TREATMENT TECHNOLOGIES AND POLLUTION CONTROL IN THE LIGHT OF ITS NATURE

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Abstract

This paper discusses an externality-generator called an offender's behavior in employing technologies to treat an externality under standard, tax, and subsidy policies. We analyze his decision making process about production and/or treatment activities of the externality by measuring his surplus or net benefit from those activities. In the analysis, we focus on one nature of the externality; whether it continues to exist until its production process is finished. We will show that not only the offender's decision variables (production, emission and/or treatment) to regulate but also the nature of externalities plays an important role in carrying out the efficient policymaking.

I Introduction

Innovation can influence human activities in both affirmative and negative ways in a sense. This naturally applies to externality control problems including pollution. The purpose of this paper is to demonstrate effects of innovation in pollution treatment technologies on the relationship between pollution control policies and an agent' behavior. In doing so, we will show what is affirmative and negative in pollution control decision-makings by making clear the behavior of an externality-generator called an offender.

The relationship between pollution control policies and technological innovation has been discussed with respect to various issues in the literature. Among them Orr (1976) asserted prospective effects of effluent charge on efficient resource use. Magat (1978) focused on a polluting firm's dynamic decision making about both production and abatement activities under tax and standard policies. On the other hand, a series of researches has been pursued, which investigated a polluter's incentive to adopt innovative technologies by measuring the size of cost reduction resulting from the innovation in a diagrammatic way. Wenders (1975) as one of pioneers in this field showed that tax policy is superior to emission standard or subsidy policy in respect of giving a polluter an incentive to adopt cost-effective pollution control technologies, by measuring effects of cost reduction under each policy regime after specifying an externality treatment cost function form. Downing and White (1986) examined social optimality of pollution control policy instruments in terms of those effects on a polluter's choice concerning abatement level and the extent of the resulting cost reduction in varied conditions. Malueg (1989) took up an emission credit trading program and showed that there are both possibilities of promoting and impeding the incentive to adopt innovative technologies in this program. Likewise, Milliman and Prince hereafter called M-P (1989) discussed the effects of innovation on both innovator's and non-innovator's incentives above under five policy instruments in various circumstances by partitioning the innovation process into three steps, while Jung, Krutilla, and Boyd (1996) re-examined the results in M-P (1989) in the industry level as a whole.

This paper belongs to the genealogy of these researches, but we examine the interaction between the offender's technological innovation and the regulator's control adjustment explained below, and then discuss the possibility for the regulator to achieve social optimality by making the offender's behavior more realistic in the following senses. First, following Magat (1978), we incorporate the offender's decision about production and control (emission and/or treatment) of the externality in a simple way.[1] By doing so, we can renew our understanding of his option to control it under pollution control policies. That is, we can elucidate his overall target of maximizing his surplus or net benefit from consuming an externality-generating good, not merely minimizing abatement cost. It follows from considering this point that innovation might induce a change in the externality *production* (not only emission) level itself, and it is reminded that a polluter is able to comply with pollution control policies in the simplest way, i.e., by curtailing his production and as a result of which he is not willing to adopt outcomes of innovation in a certain circumstance.

Secondly, related to the first respect, we introduce a new step called *production adjustment* in the innovation process in addition to the three steps shown in M-P (1989) to recognize the importance of classifying externalities according to their nature: possibility to treat them after their production is completed. It will be shown that subsidy policies are crucially affected by this classification; they need a complicated form in one category.

The rest of the paper is constructed as follows. In section II we present fundamental structure of the model and concepts utilized in it. Section III compares three policy instruments (standard, tax, and subsidy) with respect to effects on the agents' behavior. Section IV concludes the paper.

II　The Model

II-1. Basic Circumstance

Suppose that a society consisting of two agents faces an (negative) externality problem. They are an offender and a victim who are different from each other. The offender enjoys benefit $B(X)$, by consuming a good, X, at the cost of $C(X)$. These functions have properties such that $B(0)=0$, $B'>0$, $B''<0$, $C(0)=0$, $C'>0$, $C''>0$.[2] The victim is the sufferer from the X-producing and consuming activity by the offender. His damage is represented by $D(X_v^e)$ where X_v^e denotes a part of X ($X_v^e \leq X$) to which the victim is ex-

1) A similar model as shown here can be found in Segerson and Tietenberg (1992).

2) Hereafter we let single primes denote first derivatives and double primes second ones of the functions, and assume that the second-order derivatives are constant.

posed, which also has well-behaved properties such as $D(0)=0, D'>0$ and $D''>0$. The offender naturally produces and consumes X so as to maximize his net benefit, $B(X)-C(X)$ in a *laissez-faire* regime, not taking account of the damage his behavior brings to the victim. Then the offender would produce and consume X by a familiar procedure at the level where

$$B'=C' \qquad (1)$$

is observed. We demonstrate this level by X^0 in Figure 1.[3]

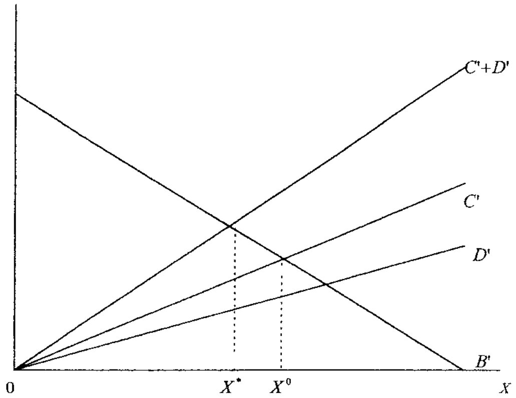

Figure 1

On the other hand, the socially optimal production level of X in the sense that the damage for the victim is also considered in social welfare calculation in addition to the offender's net benefit above is attained where the condition,

$$B'=C'+D' \qquad (2)$$

is met. Let this level be X^* in Figure 1.

3) Strictly speaking, the diagrammatic analysis in this paper requires a complicated process to derive the figures in order to maintain the validity of the results in the text. This task is shown in another paper.

II-2. Modeling Technologies to Treat the Externality

It is naturally imagined that people try to improve their lives in various circumstances. This applies to the externality problem. The victim would attempt to reduce the damage that he receives by means of some devices in the absence of any policies to control the externality by government. The offender, on the other hand, would have an incentive to decrease X_v^e in some X-regulatory regimes. In this paper, however, we take up only the latter case. We introduce such activities to abate the victim's damage resulting from X_v^e by calling them *treatment* activities.

We specify the treatment technologies as follows. First, the treatment cost depends only on the amount of X which is treated (X_i^t) by agent i ($i=o$ by assumption) and increases proportional to the quantity of the treatment activity. Formally $T_i(X_i^t)$ denotes the treatment cost function characterized by $T_i(0)=0, T_i'>0$ and $T_i''>0$. Secondly, we assume that the treatment activity is completely implemented in the sense that once a certain amount of X is treated by the offender the treated amount of X (X_i^t) brings about no damage to the victim and that the emitted X involves no treatment cost. Formally,

$$\forall X=X_o^e+X_i^t,\ D'(X_i^t)=T'(X_v^e)=0 \quad (3).$$

Thus, it follows that X can be perfectly divided into X_v^e and X_i^t or be equal to either one.

Thirdly, we focus on one characteristic of the externality. There is a wide range among externalities with respect to the time when they can exist or people can recognize them. For example, noise and vibration diminish immediately after being produced per unit, while air or water pollution can continue to exist for a long time. Let us call the former type of externalities *temporary*, since the effects of them cannot last continuously after they are produced, and the latter ones *persistent* because the effects of them can endure for a certain time. This feature of externalities is essential to examining treatment activities. When we face temporary type externalities it is no longer possible to treat them after the production process is completed. They need treating or reducing *before* their production is finished. In this sense, to treat temporary externalities means to control them *ex ante* or to prevent their occurrence. On the other hand, if the externalities belong to the persistent type, we can treat them even after the production process is entirely finished since the effects of them have remained yet. Therefore, it is possible to treat persistent externalities both *ex ante* and *ex post* with regard to the time of their production.[4]

Then, the socially optimal production levels of X in the presence of treatment technologies should be determined taking into account the nature of the good. First, if X belongs to the temporary type, its socially

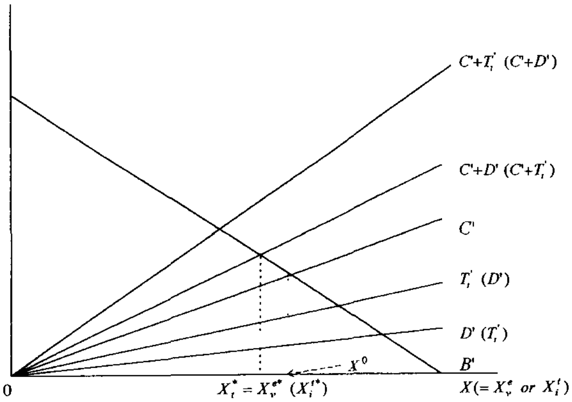

Figure 2

optimal level is obtained by maximizing $B(X)-C(X)-Min\{D(X_v^e), T_i(X_i^t)\}$ subject to $X=X_v^e=X_i^t$. The necessary condition is

$$X_v^e{:}B'=C'+D' \text{ or } X_i^t{:}B'=C'+T_i' \qquad (4)$$

This solution is demonstrated as $X_t{}^*$ in Figure 2.[5] On the other hand, when the good turns out to be persistent, its optimal level is chosen by maximizing social welfare defined such as $B(X)-C(X)-D(X_v^e)-T_i(X_i^t)$ subject to $X=X_v^e+X_i^t$. This level is realized where

$$X_v^e;B'=C'+D' \qquad (5a),$$

$$X_i^t;B'=C'+T_i' \qquad (5b)$$

are satisfied simultaneously. Such a production level is shown as $X_p{}^*$ in Figure 3.[6] Notice that in the figure X_i^t is measured towards the origin from $X_p{}^*$. Comparing X^* and $X_t{}^*$ or $X_p{}^*$ leads to the following evident proposition.

4) Barrett and Segerson (1997) focused on a similar distinction of externality control activities as we do here in a somewhat different context from the one in this paper. They call the activity which is implemented prior to the generation of externalities *prevention*, while they call the one which is operated after that *treatment*. A remarkable discrepancy between their and our analyses lies in the agents whose behavior is examined. Barrett and Segerson investigated effects of exogenous variables on the socially optimal prevention as well as treatment levels chosen by government with various objectives, while we mainly explore here the tendency of those variables determined by the offender such as a polluter.

5) Assuming that the second derivatives of the functions are constant, one of the first derivatives of $D(\cdot)$ and $T_i(\cdot)$ exceeds the other through the overall domain of X.

6) It is possible to exchange the location of the $C'+D'$ curve with that of the $C'+T_i'$ curve. But we focus on the case of ex post treatment in order to clearly contrast this case with the temporary case.

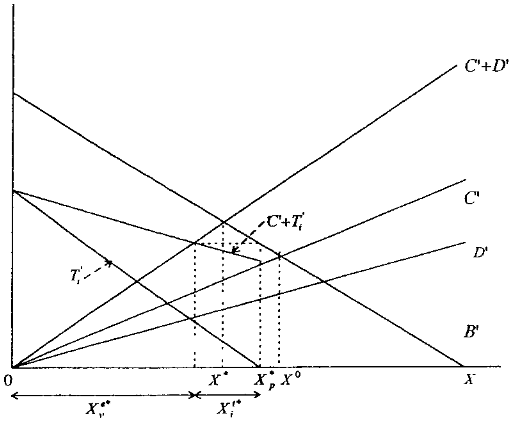

Figure 3

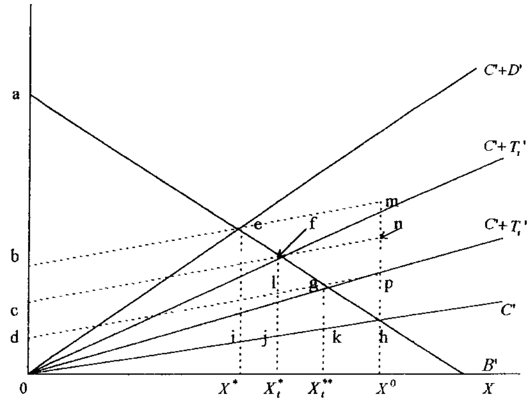

Figure 4a

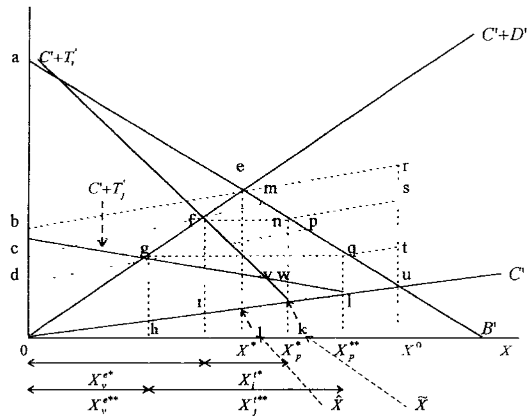

Figure 4b

PROPOSITION 1. It holds that $X^* \leq X_t^*$ and $X^* \leq X_p^*$.

II-3. Modeling Innovation

The offender have an incentive to develop treatment technologies which cost as low as possible to acquire larger benefits. We define innovation or technological progress with respect to externality treatment activities as the achievement of developing technologies with lower marginal costs than the existing ones. Formally, we observe innovation if and only if $\forall X \geq 0, T_j'(X) < T_i'(X)$ where T_j' denotes marginal cost of an innovative technology belonging to agent j which is either $=$ or $\neq i$. However, it is maintained hereafter that $i = j = o$. This inequality implies that the innovative technology is more efficient than the older one in the sense that the former always costs less than the latter for any level of X. Explaining this diagrammatically, the T_j' curve is always located below the T_i' curve throughout the domain.

As the result of innovation, the socially optimal production levels of X should be modified. In the case of temporary type externalities, we should replace D' or T_i' with T_j' if we observe that

$$\forall X = X_j^t = X_i^t = X_v^e, T_j'(X_j^t) < Min. \{D'(X_v^e), T_i'(X_i^t)\} \quad (6).$$

Then, the necessary condition to derive the optimal production level of X in this case is

$$B' = C' + T_j' \quad (7)$$

which is illustrated as X_t^{**} in Figure 4a.

In the case of persistent type externalities, on the other hand, after replacing T_i' with T_j', the new socially optimal production level of X is obtained by a similar procedure as done above when equation (5b) is changed into

$$X_j^t; B' = C' + T_j' \quad (5b)'.$$

It is demonstrated as X_p^{**} in Figure 4b. Here, we can present the following proposition.

PROPOSITION 2. Other things being equal, if both types of externalities can be treated by the same treatment technology with respect to its cost, then technological innovation brings about a larger increase in X_t^* than in X_p^*.

PROOF: See Appendix.

III Effects of Technological Innovation on Policy Instruments

In this section we investigate effects of so-called pollution control policies on the offender's incentive to employ cost-effective technologies to treat externalities. In the literature including M-P (1989) and Jung, Krutilla and Boyd (1996), it is changes in the size of cost reduction in attaining a target pollution level determined by the difference between using old technologies and employing new or cost-effective ones that matters in evaluating a polluter's incentive to utilize efficient technologies; the larger the size of cost reduction is, the more they would try to make use of them. However, we make use of a more comprehensive criterion: an increase in size-difference with regard to surplus or gains from trade represented as net benefit (= benefit of consuming X minus production cost minus treatment cost) for the offender between the two circumstances mentioned above.

By considering surplus instead of mere pollution abatement costs, we can point out one important process which M-P (1989) missed; adjustment of production level of X on the part of the offender in the face of technology innovation. M-P (1989) presented three steps observed in the process of technological progress; *innovation, diffusion,* and *control adjustment.* However, if new pollution control technologies are developed, the socially optimal production (not emission) level of X itself is naturally modified by the offender as presented in Propositions 1 and 2, which implies that e^m or E^m from which abatement starts in M-P (1989) should also be adjusted, which furthermore affects a policy-maker's decision. We introduce this process by calling it *production adjustment* between diffusion which has nothing to do with in this paper and control adjustment steps in M-P (1989).

Let us explore effects of pollution control policies on the offender's behavior in detail. Here we focus on three policy instruments; standard, tax, and subsidy policies, since permit issue policies are inappropriate in the model here because of the thinness of the permit markets.[7]

III-1. Control of Temporary Type Externalities

First of all, we look into the offender's surplus from consuming X with a temporary type characteristic when confronting innovation. Let us keep our eyes on Figure 4a. The offender obtains surplus of aOh in a laissez-faire regime by producing and consuming X^0.

7) Although to issue permits is not suitable for the situation in the text, it might be possible to introduce this policy instrument here by imaging that the beneficiary has to buy permits from government to justify his discharge of X which are issued and whose price is determined properly by the government. A possible program with such a property called a system of rental emission permits was discussed in Collinge and Oates (1982).

In order to make the offender produce X^* in the absence of treatment technologies, we introduce pollution control policies. Under these circumstances, it depends on the object on which the policies are set up whether the policies succeed in achieving efficient production and emission levels of X. If we control his behavior directly by setting up standards for production of X at X^* with prohibitive fine for non-compliance (excess production), then he would choose to conform to that policy and consume $0X^*$ and enjoy surplus of *aOie*. Even if the standard is set for emission, he would behave in the same way. Next, if production standard is modified from X^* to X_t^* because of the development of a pollution treatment technology whose marginal cost is given by T_i' and the subsequent production adjustment, he would again choose to obey the standard by producing $0X_t^*$ without operating the technology, since this option brings him surplus of *aOjf* which is larger than *aOf*, the surplus with the operation, by *Ojf*. However, if the same standard is set for treatment (with prohibitive penalty for the treatment level less than the standard), he would choose to produce and treat $0X_t^*$ and get *a0f*. Thirdly, if we further change the standard for production from X_t^* to X_t^{**} reflecting innovation which replaces T_i' with T_j', then he would remain complying with the standard without treating the good, and receives *aOkg* as surplus. But if he encounters the same standard for treatment, then he would comply with the standard and treat $0X_t^{**}$ enjoying *a0g*. Thus, it is concluded that in society without treatment technologies standard policies for both production and emission will succeed in attain the efficient situation, while in society with such technologies only standard policies for treatment can attain it.

How does the offender change his behavior if we adopt the Pigouvian tax policy as the pollution control policy? If the tax is set for his production of X in a world without treatment technologies, he would capture surplus of *abe* by consuming $0X^*$ after tax-payment of *bOie* where the tax rate is *ei* in Figure 4a. Taxation on emission would not change his behavior. If he develops a control technology whose marginal cost corresponds to T_i', then the tax rate would decrease to *fj* as a result of control adjustment. If his production activity is taxed, he would choose to consume $0X_t^*$ without treatment since treatment does not contribute to cost reduction, and earn *acf*. On the other hand, if the tax base is his non-treatment or emission, he would consume $0X_t^*$, all of which is treated, i.e., $X_t^* = X_i^{t*}$ in order to save tax-payment by *cOf*, so that his surplus amounts to *aOf*. Furthermore, suppose that innovation reduces the tax rate to *gk*. Then, tax for production of X will make the offender produce $0X_t^{**}$ without treatment, whereas tax for non-treatment will make him produce and treat the same amount of X. Thus, we can assert that tax policy towards non-treatment always gives the offender the appropriate incentive to behave efficiently from a social view point including to employ the efficient treatment technology without paying tax in effect.

Finally, if a subsidy policy is selected as the pollution control policy, the offender would be expected to behave as follows in Figure 4a. Notice here that X^o is established as the benchmark from which the subsidy for production abatement is worked out, while $X=0$ is the benchmark to figure out the

TABLE I

Possibility for Pollution Control Policies to Achieve Social Optimality in the Case of A Temporary Type Externality

Policy	Standard		Tax		Subsidy	
Policy Variable	Production	Treatment*	Production	Treatment*	Production	Treatment*
No Technology	○	○	○	○	○	○
Less-efficient Tech.	×	○	×	○	×	○
More-efficient Tech.	×	○	×	○	×	○

The mark ○ implies that this policy can achieve the socially optimal levels of production as well as emission and/or treatment of the externality.
The mark × implies that this policy cannot achieve the socially optimal levels with regard to at least one of the above components.
*In the case without treatment technologies, "treatment" needs to be replaced with "emission".

subsidy for his treatment activity. If he does not own any treatment technologies, he would produce X up to X^* from which he receives $aOie+eihm$, in which the first term is guaranteed as surplus by consuming $0X^*$ while the second term arises from the subsidy revenue at the rate of mh, when the subsidy is based on his production abatement. It has no effect on his behavior to shift the subsidy towards emission reduction. If he owns a pollution control technology whose marginal cost is represented by T_i', the subsidy rate is reduced to nh, which gives him $aOjf+fjhn$ on condition that subsidy for production abatement is implemented and he produces $0X_t^*$ without operating the technology. However, if the subsidy is calculated based on extension of treatment activity, he would produces $0X_t^{**}$ and treat the whole amount of X, obtaining $aOjf+c0f$. If the subsidy rate for production abatement is further cut down reflecting innovation to ph by control adjustment, he would generate the externality up to X_t^{**} to get $aOkg+gkhp$ ignoring the innovation. But the same subsidy rate is based on treatment extension, he would gain $aOkg+d0g$ by producing and treating $0X_t^{**}$ at the same time. In conclusion, the subsidy policy succeeds in inducing the offender to engage himself in treatment activity if the policy targets his treatment activity when the technologies are available.

The result obtained from the above argument is summarized in Table I from which we can derive the next proposition.

PROPOSITION 3. In control of temporary type externalities under perfect enforcement, it is necessary in order to attain social optimality to regulate the offender's production in the absence of treatment technologies, while it is to control his treatment activity in the presence of them.

III-2. Control of Persistent Type Externalities

In this subsection, we investigate effects of pollution control policies on the offender's externality treatment activity in the case of persistent type externalities. Let us focus on Figure 4b. First of all, the offender enjoys aOu as surplus by generating $0X^o$ in a laissez-faire regime.

When a standard policy is implemented as the pollution control policy, the offender is expected to behave in the similar manner as in the temporary type externality case; if the standard is set for production, he would produce $0X^*$, $0X_p^*$, and $0X_p^{**}$ to get *aOje*, *aOkn*, and *aOlq* as net benefits respectively, without any treatment technologies, with a less efficient technology whose marginal cost is T_i', and with a more efficient technology whose marginal cost equals T_j'. Again, he has no incentive to carry out treatment activities due to the possibility to adjust the production level so as to meet the standard. If the standard is implemented towards treatment, however, he would produce the same amounts of X as the above case and treat them properly if possible and earn *aOje*, *aOifkn*, and *aOhglq*, respectively.

If the regulator adopts a tax policy based on production, then the offender would react as follows. In a circumstance with no treatment technology in which the tax rate is set as *ej*, he would get *abe* as surplus by producing and emitting $0X^*$ after paying *bOje* as total tax. If he possesses a treatment technology which marginally costs T_i', the tax rate is modified to *fi* as a result of control adjustment. Then, he would choose to produce $0\hat{X}$ without treating so as to obtain *acm* as the maximum surplus. Likewise, if the tax rate is cut to *gh* due to innovation bringing about an efficient treatment technology whose marginal cost is represented by T_j', he would produce and emit $0\tilde{X}$ to get *adp*. If the tax is based on emission or non-treatment, on the other hand, he would behave efficiently in either circumstance; he would produce and emit $0X^*$ by paying *boje* to acquire *abe* with no treatment technology, produce $0X_p^*$ in which $X_v^{e^*}$ is emitted and $X_i^{t^*}$ is treated so as to get *acfkn* with a less efficient technology whose marginal costs is T_i', and produce $0X_p^{**}$ in which $X_v^{e^{**}}$ is emitted and $X_j^{t^{**}}$ is treated in order to obtain *adglq* with a more efficient technology represented by T_j' as its marginal cost. This shows that the offender adopts more efficient technologies not because the treatment cost is merely reduced than before, but because the benefit increase arising from the choice (represented by $cdgvf+nwlq$) is larger than the resulting cost increase (vkw). This point has not been fully recognized in the literature.

Finally, if a subsidy policy is selected as the pollution control instrument, we should be more careful. First, suppose that the subsidy is paid for the abatement of production. When there is no technology to treat X, the optimal subsidy rate is to be *ej*, and the offender would produce $0X^*$ after receiving *ejur* as the subsidy revenue for curtailing his production by X^*X^0. Then, he earns $a0je+ejur$ as net surplus. If a treatment technology whose marginal cost is T_i' is developed, the subsidy rate needs changing into *nk*. Then, he would produce $0X_p^*$ after gaining subsidy revenue of *nkus*, and his total surplus amounts to $a0kn+nkus$ without operating the technology. If innovation gives rise to a more efficient technology with T_j' as its marginal cost, encountering *ql* as the subsidy rate, he would produce $0X_p^{**}$ owing to receiving *qlut* as the resulting revenue, thus obtaining $a0lq+qlut$ in total, not engaging himself in treatment activity.

Next, let the subsidy policy be related to his emission or treatment activity. Without any technologies, the offender produces and

TABLE II

Possibility for Pollution Control Policies to Achieve Social Optimality in the Case of A Persistent Type Externality

Policy	Standard		Tax		Subsidy	
Policy Variable	Production	Treatment*	Production	Treatment*	Production	Treatment*
No Technology	○	○	○	○	○	○
Less-efficient Tech.	×	○	×	○	×	×
More-efficient Tech.	×	○	×	○	×	×

emits $0X^*$ as before. With the less efficient technology which marginally costs as T_i' shows, the appropriate subsidy rate is fi if the subsidy is reckoned from $X_p{}^*$. Similarly, the optimal subsidy rate should be gh with the more efficient technology represented by T_j' as its marginal cost if the subsidy payment is calculated from $X_p{}^{**}$. Yet it is doubtful that the offender produces $0X_p{}^*$ or $0X_p{}^{**}$ in these circumstances. From the above discussion, we can conclude that in order to control persistent type externalities efficiently via subsidy policies, it is needed to establish double subsidy rates; one for production, the other for treatment, which in general take distinct values.

The above discussion is summarized in Table II, which shows the following proposition.

PROPOSITION 4. In control of persistent type externalities under perfect enforcement, standard and tax policies has the ability to achieve social optimality on condition that their policy variables are chosen properly, whereas subsidy policies cannot attain social optimality unless they regulate both the offender's production and treatment activities simultaneously except for the case with no treatment technology.

The difference between the two types of externalities with respect to the validity of subsidy policies demonstrates the essence of this distinction of externalities clearly. Temporary type externalities must be controlled in a all or nothing manner in the sense that all of produced X is either emitted or treated as the whole. Therefore, the produced amount is always equal to the controlled (emitted or treated) amount, so that the regulator has only to target either the offender's production or control activity. On the other hand, persistent type externalities in general involve emission and treatment which are both positive. This means that his efficient production differs from his efficient treatment. Thus, it is required to regulate them separately. Standard and tax policies are immune from this problem since their benchmarks by which the policies are implemented are fixed; standards are set at the efficient amounts, while tax base is $X=0$.

IV Concluding Remarks

We have shown that social optimality in externality control related to innovation in treatment technologies has to cover its production as well as abatement or emission levels. These components need determining simultaneously.

We have investigated the relationship between the offender's optimization behavior and the nature of externalities, temporary or persistent type, under several pollution control policies, taking account of production adjustment between innovation and control adjustment steps presented in M-P (1989). Then, we obtained the following results. In controlling temporary type externalities, it follows that either pollution control policy has the ability to achieve social optimality under perfect enforcement as long as its policy target is properly chosen, whereas in controlling persistent type externalities, standard and tax policies have the ability but subsıdy policy is not endowed with it unless the policy regulates both of production and treatment activities separately. Furthermore, when pollution control policies can attain the efficient situations, it is verified that the offender has an incentive to adopt more cost-effective treatment technologies.

We have some limitations and thereby directions for extension. First of all, we presumed that government has all information it needs to implement pollution control policies, and that the offender be naive in the sense that he does not behave strategically to manipulate government's choice of policy variables in their favor. To relax these assumptions might hurt the above results. Secondly, we assumed that the treatment technology owner is solely the offender. However, if the victim alone has or both of them at the same time have such technologies, the conclusions would largely be affected. Social optimality would probably require a delicate implementation of pollution control policies. Furthermore, in this circumstance, if the externality which we face is a temporary type one, we are disturbed by an additional problem related to non-convexities.[8] It is virtually impossible to operate both of their technologies according to the optimality condition like (4) due to the nature of the externality. Therefore, it is inevitable that either party carries out his treatment technology alone. The choice of who should engage in this activity would belong to the non-convexity problem. Thirdly, if technological treatment costs depend not only on the amount of X treated but also the level at which it is operated, then arguments would become complicated. They would need to specify forms of the cost functions in order to derive suggestive results.

APPENDIX

In this appendix, we prove PROPOSITION 2 by examining effects of innovation in externality control technologies on $X_p{}^*$ and $X_t{}^*$ by means of comparative statics.

Let us take the case of control implementation posterior to the discharge of X. Restating the first order conditions necessary to maximize social welfare in the presence of an externality control technology, we present

$$X^e_v; B'(X(\theta)) = C'(X(\theta)) + D'(X^e_v(\theta)) \quad (1A),$$

$$X^t_i; B'(X(\theta)) = C'(X(\theta)) + T_i'(X^t_i(\theta), \theta) \quad (2A)$$

where θ represents a shift parameter implying the shift of marginal control cost func-

8) Non-convexity problems in connection with externalities has been one of formidable difficulties which attracted many researchers. Kohn and Aucamp (1976) and Shıbata and Winrich (1983) were the pioneers in this subject.

tion. That is, $\frac{\partial T_i'}{\partial \theta} < 0$ indicates that marginal cost function shifts downwardly because of innovation. For example, θ implies the replacement of T_i' with T_j' in the text.

Differentiating (1A) and (2A) with respect to θ respectively, we obtain

$$B''\frac{dX_v^e}{d\theta}+B''\frac{dX_i^t}{d\theta}=C''\frac{dX_v^e}{d\theta}+C''\frac{dX_i^t}{d\theta}+D''\frac{dX_v^e}{d\theta} \quad (1A)',$$

$$B''\frac{dX_v^e}{d\theta}+B''\frac{dX_i^t}{d\theta}=C''\frac{dX_v^e}{d\theta}+C''\frac{dX_i^t}{d\theta}+T_i''\frac{dX_i^t}{d\theta}+\frac{dT_i'}{d\theta} \quad (2A)'.$$

Arranging these equations, we can get a matrix form such as

$$\begin{bmatrix}(B''-C''-D'') & (B''-C'') \\ (B''-C'') & (B''-C''-T_i'')\end{bmatrix}\begin{bmatrix}\frac{dX_v^e}{d\theta} \\ \frac{dX_i^t}{d\theta}\end{bmatrix}=\begin{bmatrix}0 \\ \frac{dT_i'}{d\theta}\end{bmatrix} \quad (3A).$$

The determinant of the 2×2 matrix on the LHS of (3A) is calculated as

$$(B''-C''-D'')(B''-C''-T_i'')-(B''-C'')^2$$
$$=T_i''D''-(B''-C'')(T_i''+D'')\equiv\delta>0 \quad (4A).$$

By means of the Cramer's rule, it is shown that

$$\frac{dX_v^e}{d\theta}=\frac{1}{\delta}\begin{vmatrix}0 & (B''-C'') \\ \frac{dT_i'}{d\theta} & (B''-C''-T_i')\end{vmatrix}=\frac{-(B''-C'')}{\delta}\frac{dT_i'}{d\theta}<0 \quad (5A),$$

$$\frac{dX_i^t}{d\theta}=\frac{1}{\delta}\begin{vmatrix}(B''-C''-D'') & 0 \\ (B''-C'') & \frac{dT_i'}{d\theta}\end{vmatrix}=\frac{(B''-C''-D'')}{\delta}\frac{dT_i'}{d\theta}>0 \quad (6A).$$

Thus, $\frac{dX_p}{d\theta}=\frac{dX_v^e}{d\theta}+\frac{dX_i^t}{d\theta}=\frac{-D''}{\delta}\frac{dT_i'}{d\theta}>0$ (7A).

On the other hand, in the case of control activity prior to the discharge of X, the socially optimal generation level of X_t is obtained by achieving (8) in the text, that is,
$B''(X(\theta))=C''(X(\theta))+T_i'(X(\theta),\theta)$ (8A).
Differentiating (8A), we get

$$B''\frac{dX}{d\theta}=C''\frac{dX}{d\theta}+T_i''\frac{dX}{d\theta}+\frac{dT_i'}{d\theta} \quad (9A),$$

which shows that $\frac{dX_p}{d\theta}=\frac{\frac{dT_i'}{d\theta}}{(B''-C''-T_j'')}>0$

(10A).

Subtracting (10A) from (7A) shows that

$$\frac{-D''}{\delta}\frac{dT_i'}{d\theta}-\frac{\frac{dT_i'}{d\theta}}{(B''-C''-T_i'')}=\frac{dT_i'}{d\theta}\frac{T_i''(B''-C'')}{\delta(B''-C''-T_i'')}<0. \quad (11A)$$

That is, other things being equal, innovation raises the optimal production level of X more in the case of temporary externalities than in the case of persistent ones. ■

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