Economics Bulletin

Volume 34, Issue 4

Environmental technology transfer in a Cournot duopoly: the case of fixed-fee licensing

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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 tax on the incentives of firms to transfer technology and the firms' total pollution level, and examine the properties of the optimal emissions tax policy. We show that a higher emissions tax weakens the incentives of technology transfer and that this can lead to a perverse increase in the total pollution level. We also find that as the degree of the initial technology gap between firms widens, the optimal emissions tax can (weakly) decrease, which is contrary to the result when a licensing option is not available.

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 also thank the editor and three anonymous referees for constructive comments and suggestions. 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.
Citation: Akira Miyaoka, (2014) ''Environmental technology transfer in a Cournot duopoly: the case of fixed-fee licensing'', *Economics Bulletin*, Vol. 34 No. 4 pp. 2253-2266.
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Submitted: February 08, 2014.   **Published:** October 24, 2014.

1. Introduction

For the mitigation of environmental degradation, an important concern for policy makers is the diffusion of environmentally friendly technology. While 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 license their superior technologies strategically to both domestic and foreign rivals. For example, the famous Japanese automobile manufacturer Toyota entered into a licensing agreement with another automobile manufacturer Mazda to transfer 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.

This study analyzes the effects of emissions tax and the properties of the optimal tax rate when environmental technology transfers take place between firms through fixed-fee licensing. We consider a Cournot duopoly model in which one firm uses clean technology and emits less pollution than another firm in its production process. 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 emissions tax on the technology transfer incentives of firms and the level of total pollution. We show that a higher emissions tax makes a technology transfer less likely and can lead to a perverse increase in the total pollution level. We further explore the properties of the optimal emissions tax when licensing is possible compared to when licensing is not available. We find that the possibility of licensing can reverse the relationship between the optimal tax rate and extent of initial technology gap between firms: as a dirty technology becomes more polluting, the optimal emissions tax (weakly) decreases when licensing is possible, although it increases when licensing is not available.

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

The closest study to ours is Chang et al. (2009), who compare the fixed-fee and royalty licensing of less polluting technologies in a setting similar to ours. They also show that a higher emissions tax discourages technology transfers under fixed-fee licensing, but they do not provide a detailed analysis of the optimal emissions tax under fixed-fee licensing, because the licenser adopts royalty licensing in equilibrium. However, there can be situations where it is difficult for the licenser to use royalty licensing. For example, a licensee having a licensed technology may be able to easily imitate the technology, produce output with the imitation, and thereby avoid per-unit charges (Katz and Shapiro 1985; Rockett 1990). In this case, the licenser is restricted to fixed-fee licensing.[2] Thus, a careful analysis of the case of fixed-fee licensing should be important.

[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).

[2] For a formal proof of this statement, see the supplementary appendix available from the author upon request.

Our study complements Chang et al. (2009) by analyzing the emissions tax under fixed-fee licensing in more detail. We find a non-monotonic relationship between the emissions tax and total pollution level; we then provide a full characterization of the optimal emissions tax by considering a corner solution as well as an interior solution. Neither of these results is mentioned in their work.

Our study is also related to the literature on optimal emissions tax 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 clean technology through a licensing contract and show that the possibility of technology transfer can alter the properties of the optimal emissions tax levied by the government.

2. The model

We consider a market consisting of two heterogeneous firms, one clean (firm 1) and one dirty (firm 2), both producing a homogeneous product. Firm 1 emits e_1 units of pollution per unit of output, whereas firm 2 emits a higher level of pollution $e_2 (> e_1)$ 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 and x_i denotes the output level of firm $i \in \{1, 2\}$.

We employ a three-stage game. In stage 1, the government levies an emissions tax (uniformly) to maximize social welfare. In stage 2, firm 1, which has a clean technology, decides whether to license its superior technology to firm 2 for a fixed fee F, which is independent of firm 2's output. If licensing occurs, both firms 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 backward. First, we derive the Cournot equilibrium in stage 3 when the technology transfer has taken place in stage 2. In this case, since both firms have clean technologies, the profit of firm i (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 the emissions tax imposed per unit of emission. In 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 the clean technology of firm 1 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 its technology remains dirty, firm 2 emits e_2 units of pollution per unit output. In this case, firm i's equilibrium output and profit are, respectively,

$$x_i^N = \frac{1 - (2e_i - e_j)t}{3}, \quad \pi_i^N = \frac{(1 - (2e_i - e_j)t)^2}{9}, \quad i, j = 1, 2, \quad i \neq j. \tag{2}$$

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

$$x_1^M = \frac{1 - e_1t}{2}, \quad x_2^M = 0; \quad \pi_1^M = \frac{(1 - e_1t)^2}{4}, \quad \pi_2^M = 0. \tag{3}$$

3. The impacts of emissions tax on licensing incentives

In this section, we first analyze the firms' licensing decisions. We focus on a fixed-fee licensing contract and assume that firm 1 has all the bargaining power. At the licensing stage, firm 1 first offers firm 2 a fixed licensing fee F in a take-it-or-leave-it manner. If firm 2 accepts the offer, firm 1 licenses its clean technology for F. If firm 2 rejects the offer, licensing does not take place.

First, if $0 \leq t < \bar{t}(e_1, e_2)$, because firm 2's equilibrium profit without licensing is π_2^N, firm 2 accepts licensing if and only if $\pi_2^T - F \geq \pi_2^N$. The maximum licensing fee that firm 1 can charge is $F = \pi_2^T - \pi_2^N$.[3] In this case, if licensing takes place, the total profit of firm 1 is

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

From (2) and (4), we have $\pi_1^T + F \geq \pi_1^N$ 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 $\hat{t}(e_1, e_2) < t < \bar{t}(e_1, e_2)$.

Second, if $t \geq \bar{t}(e_1, e_2)$, when there is no licensing, firm 2 exits the market and its equilibrium profit becomes $\pi_2^M = 0$. In this case, firm 2 accepts licensing if and only if $\pi_2^T - F \geq \pi_2^M$, implying that the maximum fee that firm 1 can charge is $F = \pi_2^T - \pi_2^M$, and the total profit of firm 1 under licensing becomes

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

From (3) and (5), we obtain $\pi_1^T + F < \pi_1^M$. Therefore, when $t \geq \bar{t}(e_1, e_2)$, firm 1 does not have an incentive to license its clean technology and consequently becomes a monopoly. To summarize, we have the following proposition.

Proposition 1. *Firm 1 transfers its clean technology to firm 2 if and only if* $0 \leq t \leq \hat{t}(e_1, e_2)$.

The reason that licensing does not occur under a high emissions tax is as follows. 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, the market share of firm 2 is very small (or zero) and firm 1 becomes a near (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 of the firms becomes smaller than that without licensing, because firm 2 obtains clean technology and the market becomes more competitive. Therefore, under a high emissions tax, the clean technology of firm 1 is not licensed. The shaded area in Figure 1 indicates the pair (e_2, t) such that technology transfer occurs.

From this negative impact on licensing incentives, a higher emissions tax can have a perverse effect on the total pollution level. Following the above analysis, we obtain the total pollution level with technology licensing (for $0 \leq t \leq \hat{t}(e_1, e_2)$), without technology licensing (for $\hat{t}(e_1, e_2) < t < \bar{t}(e_1, e_2)$), and when firm 1 monopolizes the market (for $t \geq \bar{t}(e_1, e_2)$), respectively, as

$$E^T(t) = e_1(x_1^T + x_2^T), \quad E^N(t) = e_1 x_1^N + e_2 x_2^N, \quad E^M(t) = e_1 x_1^M. \tag{6}$$

Not surprisingly, a higher emissions tax reduces the total pollution level in each case; that is, $dE^h/dt < 0$ for $h = T, N, M$. However, an increase in the emissions tax above $\hat{t}(e_1, e_2)$ undermines the incentive for technology transfer between firms and the failure of technology licensing can (discontinuously) *increase* the total pollution level. More precisely, we have the following result:

[3] For $0 \leq t < \bar{t}(e_1, e_2)$, licensing never reduces the gross profit of firm 2, that is, $\pi_2^T \geq \pi_2^N$. Therefore, the maximum licensing fee that firm 1 can charge in this case is always non-negative, that is, $F = \pi_2^T - \pi_2^N \geq 0$.

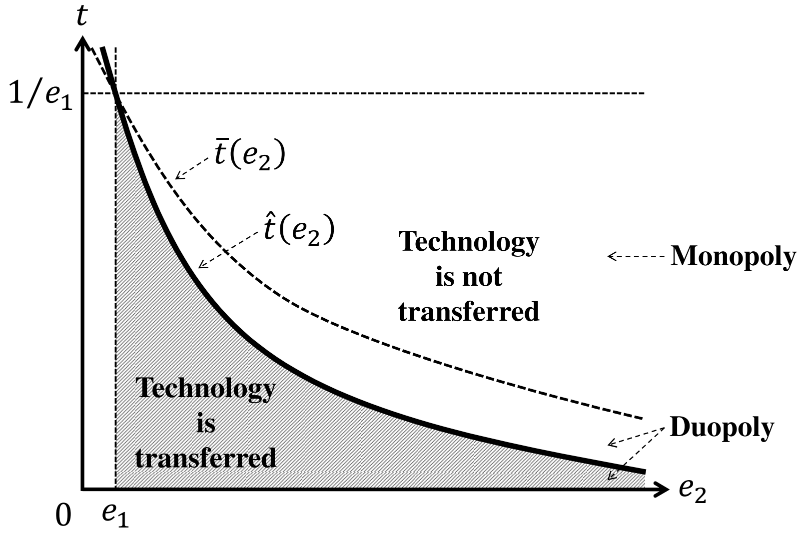

Figure 1: Area of technology transfer

Proposition 2. *When $e_2 > 3e_1$, a slight increase in the emissions tax above $\hat{t}(e_1, e_2)$ increases the total pollution level; that is, $E^T(\hat{t}(e_1, e_2)) < E^N(\hat{t}(e_1, e_2) + \epsilon)$, where $\epsilon > 0$ is an arbitrarily small number. In this case, the relationship between the emissions tax and the total pollution level is non-monotonic.*

Figure 2 illustrates the relationship between the emissions tax and the total pollution level when $(e_1, e_2) = (1, 5)$. The failure of technology licensing owing to a high emissions tax has two opposite effects on total emissions: while it reduces the total output of both firms, it increases the pollution level of firm 2 per unit of output. If the initial technology gap between firms is large enough, $\hat{t}(e_1, e_2)$ becomes lower and 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, in this case, raising the emissions tax above $\hat{t}(e_1, e_2)$ leads to a perverse increase in total pollution.[4]

4. 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 initial technology gap between two firms. In the following analysis, we consider e_1 to be fixed and interpret $e_2 \in (e_1, \infty)$ as the extent of initial technology gap between two firms.[5]

Following the previous literature (e.g., Requate (2006)), we assume that the government sets an emissions tax to maximize social welfare W, which consists of consumer surplus, producer surplus (aggregate profits net of taxes), tax revenue, and environmental damage from pollution. Now, let us first derive the locally optimal tax rate in each of the following three cases: $0 \leq t \leq \hat{t}(e_2)$, $t \geq \bar{t}(e_2)$, and $\hat{t}(e_2) < t < \bar{t}(e_2)$. By comparing the maximum welfare level of each case, we derive the globally optimal emissions tax rate.

In this study, we assume that environmental damage is a linear function of the total pollution.

[4] Roy Chowdhury (2008) obtains a similar result, but it is driven by the endogeneity of market structure.
[5] We exclude e_1 from the argument of the functions in this section.

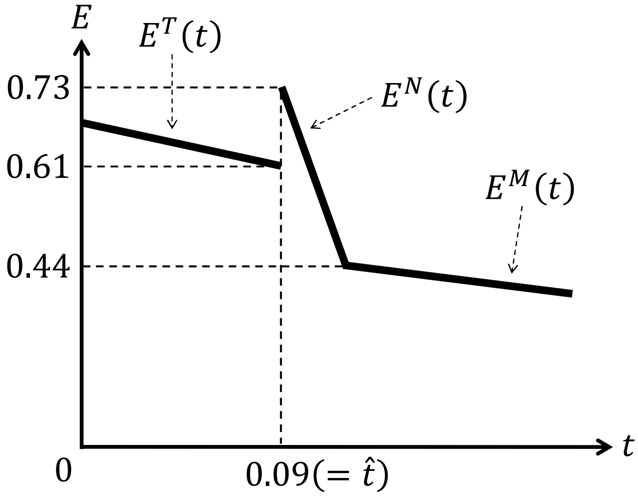

Figure 2: The level of total pollution when $(e_1, e_2) = (1, 5)$

Note that consumer surplus is given by $(x_1 + x_2)^2/2$. Then, the social welfare for each of the above three cases, W^T, W^M, and W^N, is obtained as follows:

$$W^h \equiv \frac{1}{2}\left(x_1^h + x_2^h\right)^2 + \left(\pi_1^h + \pi_2^h\right) + tE^h - dE^h, \quad h = T, M, N, \tag{7}$$

where d is the constant marginal damage from total emissions.

First, for $0 \le t \le \hat{t}(e_2)$, in which technology transfer occurs, the government chooses t to solve $\max_{0\le t\le \hat{t}(e_2)} W^T(t)$. Assuming an interior solution, we obtain the optimal tax rate and the corresponding social welfare level, respectively, as follows:

$$t^T = \frac{3e_1 d - 1}{2e_1}, \quad W^T(t^T) = \frac{(1 - e_1 d)^2}{2}. \tag{8}$$

We assume that $0 < t^T < 1/e_1$, or, equivalently, $1/(3d) < e_1 < 1/d$. 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 output of both firms, given by (1) with $t = t^T$, is positive. Since (8) is valid as long as $t^T \le \hat{t}(e_2)$, the optimal tax rate when $t^T > \hat{t}(e_2)$ is given by $\hat{t}(e_2)$.

Second, if $t \ge \bar{t}(e_2)$, firm 2 exits the market and firm 1 becomes a monopoly. In this case, the government solves $\max_{t\ge \bar{t}(e_2)} W^M(t)$. Assuming an interior solution, we obtain the optimal tax rate and the corresponding welfare level, respectively, as follows:

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

We assume that $0 < t^M < 1/e_1$, or, equivalently, $1/(2d) < e_1 < 1/d$. This 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 (3) 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 (9) is valid as long as $t^M \ge \bar{t}(e_2)$. Therefore, when $t^M < \bar{t}(e_2)$, the optimal emissions tax becomes $\bar{t}(e_2)$.

Finally, for $\hat{t}(e_2) < t < \bar{t}(e_2)$, although technology transfer does not occur, firm 2 is still active in the market. The government's problem is $\max_{\hat{t}(e_2)<t<\bar{t}(e_2)} W^N(t, e_2)$. Assuming an interior solution, we obtain the optimal tax rate and the corresponding welfare level, respectively, as follows:

$$t^N(e_2) = \frac{6d(e_1^2 + e_2^2 - e_1 e_2) - (e_1 + e_2)}{(e_1 + e_2)^2}, \tag{10}$$

$$W^N(t^N(e_2), e_2) = \frac{(e_1 + e_2)^2 - 2d(e_1 + e_2)(e_1^2 + e_2^2) + 4d^2(e_1^2 - e_1 e_2 + e_2^2)^2}{2(e_1 + e_2)^2}. \tag{11}$$

Since (10) and (11) are valid as long as $\hat{t}(e_2) < t^N(e_2) < \overline{t}(e_2)$, the maximum welfare level can be attained at a corner solution, $\hat{t}(e_2) + \epsilon$ or $\overline{t}(e_2) - \epsilon$, where $\epsilon > 0$ is an arbitrarily small number.

Now, we compare the maximized welfare levels of the above three cases and 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* $e_2 > e_1$*:*

$$\max_{\hat{t}(e_2)<t<\overline{t}(e_2)} W^N(t, e_2) < \max\{\max_{0\le t\le\hat{t}(e_2)} W^T(t), \max_{t\ge\overline{t}(e_2)} W^M(t)\}. \tag{12}$$

Lemma 1 implies that from the government's perspective, an emissions tax rate that enables firm 2 to be active even without technology licensing can never be socially optimal. In other words, social welfare is maximized either under a duopoly with technology transfer or when firm 1 is a monopoly. Therefore, in order to derive a socially optimal tax rate, we need to only compare the welfare levels under these two conditions. The optimal emissions tax rate when technology licensing is possible can be obtained 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*

$$t^*(e_2) = \begin{cases} t^T & \text{if } e_1 < e_2 \le \hat{e}, & \text{licensing occurs}, \\ \hat{t}(e_2) & \text{if } \hat{e} < e_2 \le \tilde{e}, & \text{licensing occurs}, \\ \overline{t}(e_2) & \text{if } \tilde{e} < e_2 \le \overline{e}, & \text{no licensing}, \\ t^M & \text{if } \overline{e} < e_2, & \text{no licensing}, \end{cases} \tag{13}$$

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

The bold line in Figure 3 represents the relationship between the optimal emissions tax rate and the initial technology gap between firms, measured by the initial technology level of firm 2, e_2. When the environmental technology gap is sufficiently small and $e_2 \in (e_1, \hat{e}]$, since technology licensing occurs even under a relatively high emissions tax, the government can induce licensing 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. Thus, when $e_2 \in (\hat{e}, \tilde{e}]$, it is optimal for the government to set a lower tax rate, $\hat{t}(e_2)$, in order 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 the technology of firm 2 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 when firm 1 is a monopoly.

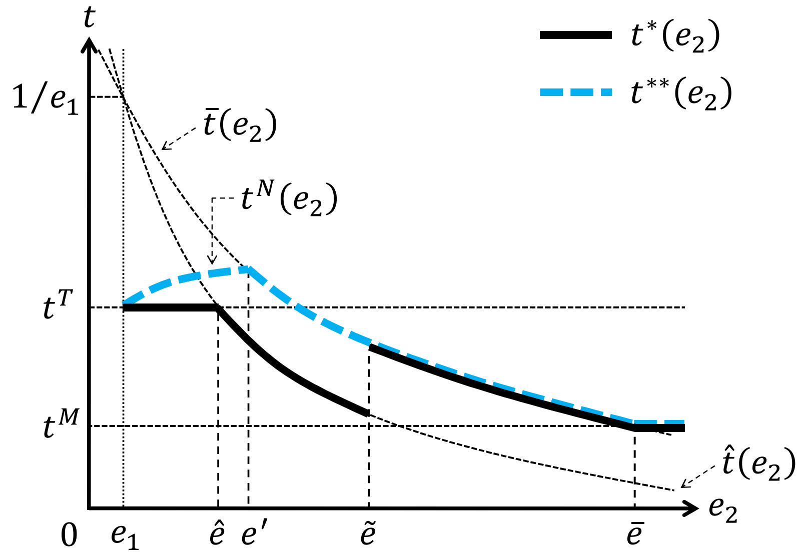

Figure 3: The optimal emissions tax

Now, we compare the optimal tax rates when technology licensing is possible and when it is not available. When the licensing option is not available, the technology of firm 2 always remains dirty. In this case, the optimal emissions tax rate is given by the following lemma.

Lemma 2. *Suppose that* $1/(2d) < e_1 < 1/d$. *Then, when technology licensing is not available, the optimal emissions tax,* $t^{**}(e_2)$, *is given by*

$$t^{**}(e_2) = \begin{cases} t^N(e_2) & \text{if } e_1 < e_2 \leq e', \\ \bar{t}(e_2) & \text{if } e' < e_2 \leq \bar{e}, \\ t^M & \text{if } \bar{e} < e_2, \end{cases} \tag{14}$$

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

The dashed line in Figure 3 illustrates the optimal emissions tax given by (14) when technology licensing is not available.[6] If the initial technology of firm 2 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 the technology of firm 2 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 initial technology gap between firms when technology licensing is possible can be the opposite of that when licensing is not available. 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 availability of technology licensing can alter the properties of the optimal emissions tax. When licensing is not available, as the initial technology of firm 2 becomes dirtier, it is socially optimal for the government to set a higher emissions tax rate and shift the market share from the dirty firm (firm 2) to the clean one (firm 1). Therefore, as long as both the

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

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 firms' incentives for technology licensing. 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 $e_2 \in (\hat{e}, \tilde{e}]$.[7]

5. Concluding remarks

This study analyzes the emissions tax policy in the presence of environmental technology transfers between duopolistic firms via fixed-fee licensing contracts. We show that because a higher emissions tax weakens the incentives for technology licensing, an emissions tax can have a perverse effect on the total pollution level and the property of the optimal emissions tax under fixed-fee licensing can be different from the case without a licensing option. Our results imply that governments should pay attention to whether superior environmental technologies can be diffused in the market in question, and if so through which channels; otherwise government policies could have adverse impacts on both the environment and social welfare. As mentioned in the Introduction, fixed-fee licensing contracts are more likely to be used when imitation by a licensee is easier. Therefore, our results could be applied especially to developing countries where patent protection is relatively weak.

Appendix

Proof of Proposition 2

From (1), (2), and (6), we have

$$E^T(t) = \frac{2e_1(1 - e_1 t)}{3}, \quad E^N(t) = \frac{(e_1 + e_2) - 2(e_1^2 - e_1 e_2 + e_2^2)t}{3}. \tag{15}$$

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

$$E^T(\hat{t}(e_1, e_2)) < \lim_{t \to \hat{t}(e_1,e_2)+0} E^N(t). \tag{16}$$

From (15) and $\hat{t}(e_1, e_2) = 2/(5e_2 - 3e_1)$, we have

$$E^T(\hat{t}(e_1, e_2)) = \frac{10e_1(e_2 - e_1)}{3(5e_2 - 3e_1)}; \quad \lim_{t \to \hat{t}(e_1,e_2)+0} E^N(t) = \frac{(e_2 - e_1)(7e_1 + e_2)}{3(5e_2 - 3e_1)}. \tag{17}$$

Therefore, by substituting (17) into (16) and rearranging it, we obtain $e_2 > 3e_1$. ■

[7] If we consider e_2 to be fixed and interpret $e_1 \in (1/(2d), \min\{e_2, 1/d\})$ as the extent of initial technology gap, the relationship between the optimal emissions tax and the degree of 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 $dt^T/de_1 > 0$ and $\partial\hat{t}/\partial e_1 > 0$, the optimal emissions tax when both the firms are active is decreasing as e_1 becomes smaller. In contrast, from (10), we can confirm that $\partial t^N/\partial e_1 < 0$ holds for a sufficiently small e_1. Therefore, if licensing is not available, the optimal tax rate when both firms are active can be increasing as e_1 becomes smaller.

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*

$$\max_{0\leq t\leq \hat{t}(e_2)} W^T(t) \lesseqgtr \max_{t\geq \overline{t}(e_2)} W^M(t) \quad \textit{if and only if} \quad e_2 \gtreqless \tilde{e}. \tag{18}$$

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

$$\hat{e} = \frac{e_1(9e_1 d + 1)}{5(3e_1 d - 1)}, \tag{19}$$

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

$$\overline{e} = \frac{de_1^2}{2de_1 - 1}, \tag{20}$$

which satisfies $t^M = \overline{t}(\overline{e})$. Note that from (19) and (20), we have

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

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

$$\max_{0\leq t\leq \hat{t}(e_2)} W^T(t) = \begin{cases} W^T(t^T) & \text{if } e_2 \leq \hat{e}, \\ W^T(\hat{t}(e_2)) & \text{if } e_2 > \hat{e}, \end{cases} \tag{21}$$

$$\max_{t\geq \overline{t}(e_2)} W^M(t) = \begin{cases} W^M(\overline{t}(e_2)) & \text{if } e_2 \leq \overline{e}, \\ W^M(t^M) & \text{if } e_2 > \overline{e}. \end{cases} \tag{22}$$

The two bold lines in Figure 4 illustrate (21) and (22). For $e_2 \in (\hat{e}, \overline{e}]$, 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 $e_2 \in (\hat{e}, \overline{e}]$, since $\overline{t}(e_2)$ is decreasing in e_2 and $\overline{t}(e_2) \geq t^M$, $W^M(\overline{t}(e_2))$ 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 $\tilde{e} \in (\hat{e}, \overline{e})$ such that $W^T(\hat{t}(\tilde{e})) = W^M(\overline{t}(\tilde{e}))$. More precisely,

$$\tilde{e} = \frac{e_1}{60de_1 - 25}\left(\sqrt{9d^2e_1^2 - 6de_1 + 61} + 33de_1 - 6\right). \tag{23}$$

Therefore, as can also be seen from Figure 4, we obtain (18). ■

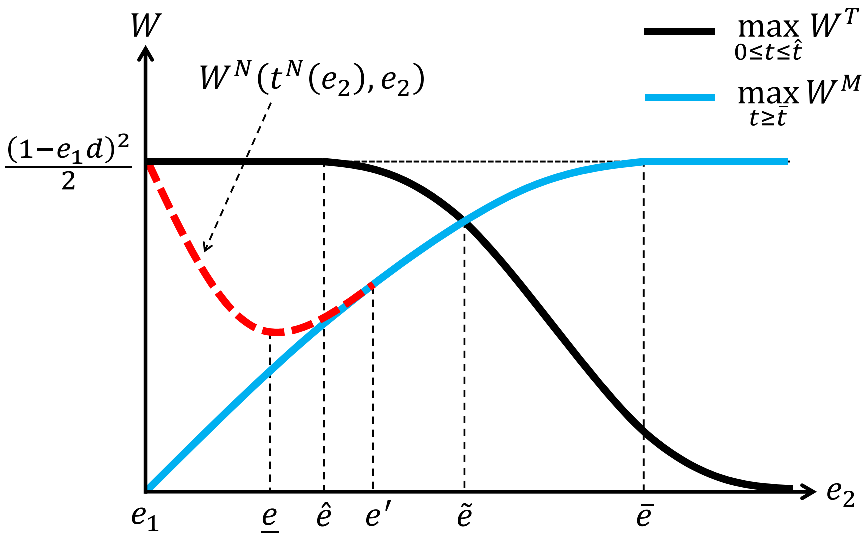

Figure 4: The maximized welfare levels

Proof of Lemma 4

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

$$\frac{dt^N(e_2)}{de_2} = \frac{(e_1+e_2)+18de_1(e_2-e_1)}{(e_1+e_2)^3} > 0. \tag{24}$$

In addition, from (10), it is easy to see that $\lim_{e_2\to e_1} t^N(e_2) = t^T$.

(b) Since $\lim_{e_2\to e_1} x_i^N = x_i^T$ and $\lim_{e_2\to e_1} \pi_i^N = \pi_i^T$ for $i = 1, 2$, we can 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

$$\frac{dW^N(t^N(e_2), e_2)}{de_2} = \frac{\partial W^N}{\partial e_2} = -\frac{(e_1+e_2)(t^N)^2+(1-6d(2e_2-e_1))t^N+3d}{9}, \tag{25}$$

$$\frac{d^2W^N(t^N(e_2), e_2)}{de_2^2} = \frac{\partial^2 W^N}{\partial t\partial e_2}\frac{dt^N}{de_2} + \frac{\partial^2 W^N}{\partial e_2^2}, \tag{26}$$

where

$$\frac{\partial^2 W^N}{\partial t\partial e_2} = \frac{18e_1d(e_2-e_1)+(e_1+e_2)}{9(e_1+e_2)} > 0,$$
$$\frac{\partial^2 W^N}{\partial e_2^2} = \frac{t^N[6d(e_1^2+5e_1e_2+e_2^2)+(e_1+e_2)]}{9(e_1+e_2)^2} > 0. \tag{27}$$

From (25) and our assumption that $1/(2d) < e_1 < 1/d$, we have

$$\lim_{e_2\to e_1} \frac{dW^N(t^N(e_2), e_2)}{de_2} = \frac{d}{2}(e_1d-1) < 0,$$
$$\lim_{e_2\to \infty} \frac{dW^N(t^N(e_2), e_2)}{de_2} = \infty > 0. \tag{28}$$

In addition, (24), (26), and (27) lead to

$$\frac{d^2 W^N(t^N(e_2), e_2)}{de_2^2} > 0. \tag{29}$$

Therefore, from (28) and (29), 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 (12), 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:[8]

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

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

$$e' = \frac{e_1}{12k}\left(1 + 6k + A + \frac{1 + 24k - 36k^2}{A}\right), \tag{30}$$

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 (23) and (30), we can confirm that $e' < \tilde{e}$ holds for $k \in (1/2, 1)$.

Next, we show that $\underline{e} < e'$. By substituting $e_2 = e'$ into (25), we obtain $dW^N(t^N(e'), e')/de_2$. 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 $W^N(t^N(e_2), e_2) < \max_{0\leq t\leq \hat{t}(e_2)} W^T(t)$ 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

$$\max_{\hat{t}(e_2)<t<\bar{t}(e_2)} W^N(t, e_2) = W^N(\bar{t}(e_2) - \epsilon, e_2) < W^N(\bar{t}(e_2), e_2) = W^M(\bar{t}(e_2)) \leq \max_{t\geq \bar{t}(e_2)} W^M(t), \tag{31}$$

where the last inequality follows from (22) and $W^M(\bar{t}(e_2)) \leq W^M(t^M)$ for all e_2.

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

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 $\max_{0\leq t<\bar{t}(e_2)} W^N(t, e_2)$ and $\max_{t\geq\bar{t}(e_2)} W^M(t)$. In the case of $e_2 > e'$, (31) implies that the maximum welfare level is attained under a monopoly by firm 1. Then, from (22), the optimal emissions tax is given by $\bar{t}(e_2)$ for $e' < e_2 \leq \bar{e}$ and t^M for $e_2 > \bar{e}$.

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

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

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

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