Discussion Papers In Economics And Business

Environmental Technology Transfer in a Cournot Duopoly: The Case of Fixed-Fee Licensing

Akira Miyaoka

Discussion Paper 14-08

Graduate School of Economics and
Osaka School of International Public Policy (OSIPP)
Osaka University, Toyonaka, Osaka 560-0043, JAPAN

Environmental Technology Transfer in a Cournot Duopoly: The Case of Fixed-Fee Licensing

Akira Miyaoka

Discussion Paper 14-08

February 2014

Graduate School of Economics and
Osaka School of International Public Policy (OSIPP)
Osaka University, Toyonaka, Osaka 560-0043, JAPAN

Environmental Technology Transfer in a Cournot Duopoly: The Case of Fixed-Fee Licensing*

Akira Miyaoka†

Abstract

This study considers a Cournot duopoly market in which a clean firm can transfer its less polluting technology to a dirty firm through a fixed-fee licensing contract. We analyze the impacts of emissions taxes on the incentives of firms to transfer technology as well as on the total pollution level, and examine the properties of the optimal emissions tax policy. We first show that higher emissions taxes weaken incentives for technology transfer and that this can lead to a perverse increase in the level of total pollution. We then compare the optimal emissions tax when technology licensing is possible with that when licensing is infeasible and show that the relationship between the optimal tax rate and the degree of the initial technology gap between firms when licensing is possible can be the opposite of that when licensing is infeasible.

JEL Classification: L13, L24, Q58

Keywords: Technology transfer; Cournot duopoly; Pollution; Emissions tax

---

*This paper previously circulated under the title "Emission Taxes and Environmental Technology Transfer." I especially thank Shingo Ishiguro, Kenzo Abe, Noriaki Matsushima, Katsuya Takii, Hiroaki Ino, Hiroshi Kitamura, Shuichi Ohori, Takayoshi Shinkuma, Leonard F.S. Wang, Akihiko Yanase, and the conference participants at the Japanese Association for Applied Economics, the Japanese Economic Association, and the Society for Environmental Economics and Policy Studies for helpful discussions and comments. I gratefully acknowledge financial support from the Japan Society for the Promotion of Science and the Global COE program "Human Behavior and Socioeconomic Dynamics" of Osaka University. The usual disclaimer applies.

†Graduate School of Economics, Osaka University, 1-7 Machikaneyama, Toyonaka, Osaka, 560-0043, Japan. E-mail: jge013ma@mail2.econ.osaka-u.ac.jp.

1 Introduction

To mitigate against environmental degradation, an important concern for policy makers is the diffusion of environmentally friendly technology. Although there are several channels through which environmental technology can be distributed, one of the most important is the transfer of technology among firms through licensing contracts. In fact, private firms often strategically license their superior technologies to both domestic and foreign rivals. For example, the famous Japanese automobile manufacturer Toyota Motor Corporation entered a licensing agreement with another automobile manufacturer, Mazda Motor Corporation, thus transferring its superior environmental technology. This also occurs in the chemical industry, where some leading firms in the polyethylene market, such as British Petroleum (BP) Chemicals and Dow Chemical, have licensed their less polluting technology to other firms.

In this study, we analyze the effects of emissions taxes and the properties of the optimal tax rate in the presence of environmental technology transfer between firms through fixed-fee licensing. We consider a Cournot duopoly model in which one firm has a cleaner technology and emits less pollution in its production process than another firm. Before the competition stage, the clean firm can transfer its superior technology to the dirty firm via a licensing contract. If technology transfer is successful, the dirty firm obtains a clean technology in exchange for a fixed licensing fee.

In this setting, we first analyze the effects of an emissions tax on the incentives of firms to transfer technology as well as on the level of total pollution. We show that a higher emissions tax makes the transfer of technology less likely and can lead to a perverse increase in the total pollution level. We then explore the properties of the optimal emissions tax when licensing is possible by comparing it with the case when licensing is infeasible. We find that the possibility of licensing can reverse the relationship between the optimal emissions tax rate and the extent of the initial technology gap between firms: as a dirty technology becomes more polluting, the optimal emissions tax is (weakly) decreasing when licensing is possible, while it is increasing when licensing is infeasible.

Although a few recent studies investigate environmental technology transfer via licensing contracts, most of them consider international technology transfers between domestic and foreign firms (Iida and Takeuchi 2009, 2011; Qiu and Yu 2009; Asano and Matsushima forthcoming).[1] In contrast, the present study explores technology transfers between two domestic firms, which may also be an important policy concern. In our setting, since an emissions tax set by the government is levied on both the licenser and licensee firms, the effects and properties of the optimal tax policy differ from those of the studies mentioned above, in which a tax set by the government of one country is only levied on either the licenser or licensee firm that is located in that country.

The most similar study to ours is Chang et al. (2009), which focuses on the licensing of less polluting technologies between two domestic firms and compares two licensing methods, fixed-fee and royalty licensing. Although their analysis is similar to ours, they mainly focus on the case of royalty licensing. The present study complements their work by providing a more detailed analysis of fixed-fee licensing. We provide a full characterization of the optimal emissions tax in the case of fixed-fee licensing by considering not only an interior solution but also a corner solution, which is not included in their study. We also compare the optimal tax rates when technology licensing is and is not possible and clarify the novel properties of the optimal emissions tax in the presence of technology licensing, neither of which is mentioned in the work of Chang et al.

Our study is also related to the literature on optimal emissions taxes under oligopolistic competition (see Requate (2006) for a survey). In particular, Simpson (1995) analyzes the optimal emissions tax in an asymmetric duopoly setting, in which the environmental technologies of both firms are exogenously fixed. In contrast to his study, we assume that the dirty firm can obtain cleaner technology through a licensing contract and show that the possibility of technology transfer can alter the properties of the optimal emissions tax set by the government.

The remainder of this study is organized as follows. Section 2 sets up the model and derives firm equilibrium outputs and profits. Section 3 considers the conditions under which technology transfer occurs. Section 4 examines the relationship between the emissions tax rate and the level of total pollution. Section 5 derives a socially optimal emissions tax rate

[1] The licensing of cost-reducing innovations has been extensively analyzed in the industrial organization literature (Gallini and Winter 1985; Katz and Shapiro 1985; Kamien and Tauman 1986; Marjit 1990; Wang 1998, 2002).

and discusses its properties. Section 6 provides concluding remarks. The proofs of some results are provided in the Appendix.

2 The model

We consider a market consisting of two heterogeneous firms, one clean (firm 1) and one dirty (firm 2), that produce a homogeneous product. Firm 1 emits e_1 units of pollution per unit of output, whereas firm 2 emits a higher level of pollution, i.e., $e_2 > e_1$, per unit of output. For simplicity, the production costs of both firms are assumed to be zero. The inverse demand function is given by $P = 1 - (x_1 + x_2)$, where P denotes the market price, x_i denotes the output level of firm $i \in \{1, 2\}$.

We employ a three-stage game. In Stage 1, the government sets a (uniform) emissions tax to maximize social welfare. In Stage 2, firm 1, which has a clean technology, decides whether to license its superior technology to firm 2. If technology transfer occurs, both firms 1 and 2 have a clean technology. Otherwise, firm 2's technology remains dirty. In Stage 3, both firms compete *à* la Cournot given the technology inherited from Stage 2.

We solve the game backwards. First, we derive the Cournot equilibrium in Stage 3 when the technology transfer has occurred in Stage 2. In this case, since both firms have a clean technology, firm i's profit (gross of licensing fee) in Stage 3 is given by:

$$\Pi_i = (1 - x_1 - x_2)x_i - te_1x_i, \quad i = 1, 2,$$

where t denotes an emissions tax imposed per unit of emissions. Assuming a symmetric equilibrium, the equilibrium output and profit are, respectively,

$$x_i^T = \frac{1 - e_1t}{3}, \quad \pi_i^T = \frac{(1 - e_1t)^2}{9}, \quad i = 1, 2. \tag{1}$$

Next, we derive the Cournot equilibrium when firm 1's clean technology has not been transferred to firm 2 in Stage 2. In this case, the profit of firm i in Stage 3 is given by:

$$\Pi_i = (1 - x_1 - x_2)x_i - te_ix_i, \quad i = 1, 2.$$

Note that since firm 2's technology remains dirty, firm 2 emits e_2 units of pollution per unit of output. Then, the equilibrium output and profit are, respectively,

$$x_1^N = \frac{1-(2e_1-e_2)t}{3}, \qquad x_2^N = \frac{1-(2e_2-e_1)t}{3}; \tag{2}$$

$$\pi_1^N = \frac{(1-(2e_1-e_2)t)^2}{9}, \quad \pi_2^N = \frac{(1-(2e_2-e_1)t)^2}{9}. \tag{3}$$

When the emissions tax rate is too high ($t \geq \overline{t}(e_1, e_2) \equiv 1/(2e_2 - e_1)$), firm 2 exits the market and firm 1 becomes a monopoly. In this case, the firms' equilibrium output and profit are, respectively,

$$x_1^M = \frac{1-e_1 t}{2}, \quad x_2^M = 0; \quad \pi_1^M = \frac{(1-e_1 t)^2}{4}, \quad \pi_2^M = 0. \tag{4}$$

3 Licensing and technology transfer

In this section, we analyze the licensing stage. This study focuses on a fixed-fee licensing contract and assumes that firm 1 (licenser) has all the bargaining power. At this stage, firm 1 first offers firm 2 a fixed licensing fee F, which is independent of firm 2's output, in a take-it-or-leave-it manner. If firm 2 accepts this offer, then firm 1 charges F and licenses its clean technology to firm 2. If firm 2 rejects the offer, licensing does not occur and firm 2's technology remains dirty.

First, if $0 \leq t < \overline{t}(e_1, e_2)$, since firm 2's equilibrium profit without licensing is π_2^N, the maximum licensing fee firm 1 can charge is $F = \pi_2^T - \pi_2^N$. Then, if licensing occurs, firm 1's total profit is

$$\pi_1^T + F = \pi_1^T + (\pi_2^T - \pi_2^N) = \frac{(1-e_1 t)^2}{9} + \frac{4(1-e_2 t)(e_2 - e_1)t}{9}. \tag{5}$$

From (3) and (5), we have that $\pi_1^T + F > \pi_1^N$ if and only if $0 \leq t \leq \hat{t}(e_1, e_2) \equiv 2/(5e_2 - 3e_1)$. Therefore, firm 1 licenses its technology if $0 \leq t \leq \hat{t}(e_1, e_2)$ but does not if $\hat{t}(e_1, e_2) < t < \overline{t}(e_1, e_2)$.

Second, if $t \geq \overline{t}(e_1, e_2)$, when technology licensing does not occur, firm 2 exits the market and its equilibrium profit is $\pi_2^M = 0$. Then, the maximum licensing fee firm 1 can charge is $F = \pi_2^T - \pi_2^M$, and firm 1's total profit under licensing becomes

$$\pi_1^T + F = \pi_1^T + (\pi_2^T - \pi_2^M) = \frac{2(1-e_1 t)^2}{9}. \tag{6}$$

Comparing (4) and (6), we always obtain $\pi_1^T + F < \pi_1^M$. Therefore, for $t \geq \bar{t}(e_1, e_2)$, firm 1 does not have an incentive to license its clean technology and consequently becomes a monopoly. To summarize these results, we have the following proposition.

Proposition 1. *Firm 1 licenses its clean technology if and only if* $0 \leq t \leq \hat{t}(e_1, e_2)$.

[Figure 1 about here.]

The reason that licensing does not occur under a high emissions tax is as follows. Note that technology licensing occurs if and only if the joint profit of the two firms with licensing, $\pi_1^T + \pi_2^T$, is higher than that without licensing, $\pi_1^N + \pi_2^N$ (or $\pi_1^M + \pi_2^M$). When the tax rate is high and there is no licensing, firm 2's market share is very small (or zero) and firm 1 has an almost (or complete) monopoly. In this case, the joint profit of the two firms is close (or equal) to the monopoly profit of firm 1. In contrast, when licensing occurs, the joint profit becomes smaller than that without licensing because firm 2 obtains a clean technology and the market becomes more competitive. Therefore, under a high emissions tax, firm 1's clean technology is not licensed.[2] In Figure 1, the shaded area indicates the pair (t, e_2) such that technology transfer takes place.

4 The level of pollution

In this section, we focus on the level of aggregate pollution, denoted by E, and examine the relationship between the pollution level and emissions tax rate. First, if $0 \leq t \leq \hat{t}(e_1, e_2)$, licensing occurs and both firms have a clean technology. Therefore, by using (1), the level of pollution in this case, $E^T(t)$, becomes

$$E^T(t) = e_1(x_1^T + x_2^T) = \frac{2e_1(1 - e_1 t)}{3}. \tag{7}$$

[2]As shown in Chang et al. (2009), if we assume a per-unit output royalty instead of a fixed licensing fee, since firm 1 (licenser) can manipulate the output of firm 2 (licensee) through a per-unit royalty rate, the former can extract all the incremental profit of the latter while maintaining the latter's output at the same level as it would be without licensing. Therefore, for any emissions tax rate, technology licensing via royalty licensing always occurs in equilibrium, and firm 1 always prefers royalty licensing to fixed-fee licensing. However, there are situations in which it is difficult for firm 1 to use royalty licensing. For example, once firm 2 has the licensed technology, it may be able to imitate the technology and produce output with the imitation, thereby avoiding per-unit charges. In this case, firm 1 is restricted to fixed-fee licensing, which is independent of firm 2's output (Katz and Shapiro 1985).

Next, if $\hat{t}(e_1, e_2) < t < \bar{t}(e_1, e_2)$, the technology is not transferred but firm 2 is active in the market. Since firm 2's technology remains dirty and the outputs are given by (2), the level of pollution in this case, $E^N(t)$, is given by

$$E^N(t) = e_1 x_1^N + e_2 x_2^N = \frac{(e_1 + e_2) - 2(e_1^2 - e_1 e_2 + e_2^2)t}{3}. \tag{8}$$

Finally, if $t \geq \bar{t}(e_1, e_2)$, firm 2 exits the market and firm 1 becomes a monopoly. By using (4), the level of pollution in this case, $E^M(t)$, is given by

$$E^M(t) = e_1 x_1^M = \frac{e_1(1 - e_1 t)}{2}.$$

From these equations, it is easy to see that a higher emissions tax t decreases the level of aggregate pollution in each case. However, since an emissions tax above $\hat{t}(e_1, e_2)$ undermines the incentive for technology to be transferred between firms, as shown in Proposition 1, a higher emissions tax can have a perverse effect on aggregate pollution. More precisely, we obtain the following result.

Proposition 2. *When $e_2 > 3e_1$, the level of pollution jumps to $t = \hat{t}(e_1, e_2)$ and the relationship between the emissions tax and the level of pollution is non-monotonic.*

[Figure 2 about here.]

Figure 2 illustrates the relationship between the emissions tax and the pollution level when $(e_1, e_2) = (1, 5)$. The failure of technology licensing caused by a higher emissions tax has two opposing effects on total emissions. Although it reduces the total output of both firms, it increases firm 2's pollution level per unit of output. When the initial technology gap between firms is sufficiently large ($e_2 > 3e_1$), even a relatively low emissions tax prevents technology licensing. At such a low tax rate, the former effect is smaller and dominated by the latter. Therefore, an increase in the emissions tax above $\hat{t}(e_1, e_2)$ results in a perverse increase in total emissions.

A similar result is also obtained by Roy Chowdhury (2008), but his result is driven by the endogeneity of the market structure. In his study, under a high emissions tax, firms opt for Cournot competition, whereas under a low tax rate, firms prefer to form joint ventures.

Therefore, an increase in the emissions tax can trigger a regime switch from joint ventures to Cournot competition, which makes the market more competitive and can cause the pollution level to increase.

5 The optimal emissions tax

In this section, we derive the socially optimal emissions tax rate and explore its properties. In particular, we focus on the relationship between the optimal emissions tax rate and the extent of the initial technology gap between two firms. In the analysis below, we therefore consider e_1 to be fixed and interpret $e_2 \in (e_1, \infty)$ as the extent of the initial technology gap between two firms.[3]

In Stage 1, the government sets an emissions tax that maximizes social welfare W, which consists of the consumer surplus CS, the producer surplus PS, tax revenues T, and the environmental damage D caused by total pollution:

$$W = CS + PS + T - D.$$

This study assumes that $D = d \cdot E$, where d is the constant marginal damage from total emissions. In addition, because of linear demand, we have $CS = (x_1 + x_2)^2/2$. Below, we first derive the locally optimal tax rate in each of the following three cases: $0 \leq t \leq \hat{t}(e_2)$, $\hat{t}(e_2) < t < \overline{t}(e_2)$, and $t \geq \overline{t}(e_2)$. Then, by comparing the maximum level of welfare in each case, we derive the globally optimal emissions tax rate.

First, for $0 \leq t \leq \hat{t}(e_2)$, in which technology transfer takes place, the government chooses t to solve the following welfare maximization problem:

$$\max_{t \leq \hat{t}(e_2)} W^T(t) \equiv \frac{1}{2}\left(x_1^T + x_2^T\right)^2 + \left(\pi_1^T + \pi_2^T\right) + tE^T - dE^T.$$

Assuming an interior solution, we obtain the optimal tax rate and the corresponding level of social welfare as follows:

$$t^T = \frac{3e_1 d - 1}{2e_1}, \quad W^T(t^T) = \frac{(1 - e_1 d)^2}{2}. \tag{9}$$

[3] We therefore exclude e_1 from the arguments of the functions in this section.

We assume that $0 < t^T < 1/e_1$, or, equivalently, that $1/(3d) < e_1 < 1/d$. This implies that at this interior solution, it is optimal for the government to levy a positive emissions tax (rather than provide a subsidy) such that the equilibrium outputs of both firms, given by (1) with $t = t^T$, are positive. Since (9) is valid as long as $t^T \leq \hat{t}(e_2)$, the optimal tax when $t^T > \hat{t}(e_2)$ is given by $\hat{t}(e_2)$.

Second, in the case of $t \geq \bar{t}(e_2)$, firm 2 exits the market and firm 1 becomes a monopoly. In this case, the government solves the following problem:

$$\max_{t \geq \bar{t}(e_2)} W^M(t) \equiv \frac{1}{2}\left(x_1^M\right)^2 + \pi_1^M + tE^M - dE^M.$$

Assuming an interior solution, the optimal tax and the corresponding welfare level are, respectively,

$$t^M = \frac{2e_1 d - 1}{e_1}, \quad W^M(t^M) = \frac{(1 - e_1 d)^2}{2}. \tag{10}$$

We assume that $0 < t^M < 1/e_1$, or, equivalently, that $1/(2d) < e_1 < 1/d$, which implies that at this interior solution, it is optimal for the government to impose a positive emissions tax such that firm 1's equilibrium output, given by (4) with $t = t^M$, is positive. Since this assumption also guarantees that $0 < t^T < 1/e_1$, we assume that $1/(2d) < e_1 < 1/d$ in the following analysis. Note that (10) is valid as long as $t^M \geq \bar{t}(e_2)$. Therefore, when $t^M < \bar{t}(e_2)$, the optimal emissions tax becomes $\bar{t}(e_2)$.

Finally, for $\hat{t}(e_2) < t < \bar{t}(e_2)$, technology transfer does not occur but firm 2 is still active in the market. Then, the government's problem is as follows:

$$\max_{\hat{t}(e_2) < t \leq \bar{t}(e_2)} W^N(t, e_2) \equiv \frac{1}{2}\left(x_1^N + x_2^N\right)^2 + \left(\pi_1^N + \pi_2^N\right) + tE^N - dE^N. \tag{11}$$

Assuming an interior solution, the optimal tax and the corresponding welfare level are, respectively,

$$t^N(e_2) = \frac{6d(e_1^2 + e_2^2 - e_1 e_2) - (e_1 + e_2)}{(e_1 + e_2)^2}, \tag{12}$$

$$W^N(t^N(e_2), e_2) = \frac{(e_1 + e_2)^2 - 2d(e_1 + e_2)(e_1^2 + e_2^2) + 4d^2(e_1^2 - e_1 e_2 + e_2^2)^2}{2(e_1 + e_2)^2}. \tag{13}$$

Since (12) and (13) are valid as long as $\hat{t}(e_2) < t^N(e_2) < \bar{t}(e_2)$, the maximum level of welfare could be attained at a corner solution, $\hat{t}(e_2) + \epsilon$ or $\bar{t}(e_2) - \epsilon$, where $\epsilon > 0$ is an infinitesimally small number.

Now, by comparing the maximized welfare levels in the three cases above, we derive the (globally) optimal emissions tax rate for a given e_2. First, we have the following lemma.

Lemma 1. *Suppose that* $1/(2d) < e_1 < 1/d$. *Then, the following inequality holds for any* $e_2 > e_1$*:*

$$\max_{\hat{t}(e_2)<t<\bar{t}(e_2)} W^N(t, e_2) \le \max\{\max_{0\le t\le \hat{t}(e_2)} W^T(t), \max_{t\ge \bar{t}(e_2)} W^M(t)\}. \tag{14}$$

Lemma 1 implies that from the government's perspective, it can never be socially optimal to set an emissions tax rate that allows firm 2 to be active without technology licensing. In other words, social welfare is maximized under either a duopoly that includes technology transfer or a monopoly by firm 1. Therefore, in order to derive the socially optimal tax rate, we only have to compare the levels of welfare under these two conditions. Then, we obtain the optimal emissions tax under the possibility of technology licensing as follows.

Proposition 3. *Suppose that* $1/(2d) < e_1 < 1/d$. *Then, when technology licensing is possible, the optimal emissions tax,* $t^*(e_2)$*, and the resultant licensing decision are given by:*

$$t^*(e_2) = \begin{cases} t^T & \text{if } e_1 < e_2 \le \hat{e}, \quad \text{licensing occurs}, \\ \hat{t}(e_2) & \text{if } \hat{e} < e_2 \le \tilde{e}, \quad \text{licensing occurs}, \\ \bar{t}(e_2) & \text{if } \tilde{e} < e_2 \le \bar{e}, \quad \text{no licensing}, \\ t^M & \text{if } \bar{e} < e_2, \quad \text{no licensing}, \end{cases} \tag{15}$$

where $\hat{e}$, $\tilde{e}$, *and* $\bar{e}$ *are defined, respectively, such that* $t^T = \hat{t}(\hat{e})$, $W^T(\hat{t}(\tilde{e})) = W^M(\bar{t}(\tilde{e}))$, *and* $t^M = \bar{t}(\bar{e})$.

[Figure 3 about here.]

In Figure 3, the bold line represents the relationship between the optimal emissions tax rate and the initial technology gap between firms, which is measured by firm 2's initial technology level, e_2. When the environmental technology gap is sufficiently small such that $e_2 \in (e_1, \hat{e}]$, since technology licensing occurs even under a relatively high emissions tax, the government can induce licensing to occur between firms while setting t^T, which is the unconstrained optimal tax rate under licensing. However, as the technology gap widens, the government cannot implement this outcome because for a larger e_2, licensing no longer occurs under t^T. Then, for $e_2 \in (\hat{e}, \tilde{e}]$, it is optimal for the government to set a lower tax rate,

$\hat{t}(e_2)$, to induce technology licensing. If the technology gap becomes even wider ($e_2 > \tilde{e}$), the government prefers to give up the possibility of technology transfer and drive firm 2 out of the market. For $e_2 \in (\tilde{e}, \overline{e}]$, since firm 2's technology is not extremely dirty, the government must set a sufficiently high emissions tax, $\overline{t}(e_2)$, in order to induce firm 2 to exit the market. However, when firm 2 is sufficiently dirty such that $e_2 > \overline{e}$, the government can drive firm 2 out of the market by setting t^M, which is the unconstrained optimal tax rate under a monopoly by firm 1.

Then, we compare the optimal tax rates between when technology licensing is possible and when it is infeasible. When technology licensing is not possible, firm 2's technology always remains dirty. In this case, the optimal emissions tax rate is given by the next lemma.

Lemma 2. *Suppose that $1/(2d) < e_1 < 1/d$. Then, when technology licensing is infeasible, the optimal emissions tax, $t^{**}(e_2)$, is given by:*

$$t^{**}(e_2) = \begin{cases} t^N(e_2) & \text{if } e_1 < e_2 \leq e', \\ \overline{t}(e_2) & \text{if } e' < e_2 \leq \overline{e}, \\ t^M & \text{if } \overline{e} < e_2, \end{cases} \tag{16}$$

where e' is defined such that $t^N(e') = \overline{t}(e')$.

In Figure 3, the dashed line illustrates the optimal emissions tax given by (16) in the absence of the possibility of technology licensing.[4] If firm 2's initial technology is not very dirty ($e_2 \leq e'$), the optimal policy is to set $t^N(e_2)$ and allow both firms to operate in the market. However, if firm 2's technology is sufficiently dirty ($e_2 > e'$), it is socially desirable to drive firm 2 out of the market.

Now, from Proposition 3 and Lemma 2, we obtain the following proposition.

Proposition 4. *Suppose that $1/(2d) < e_1 < 1/d$. Then, the relationship between the optimal emissions tax rate and the degree of the initial technology gap between firms when technology licensing is possible can be the opposite of that when licensing is infeasible. More precisely, while $t^{**}(e_2)$ is increasing in $e_2 \in (e_1, e']$, $t^*(e_2)$ is (weakly) decreasing in $e_2 \in (e_1, \tilde{e}]$.*

Proposition 4 implies that the possibility of technology licensing can alter the properties of the optimal emissions tax. When licensing is infeasible, as firm 2's initial technology becomes dirtier, it is socially optimal for the government to set a higher emissions tax and shift

[4] Depending on the values of e_1 and d, $\hat{e}$ can be larger than e'. Figure 3 illustrates the case of $\hat{e} < e'$.

market share from the dirty firm (firm 2) to the clean one (firm 1). Therefore, as long as both firms produce positive outputs for $e_2 \in (e_1, e']$, the optimal emissions tax $t^{**}(e_2)$ is increasing in e_2. In contrast, when technology licensing is possible, the government must choose the emissions tax rate while considering its effect on the possibility of licensing between firms. In particular, for $e_2 \in (\hat{e}, \tilde{e}]$, since licensing no longer occurs under t^T, it is socially optimal for the government to set a lower emissions tax in order to induce the licensing of technology between firms. Therefore, while the optimal emissions tax $t^*(e_2)$ is constant for $e_2 \in (e_1, \hat{e}]$, it is decreasing for $e_2 \in (\hat{e}, \tilde{e}]$.[5]

6 Concluding remarks

This study examines the impacts of an emissions tax and the properties of the optimal tax rate in the presence of environmental technology transfers between firms through fixed-fee licensing contracts. We show that a higher emissions tax makes technology licensing between firms less likely and can result in a perverse increase in the level of aggregate pollution. We also show that the relationship between the optimal emissions tax rate and the degree of the initial technology gap between firms when licensing is possible can be the opposite of that when licensing is infeasible.

These results clarify that when less-polluting technologies can be transferred between firms via fixed-fee licensing, there can be a trade-off between a strict environmental policy and the wide diffusion of superior environmental technologies, which significantly affects the properties of the optimal emissions tax. Our results imply that in order to design appropriate environmental policies, governments should pay attention to whether superior environmental technologies can be diffused in the market in question and through which channels. Otherwise, government policies could have adverse impacts on both the environment and social welfare.

[5] If we consider e_2 to be fixed and interpret $e_1 \in (1/(2d), \min\{e_2, 1/d\})$ as the extent of the initial technology gap, the relationship between the optimal emissions tax and the degree of the initial technology gap becomes a bit more complicated. However, we can also obtain a result similar to Proposition 4 in that case. If technology licensing is possible, since $\partial t^T/\partial e_1 > 0$ and $\partial \hat{t}/\partial e_1 > 0$, the optimal emissions tax when both firms are active is decreasing as e_1 becomes smaller. In contrast, from (12), we can confirm that $\partial t^N/\partial e_1 < 0$ holds for a sufficiently small e_1. Therefore, if licensing is infeasible, the optimal emissions tax when both firms are active can be increasing as e_1 becomes smaller.

Appendix

Proof of Proposition 2

The aggregate pollution level increases discontinuously at $t = \hat{t}(e_1, e_2)$ if and only if

$$E^T(\hat{t}(e_1, e_2)) < \lim_{t \to \hat{t}(e_1,e_2)} E^N(t). \tag{17}$$

From (7), (8), and $\hat{t}(e_1, e_2) = 2/(5e_2 - 3e_1)$, we have

$$E^T(\hat{t}(e_1, e_2)) = \frac{10e_1(e_2 - e_1)}{3(5e_2 - 3e_1)}; \quad \lim_{t \to \hat{t}(e_1,e_2)} E^N(t) = \frac{(e_2 - e_1)(7e_1 + e_2)}{3(5e_2 - 3e_1)}. \tag{18}$$

By substituting (18) into (17) and rearranging it, we obtain $e_2 > 3e_1$. ■

Proof of Lemma 1

To begin the proof, we first introduce the following two lemmas:

Lemma 3. *Suppose that* $1/(2d) < e_1 < 1/d$. *Then, we have*

$$\max_{0 \le t \le \hat{t}(e_2)} W^T(t) \lesseqgtr \max_{t \ge \overline{t}(e_2)} W^M(t) \quad \textit{if and only if} \quad e_2 \gtreqless \tilde{e}. \tag{19}$$

Lemma 4. *Suppose that* $1/(2d) < e_1 < 1/d$. *Then,* $t^N(e_2)$ *and* $W^N(t^N(e_2), e_2)$ *have the following properties:*

(a) $t^N(e_2)$ *is increasing in* e_2 *and* $\lim_{e_2 \to e_1} t^N(e_2) = t^T$.

(b) $\lim_{e_2 \to e_1} W^N(t^N(e_2), e_2) = W^T(t^T)$.

(c) There exists $\underline{e} \in (e_1, \infty)$ *such that* $W^N(t^N(e_2), e_2)$ *is decreasing in* $e_2 \in (e_1, \underline{e}]$ *and increasing in* $e_2 \in (\underline{e}, \infty)$.

Proof of Lemma 3

Since $\hat{t}(e_2)$ is decreasing in $e_2 \in (e_1, \infty)$ and $0 < \hat{t}(e_2) < 1/e_1$, there exists

$$\hat{e} = \frac{e_1(9e_1 d + 1)}{5(3e_1 d - 1)}, \tag{20}$$

which satisfies $t^T = \hat{t}(\hat{e})$. Similarly, since $\bar{t}(e_2)$ is decreasing in $e_2 \in (e_1, \infty)$ and $0 < \bar{t}(e_2) < 1/e_1$, there exists

$$\bar{e} = \frac{de_1^2}{2de_1 - 1}, \tag{21}$$

which satisfies $t^M = \bar{t}(\bar{e})$. Note that from (20) and (21), we have

$$\bar{e} - \hat{e} = \frac{e_1(1 - de_1)(1 + 3de_1)}{5(2de_1 - 1)(3de_1 - 1)} > 0.$$

Then, $\max_{0 \le t \le \hat{t}(e_2)} W^T(t)$ and $\max_{t \ge \bar{t}(e_2)} W^M(t)$ can respectively be written as follows:

$$\max_{0 \le t \le \hat{t}(e_2)} W^T(t) = \begin{cases} W^T(t^T) & \text{if } e_2 \le \hat{e}, \\ W^T(\hat{t}(e_2)) & \text{if } e_2 > \hat{e}, \end{cases} \tag{22}$$

$$\max_{t \ge \bar{t}(e_2)} W^M(t) = \begin{cases} W^M(\bar{t}(e_2)) & \text{if } e_2 \le \bar{e}, \\ W^M(t^M) & \text{if } e_2 > \bar{e}. \end{cases} \tag{23}$$

[Figure 4 about here.]

The two bold lines in Figure 4 illustrate (22) and (23). For $e_2 \in (\hat{e}, \bar{e}]$, since $\hat{t}(e_2)$ is decreasing in e_2 and $\hat{t}(e_2) < t^T$, $W^T(\hat{t}(e_2))$ is decreasing in e_2. In contrast, for $e_2 \in (\hat{e}, \bar{e}]$, since $\bar{t}(e_2)$ is decreasing in e_2 and $\bar{t}(e_2) \ge t^M$, $W^M(\bar{t}(e_2))$ is increasing in e_2. In addition, we have $W^T(t^T) = W^M(t^M) = (1 - e_1 d)^2/2$. Then, there exists $\tilde{e} \in (\hat{e}, \bar{e})$ such that $W^T(\hat{t}(\tilde{e})) = W^M(\bar{t}(\tilde{e}))$. More precisely,

$$\tilde{e} = \frac{e_1}{60de_1 - 25}\left(\sqrt{9d^2e_1^2 - 6de_1 + 61} + 33de_1 - 6\right). \tag{24}$$

Therefore, as can also be seen from Figure 4, we obtain (19). ■

Proof of Lemma 4

(a) By differentiating $t^N(e_2)$ by e_2, we have

$$\frac{\partial t^N(e_2)}{\partial e_2} = \frac{(e_1 + e_2) + 18de_1(e_2 - e_1)}{(e_1 + e_2)^3} > 0. \tag{25}$$

In addition, from (12), it is easy to see that $\lim_{e_2 \to e_1} t^N(e_2) = t^T$.

(b) From the right-hand side of (11), it is easy to see that $\lim_{e_2 \to e_1} W^N(t, e_2) = W^T(t)$. Then, together with $\lim_{e_2 \to e_1} t^N(e_2) = t^T$, we have $\lim_{e_2 \to e_1} W^N(t^N(e_2), e_2) = W^T(t^T)$.

(c) Using the envelope theorem, we have

$$\frac{dW^N(t^N(e_2),e_2)}{de_2} = \frac{\partial W^N}{\partial e_2} = -\frac{(e_1+e_2)(t^N)^2 + (1-6d(2e_2-e_1))t^N + 3d}{9}, \quad (26)$$

$$\frac{d^2W^N(t^N(e_2),e_2)}{de_2^2} = \frac{\partial^2 W^N}{\partial t \partial e_2}\frac{\partial t^N}{\partial e_2} + \frac{\partial^2 W^N}{\partial e_2^2}, \quad (27)$$

where

$$\begin{aligned} \frac{\partial^2 W^N}{\partial t \partial e_2} &= \frac{18e_1 d(e_2-e_1) + (e_1+e_2)}{9(e_1+e_2)} > 0, \\ \frac{\partial^2 W^N}{\partial e_2^2} &= \frac{t^N[6d(e_1^2+5e_1e_2+e_2^2) + (e_1+e_2)]}{9(e_1+e_2)^2} > 0. \end{aligned} \quad (28)$$

From (26) and our assumption that $1/(2d) < e_1 < 1/d$, we have

$$\begin{aligned} \lim_{e_2 \to e_1} \frac{dW^N(t^N(e_2),e_2)}{de_2} &= \frac{d}{2}(e_1 d - 1) < 0, \\ \lim_{e_2 \to \infty} \frac{dW^N(t^N(e_2),e_2)}{de_2} &= \infty > 0. \end{aligned} \quad (29)$$

In addition, (25), (27), and (28) lead to

$$\frac{d^2W^N(t^N(e_2),e_2)}{de_2^2} > 0. \quad (30)$$

Therefore, from (29) and (30), there exists $\underline{e} \in (e_1, \infty)$ such that $W^N(t^N(e_2), e_2)$ is decreasing in $e_2 \in (e_1, \underline{e}]$ and increasing in $e_2 \in (\underline{e}, \infty)$. ■

From Lemma 4(a) and the fact that $\bar{t}(e_2)$ is decreasing in e_2 and $0 < \bar{t}(e_2) < 1/e_1$, it is easy to see that there exists $e' \in (e_1, \infty)$ such that $t^N(e') = \bar{t}(e')$. In the following proof, we deal with the two cases separately, depending on whether e_2 is larger or smaller than e'.

(a) For $e_1 < e_2 \leq e'$

In order to prove (14), since $\max_{\hat{t}(e_2)<t<\bar{t}(e_2)} W^N(t, e_2) \leq W^N(t^N(e_2), e_2)$ holds, it is sufficient to show that we have $W^N(t^N(e_2), e_2) < \max_{0 \leq t \leq \hat{t}(e_2)} W^T(t)$ for $e_2 \in (e_1, e']$. First, we prove the following lemma:[6]

Lemma 5. *Suppose that* $1/(2d) < e_1 < 1/d$. *Then, we have* $\underline{e} < e' < \tilde{e}$.

[6] The *Mathematica* file for the proof of this lemma is available from the author upon request.

Proof of Lemma 5

First, we show that $e' < \tilde{e}$. By solving $t^N(e_2) = \bar{t}(e_2)$ with respect to e_2, we obtain

$$e' = \frac{e_1}{12k}\left(1 + 6k + A + \frac{1 + 24k - 36k^2}{A}\right), \tag{31}$$

where $A = \left(108k^2 + 36k + 1 + 6k\sqrt{3}\sqrt{432k^4 - 864k^3 + 648k^2 - 8k - 1}\right)^{1/3}$ and $k = e_1 d$. Note that our assumption implies $1/2 < k < 1$. Then, from (24) and (31), we can confirm that $e' < \tilde{e}$ holds for $k \in (1/2, 1)$.

We then show that $\underline{e} < e'$. By substituting $e_2 = e'$ into (26), we have $dW^N(t^N(e'), e')/de_2$. We can confirm that this is positive for $e_1 \in (1/(2d), 1/d)$. Therefore, from Lemma 4(c), we have $\underline{e} < e'$. ■

From Lemmas 4 and 5, $W^N(t^N(e_2), e_2)$ for $e_2 \in (e_1, e']$ can be depicted as the dashed line in Figure 4. Note that since $W^N(\bar{t}(e_2), e_2) = W^M(\bar{t}(e_2))$ holds by the definition of $\bar{t}(e_2)$, we have $W^N(t^N(e'), e') = W^N(\bar{t}(e'), e') = W^M(\bar{t}(e'))$. Therefore, from Figure 4, it can be seen that $W^N(t^N(e_2), e_2) < \max_{0 \le t \le \hat{t}(e_2)} W^T(t)$ for $e_2 \in (e_1, e']$.

(b) For $e_2 > e'$

In this case, since $t^N(e_2) > \bar{t}(e_2)$ holds, we have

$$\max_{\hat{t}(e_2) < t < \bar{t}(e_2)} W^N(t, e_2) = W^N(\bar{t}(e_2) - \epsilon, e_2) < W^M(\bar{t}(e_2)) \le \max_{t \ge \bar{t}(e_2)} W^M(t), \tag{32}$$

where the last inequality follows from (23) and $W^M(\bar{t}(e_2)) \le W^M(t^M)$ for all e_2.

This completes the proof of Lemma 1. ■

Proof of Proposition 3

This result follows from Lemmas 1 and 3. ■

Proof of Lemma 2

When licensing is infeasible, we must compare $\max_{0\le t<\bar{t}(e_2)} W^N(t, e_2)$ and $\max_{t\ge\bar{t}(e_2)} W^M(t)$. In the case of $e_2 > e'$, (32) implies that the maximum welfare level is attained under a monopoly by firm 1. Then, from (23), the optimal emissions tax is given by $\bar{t}(e_2)$ for $e' < e_2 \le \bar{e}$ and t^M for $e_2 > \bar{e}$.

Next, we consider the case of $e_2 \le e'$. In this case, since $t^N(e_2) \le \bar{t}(e_2)$ holds, we have $\max_{0\le t<\bar{t}(e_2)} W^N(t, e_2) = W^N(t^N(e_2), e_2)$. On the other hand, since $e_2 \le e' < \bar{e}$ holds, we have $\max_{t\ge\bar{t}(e_2)} W^M(t) = W^M(\bar{t}(e_2))$. Then, we have

$$\max_{0\le t<\bar{t}(e_2)} W^N(t, e_2) = W^N(t^N(e_2), e_2) \ge W^N(\bar{t}(e_2), e_2) = W^M(\bar{t}(e_2)) = \max_{t\ge\bar{t}(e_2)} W^M(t).$$

Therefore, for $e_2 \le e'$, the optimal emissions tax is given by $t^N(e_2)$. ■

References

Asano, T. and N. Matsushima (forthcoming) "Environmental Regulation and Technology Transfers" *Canadian Journal of Economics*.

Chang, M.C., J.L. Hu and G.H. Tzeng (2009) "Decision Making on Strategic Environmental Technology Licensing: Fixed-Fee versus Royalty Licensing Methods" *International Journal of Information Technology & Decision Making* 8, 609–624.

Gallini, N.T. and R.A. Winter (1985) "Licensing in the Theory of Innovation" *RAND Journal of Economics* 16, 237–252.

Iida, T. and K. Takeuchi (2009) "Environmental Technology Transfer via Free Trade" *Economics Bulletin* 30, 948–960.

Iida, T. and K. Takeuchi (2011) "Does Free Trade Promote Environmental Technology Transfer?" *Journal of Economics* 104, 159–190.

Kamien, M.I. and Y. Tauman (1986) "Fees versus Royalties and the Private Value of a Patent" *Quarterly Journal of Economics* 101, 471–491.

Katz, M. and C. Shapiro (1985) "On the Licensing of Innovations" *RAND Journal of Economics* 16, 504–520.

Marjit, S. (1990) "On a Non-Cooperative Theory of Technology Transfer" *Economics Letters* 33, 293–298.

Qiu, L.D. and Z. Yu (2009) "Technology Transfer and the South's Participation in an International Environmental Agreement" *Review of International Economics* 17, 409–427.

Requate, T. (2006) "Environmental Policy under Imperfect Competition" in *The International Yearbook of Environmental and Resource Economics 2006/2007* by T. Tietenberg and H. Folmer, Eds., Edward Elgar.

Roy Chowdhury, I. (2008) "Joint Ventures, Pollution and Environmental Policy" *Bulletin of Economic Research* 60, 97–121.

Simpson, R.D. (1995) "Optimal Pollution Taxation in a Cournot Duopoly" *Environmental and Resource Economics* 6, 359–369.

Wang, X.H. (1998) "Fee versus Royalty Licensing in a Cournot Duopoly Model" *Economics Letters* 60, 55–62.

Wang, X.H. (2002) "Fee versus Royalty Licensing in a Differentiated Cournot Duopoly" *Journal of Economics and Business* 54, 253–266.

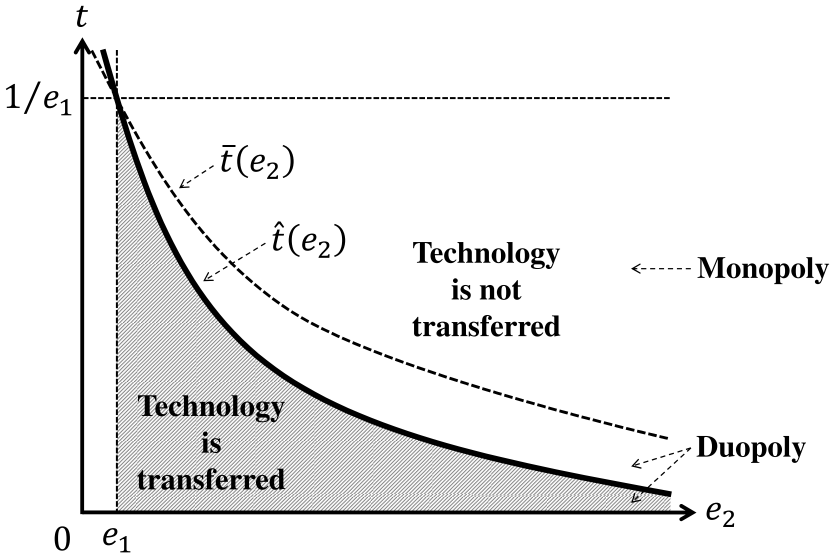

Figure 1: Area of technology transfer

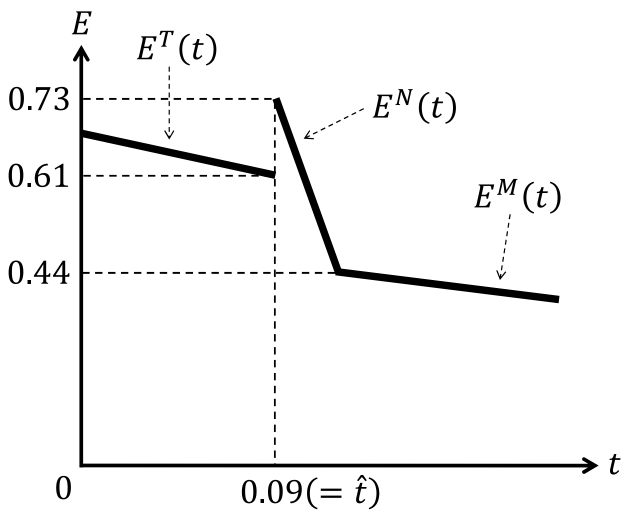

Figure 2: The level of total pollution when $(e_1, e_2) = (1, 5)$

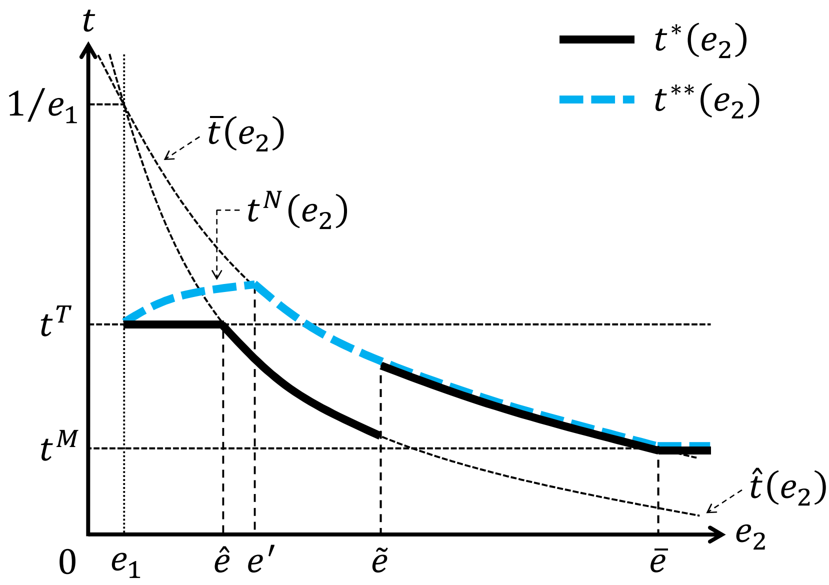

Figure 3: The optimal emissions tax

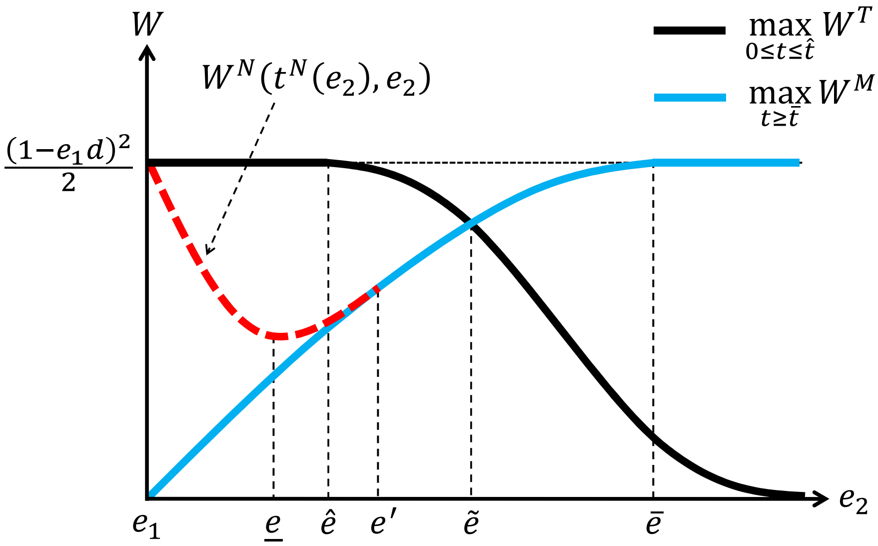

Figure 4: The maximized welfare levels