger t_1, firm 1 can save on pollution control costs (due to the larger x_1). Change in its compensation payment, however, is ambiguous: though total damage $D(X)$ becomes smaller, its payment share η_1 $(= x_1/X)$ becomes larger. The result is partial diffusion on the part of firm 1:

$$\tilde{t}_1 \in (0, 1), \quad \tilde{t}_2 = 1, \quad \tilde{T}_2 = \tilde{t}_1 \cdot \tilde{t}_2 \in (0, 1),$$

which obviously deviates from the socially efficient full diffusion of $T_2^* = 1$.

Contrary to what we might expect from the free transfer assumption, firm 1 is still unwilling to fully share its technology even if doing so incurs no extra cost. As explained in the previous paragraph, helping sluggish firms will adversely raise the superior firms' liability as the former firms abate more emissions.

4.2.2 Costly Diffusion of Technology

We have shown in Section 3 that the social optimum in the presence of diffusion costs requires only a partial diffusion that satisfies conditions (3). Now with positive diffusion costs, firm objectives (12)(13) become:

$$\min_{x_1} \; C^1\left(x_1, 1\right) + \left\{kx_1 + \frac{sx_1\left[x_1 + x_2\right]}{2}\right\}, \tag{16}$$

$$\min_{x_2} \; C^2\left(x_2, t_1 t_2\right) + \left\{kx_2 + \frac{sx_2\left[x_1 + x_2\right]}{2}\right\}. \tag{17}$$

And the first-order conditions (14) (15) require only minor modification now with t_1 replaced with $t_1 t_2$ in (15):

$$C_x^1\left(x_1, 1\right) + k + sx_1 + \frac{sx_2}{2} = 0, \tag{18}$$

$$C_x^2\left(x_2, t_1 t_2\right) + k + sx_2 + \frac{sx_1}{2} = 0, \tag{19}$$

which define the firm emission choices as functions of the firm diffusion rates (t_1, t_2) set in Stage 1:

$$\hat{x}_1\left(t_1, t_2\right), \quad \hat{x}_2\left(t_1, t_2\right).$$

It can be noted, by comparing (18) (19) with (14) (15), that:

$$\frac{d\hat{x}_1}{dt_1} = \frac{t_2}{t_1} \cdot \frac{d\hat{x}_1}{dt_2} > 0,$$
$$\frac{d\hat{x}_2}{dt_1} = \frac{t_2}{t_1} \cdot \frac{d\hat{x}_2}{dt_2} < 0,$$

and

$$\frac{d\hat{X}}{dt_1} = \frac{t_2}{t_1} \cdot \frac{d\hat{X}}{dt_2} < 0,$$
$$\frac{dD\left(\hat{X}\right)}{dt_1} = \frac{t_2}{t_1} \cdot \frac{dD\left(\hat{X}\right)}{dt_2} < 0.$$

In Stage 1, the firms choose their diffusion rates by carrying out the calculations (10) and (11), respectively:

$$\min_{t_1} \ \mathrm{TC}_c^1 \equiv C^1\left(\hat{x}_1, 1\right) + \left\{k\hat{x}_1 + \frac{s\hat{x}_1\left[\hat{x}_1 + \hat{x}_2\right]}{2}\right\} + c_1 t_1, \tag{20}$$
$$\min_{t_2} \ \mathrm{TC}_c^2 \equiv C^2\left(\hat{x}_2, t_1 t_2\right) + \left\{k\hat{x}_2 + \frac{s\hat{x}_2\left[\hat{x}_1 + \hat{x}_2\right]}{2}\right\} + c_2 t_2. \tag{21}$$

The corresponding first-order conditions are:

$$\left[c_x^1 + k + s\hat{x}_1 + \frac{s\hat{x}_2}{2}\right] \cdot \frac{d\hat{x}_1}{dt_1} + \frac{s\hat{x}_1}{2} \cdot \frac{d\hat{x}_2}{dt_1} = -c_1, \tag{22}$$
$$\left[c_x^2 + k + s\hat{x}_2 + \frac{s\hat{x}_1}{2}\right] \cdot \frac{d\hat{x}_2}{dt_2} + \frac{s\hat{x}_2}{2} \cdot \frac{d\hat{x}_1}{dt_2} + t_1 C_T^2 = -c_2. \tag{23}$$

To see how diffusion costs may affect firm incentives with regard to technology sharing/adoption, we conduct comparative statics on (22) and (23) and find:

$$\frac{d\hat{t}_1}{dc_1} < 0, \quad \frac{d\hat{t}_2}{dc_1} < 0, \quad \forall c_1 > 0,$$
$$\frac{d\hat{t}_1}{dc_2} < 0, \quad \frac{d\hat{t}_2}{dc_2} < 0, \quad \forall c_2 > 0.$$

It is intuitively clear, for the interior case, that higher diffusion costs will dampen firm enthusiasm for transferring technology. Therefore, the technology diffusion process can only be partial when it is costly, and will be even less than in the free diffusion case:

$$\hat{t}_1 < \tilde{t}_1 < 1,$$
$$\hat{t}_2 < \tilde{t}_2 = 1.$$

As diffusion costs lessen the firms' incentives to share technology, it will be up to the EPA to provide proper channels for firms to easily transfer abatement technology. One possibility is to have the EPA act as an information and technology intermediary.

5 Conclusions and Policy Implications

We investigate the interaction between firms with different states of technology under the proportional liability rule. Our findings can be summarized in the table below:

		Market Equilibrium	
Tech Diffusion	Social Optimum	Linear Damage	Increasing Damage
Free	Complete	Complete	Partial
	$(t_1^* = t_2^* = 1)$	$(t_1 = t_2 = 1)$	$(\tilde{t}_1 < 1, \tilde{t}_2 = 1)$
Costly	Partial	Zero	Partial
	$(t_1^{**}, t_2^{**} < 1)$	$(t_1 = t_2 = 0)$	$(\hat{t}_1, \hat{t}_2 < 1)$

It is found that, when pollution damage is linear, the market outcome is always at a corner. We have either full technology transfer (in the absence of diffusion costs), or no transfer at all (in the presence of diffusion costs). The former coincides with social efficiency, whereas the latter does not.

If instead marginal pollution damage is increasing, market equilibrium will always be an interior solution (diffusion rate $t_i \in (0, 1)$), whether diffusion is costly or not. The transfer is only partial, and the extent of the transfer falls below the socially efficient level. Firms do have some incentive to diffuse/adopt advanced technology, but the incentive diminishes as its cost (c_i) rises.

With the above findings, it is clear that appropriate government policies will depend on the functional form of the damage. With linear damage and free transfer, market diffusion is complete and efficient, and hence there is no need for EPA intervention. In other cases especially with increasing damage, market outcomes are always inefficient; so it is up to the EPA to provide economic incentives to promote social efficiency. The government should either force firms to diffuse superior technology for pollution abatement (i.e., direct control) or provide economic incentives (e.g., a subsidy for diffusion, or a tax for insufficient diffusion).

Though inspired by Endres and Friehe (2011), this current paper establishes two results fundamentally different from theirs. Firstly, our findings are applicable to the proportional liability rule, as opposed to their strict liability and negligence rules, and hence provide a different perspective on the issue of voluntary technology transfer. Secondly, the efficiency of market equilibrium in our model depends crucially on the structure of the pollution damage function as well as the existence/absence of the cost of technology transfer, which is lacking in Endres and Friehe (2011). It is therefore our hope that this paper offers a more rounded, if not full-fledged, model of environmental technology diffusion.

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比例責任制下廠商防汙技術移轉之誘因

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本文分析兩污染廠商間之技術移轉決策。其中擁有較先進防汙技術之廠商須決定要分享多少技術給落後的廠商, 而技術落後的廠商則須決定要採納多少先進廠商所釋放出來的技術。本文和既存文獻的分析有兩點主要差異: 首先, 本文探討「比例責任制」的廠商汙染傷害賠償, 而非文獻常假設的「嚴格責任」或「過失主義」。其次, 本文模型中加入技術移轉成本, 此爲過去文獻所無。本文發現, 廠商防汙技術之分享與接納程度均與汙染傷害之函數型式和技術移轉成本有關。只有當汙染傷害爲線型, 且技術移轉沒有成本時, 市場均衡才具有效率性。否則, 均衡下之廠商技術移轉程度皆低於社會最適。

關鍵詞: 汙染排放, 技術移轉, 比例責任制
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