Citizen Participation and Incentive Compatible Mechanisms for Pollution Control

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Abstract

An interesting feature of pollution permit markets is that citizens may participate to directly lower the levels of pollution. We analyze the effects of citizen participation on incentive compatible mechanisms for pollution control. We show that Kwerel's mechanism (Review of Economic Studies 1977) is not incentive compatible when citizens participate. We show that two other mechanisms—the simple mechanism and the

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minimum-price mechanism— are at least weakly incentive compatible when citizens participate. Furthermore, the minimum-price mechanism is robust to changes in the severity of free-riding among citizens.

1 Introduction

The analysis of pollution permit markets traditionally focuses on trade among firms that generate pollution. A number of recent papers, however, allow for the possibility that citizens harmed by pollution may participate in permit markets.[1] When citizens buy and "retire" permits, they lower the quantity of pollution. The equilibrium level of pollution is determined by the actions of firms and citizens, rather than by a government regulator.

In this paper we analyze the effects of citizen participation on incentive compatible mechanisms for pollution control. We revisit Kwerel's (1977) classic analysis and show that his mechanism is not incentive compatible when citizens participate in the permit market. We also present two other mechanisms and analyze their properties. These mechanisms are at least weakly incentive compatible in the presence of citizen participation.

In Kwerel's model, the government knows the damage from pollution, but does not know the firms' abatement costs. Firms purchase permits in a competitive market. Kwerel describes a mechanism in which the government asks the firms to submit their abatement costs and uses their responses in conjunction with a fixed rule to determine two parameters of the permit market. The first parameter is the endowment of permits and the second

[1] Boyd and Conley (1997) and Conley and Smith (2005) consider markets in which citizens are charged personalized prices. Markets in which citizens are charged a common price are analyzed by Ahlheim and Schneider (2002), Shrestha (1998), Smith and Yates (2003), and Malueg and Yates (2005). Israel (2002) documents the degree to which citizens actually retire permits in the EPA's acid rain program.

parameter is a subsidy for reducing pollution below the number of permits held. Under the assumptions of his model, Kwerel's mechanism is incentive compatible. In particular, Kwerel shows that firms' total costs (abatement cost and permit purchases) are minimized when the government selects a permit endowment equal to the efficient level of pollution. Thus firms have the incentive to tell the truth about their abatement costs.

We add a demand for permits from citizens to Kwerel's model. The citizens' demand arises from damages due to pollution. At first we assume that this demand fully captures damages. Under Kwerel's mechanism, firms' total costs are minimized when the government selects a permit endowment less than the efficient level of pollution. Thus firms have an incentive to understate their abatement costs. Turning to the other mechanisms, the first one is called the *simple mechanism*. The government selects the endowment of permits according to the same rule as in Kwerel's mechanism but there is no subsidy. Under this mechanism, firms will not understate their abatement costs, but they are indifferent between overstating and telling the truth. The second mechanism is called the *minimum-price mechanism.* The government uses the same rule as in the other mechanisms to select the endowment of permits but also enforces a minimum price in the permit market. This mechanism induces firms to tell the truth.

We analyze the robustness of these results to the assumption that the citizens' demand fully captures damages. Pollution reduction is a pure public good. Because some citizens may free-ride on the permit purchases by others, the demand revealed in the market by citizens may be less than actual damages. The performance of Kwerel's mechanism improves as the free-riding problem becomes more severe whereas the performance of the simple mechanism deteriorates. In contrast, the minimum-price mechanism is not affected by the severity of the free-riding problem. Firms tell the truth and the efficient outcome is attained, no matter how severe the free-riding problem.

2 Kwerel's Mechanism

We begin by reviewing Kwerel's model and mechanism. Following his notation and assumptions, let X be total emissions of pollution. The government knows the damage from pollution. Damage as a function of emissions is denoted by $D(X)$. The first derivative D' and the second derivative D'' are both positive.

There are many polluting firms and they purchase pollution permits in a competitive market. Each firm has an abatement cost function which is not known by the government. Each firm's objective is to minimize total costs (the sum of abatement costs and net expenditures in the permit market.) So each firm selects permit holdings such that it's individual marginal abatement cost is equal to the price of permits. It follows that the marginal abatement costs are equal across all firms. So without loss of generality, we need only consider the aggregate abatement cost function[2], which we denote by $C(X)$. Again following Kwerel, the first derivative C' is negative and second derivative C'' is positive. The efficient level of pollution is the value X^* that satisfies $D'(X^*) = -C'(X^*)$.

In a mechanism, the government asks the firms to report their abatement cost functions. Based on their responses, the government determines the structure of the pollution permit market and firms purchase permits in the resulting market. The firms know how the government is going to use the information that the firms report. Let the reported aggregate

[2]Let firm j have emissions x_j and abatement cost $c_j(x_j)$. The aggregate abatement cost is defined by $C(X) = \min \sum c_j(x_j)$ such that $\sum x_j = X$.

abatement cost function be denoted by $\hat{C}(X)$.

We first consider the case in which citizens do not participate in the permit market. (Kwerel implicitly made this assumption.) Kwerel's mechanism is as follows.

Kwerel mechanism. *The government issues an endowment of permits L. It also pays a subsidy e per permit held in excess of emissions. The government selects the parameters L and e such that $D'(L) = -\hat{C}'(L) = e$.*

In the Kwerel mechanism, the government selects the permit endowment such that marginal damage is equal to reported marginal abatement cost. The subsidy is equal to the value of marginal damage at this endowment.

Let p be the price of permits. The firms' demand for permits, as described by Kwerel, is

$$\begin{cases} -C'(X) & \text{for} \quad p > e \\ \text{indeterminate} & \text{for} \quad p = e \\ \infty & \text{for} \quad p < e \end{cases}$$

If the price is above the subsidy, the firms' demand curve follows marginal abatement costs. If the price is equal to the subsidy, then firms are indifferent between buying and holding an extra permit. If the price is below the subsidy, then demand is infinite because firms can always make money by buying an extra permit and collecting the subsidy. Because there is a fixed supply of permits, the subsidy acts as a lower bound on the equilibrium price.

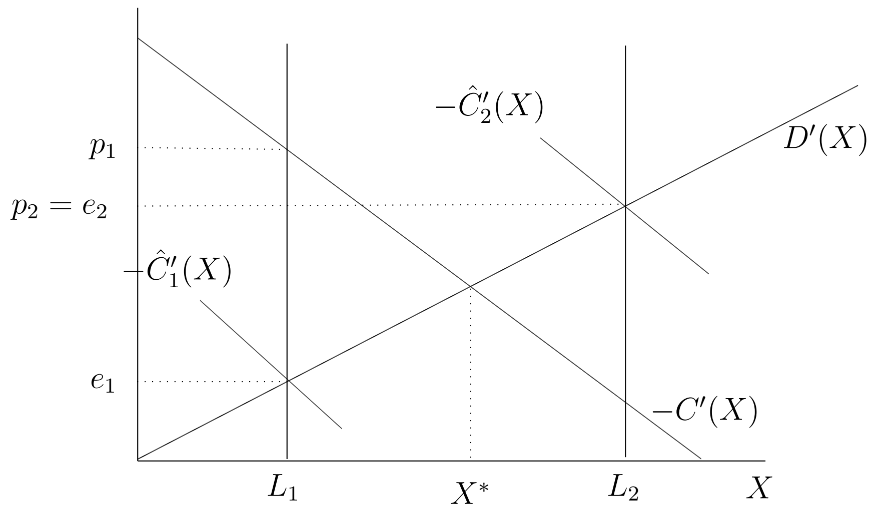
Rather than directly stating Kwerel's theorem, we state a proposition based on the key step in the proof of his theorem. Let $p(L)$ be the equilibrium price of permits as a function of the permit endowment.

k1 **Proposition 1.** *Suppose that citizens do not participate in the permit market, and the government uses the Kwerel mechanism. Then $p(L)$ attains a strict global minimum at $L = X^*$.*

With this proposition in hand, we are only a corollary or two away from Kwerel's theorem. Because each firm's total cost is increasing in p, it follows that each firm's total costs are minimized when the government picks $L = X^*$. If every other firm reports their true abatement costs, then the best strategy for a given firm is to report their true abatement costs. In other words, telling the truth is a Nash equilibrium.

Proposition 1 can be understood by reference to Figure 1. The marginal abatement cost and marginal damage intersect at X^*. Suppose that the firms understate their abatement costs and report $\hat{C}_1$. The government selects a permit endowment L_1 at the intersection of marginal damage and the reported marginal abatement cost $\hat{C}_1'$. The subsidy e_1 is equal to the value of marginal damage at L_1. Because the actual marginal abatement cost at the permit endowment is greater than the subsidy, the equilibrium price of permits p_1 is found at the intersection of the permit endowment and the actual marginal abatement cost. Now suppose that the firms overstate their abatement costs and report $\hat{C}_2$. The government selects a permit endowment L_2 at the intersection of marginal damage and the reported marginal abatement cost $\hat{C}_2'$. The subsidy e_2 is equal to the value of marginal damage at L_2. In this case, the actual marginal abatement cost at L_2 is less than the subsidy, so the equilibrium price of permits is equal to the subsidy. If firms tell the truth, then the government selects $L = X^*$. The subsidy and the equilibrium price of permits are found at the intersection of actual marginal abatement cost and marginal damage. This is the lowest price the firms can obtain, so it is in their interests to tell the truth.

Figure 1: Kwerel Mechanism kwf



3 Citizen Participation

In this section, we analyze the effect on Kwerel's mechanism of including citizens in the permit market. Because citizens do not generate emissions, they obtain the subsidy for every permit purchased. So their effective price for permits is $p - e$. The government could try to prevent citizens from participating in the market, or at least obtaining the subsidy, but such efforts are costly and may be futile. Even if explicitly prohibited from obtaining the subsidy, citizens would have an incentive to bargain on the side with a firm to buy and hold some permits in excess of emissions.

Both citizens and firms have a demand for permits. The firms' demand was described above. To determine the citizens' demand, we assume at first that citizens act in concert as a single entity. Subsequently we analyze the effects of free-riding by citizens. Let R be the quantity of permits purchases by citizens. Given the government's choice of L and e and given the price of permits p, the citizens solve

$$\min_{R} \; D(L-R) + (p-e)R$$
$$\text{such that } R \geq 0.$$

The market price determines whether the constraint is binding. If $p \geq D'(L)$, then citizens are "priced out" of the market. The marginal damage at the endowment of permits is less than the price and so permits are too expensive to retire. If $p < D'(L)$, then citizens retire permits such that first-order condition

$$p = D'(L-R) + e \tag{1}$$ focc

is satisfied. Thus the citizens' demand for permits can be summarized by

$$\begin{cases} 0 & \text{for} \quad p \geq D'(L) \\ D'(L-R) + e & \text{for} \quad p < D'(L) \end{cases}$$

The case in which $p < D'(L)$ illustrates the effect of the subsidy on the citizens' demand for permits. In the absence of the subsidy, citizens' demand would be $D'(L-R)$. So the subsidy shifts demand vertically by an amount equal to the subsidy.

Once again the equilibrium price is a function of the permit endowment. Figures 2 and 3 illustrate the two cases. In Figure 2, the permit endowment is such that the value of permits to firms is greater than value of permits to citizens. In other words

$$-C'(L) \geq D'(L) + e. \tag{2}$$

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Thus citizens are priced out of market and $p = -C'(L)$. In Figure 3, the endowment is such that the value of permits to citizens is greater than the value of permits to firms. Both firms and citizens purchase permits. The equilibrium quantity of pollution is found at the intersection of marginal damage plus the subsidy and marginal abatement cost. So the market price and equilibrium level of pollution are determined by

$$D'(X) + e = p = -C'(X). \tag{3}$$

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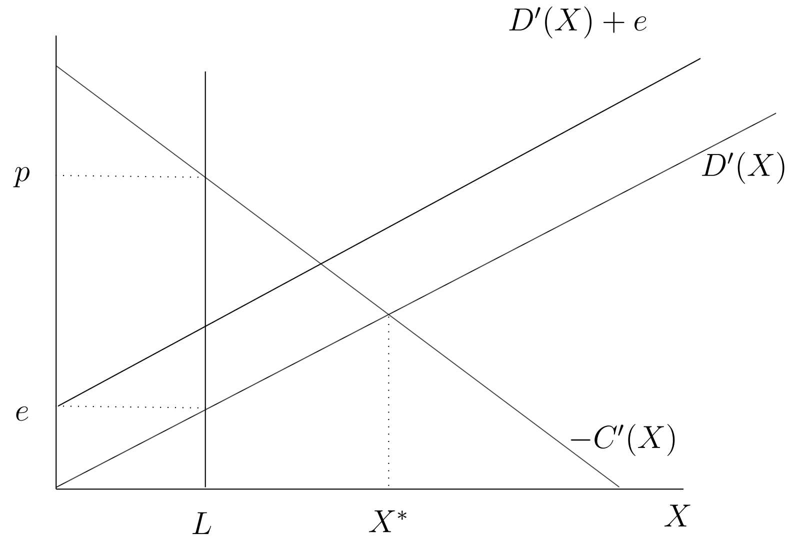
In equilibrium, citizens retire $R = L - X$ permits.

By participating in the permit market, then, citizens may effect the equilibrium price of permits. The following proposition delineates the effects of their participation on the Kwerel Mechanism. (All proofs are in the Appendix.)

k2 **Proposition 2.** *Suppose that citizens participate in the permit market, and the government uses the Kwerel mechanism. Then there exists a L_k (with $L_k < X^*$), such that $p(L)$ attains a strict global minimum at L_k.*

Because $p(L)$ attains a strict global minimum at a value less than the efficient level, firms have an incentive to understate their costs. The problem is the subsidy induces citizens to purchase more permits than they otherwise would. This drives the price up, which hurts firms. The best strategy for firms is to understate costs so that citizens are just priced out

Figure 2: Kwerel Mechanism with Citizens Priced Out kwcs



of the market.

4 Simple Mechanism

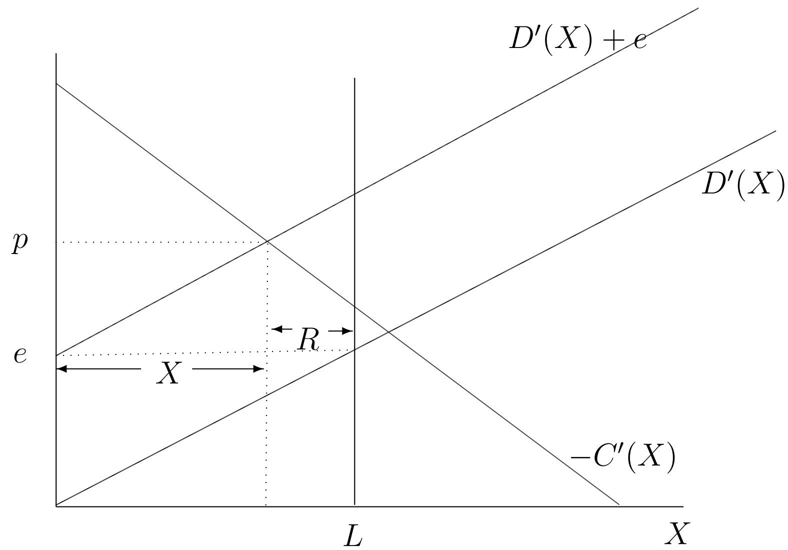
Because the subsidy induces citizens to purchase too many permits, one idea is to simply remove it from Kwerel's mechanism. Perhaps surprisingly, the resulting mechanism is weakly incentive compatible.

Simple mechanism. *The government issues an endowment of permits L. The government selects L such that $D'(L) = -\hat{C}'(L)$.*

The government selects the endowment of permits in the same way as in the Kwerel mechanism.

The firms' demand for permits is equal to $-C'(X)$ and the citizens' demand for permits

Figure 3: Kwerel Mechanism with Citizens Purchasing Permits kwcl



is summarized by

$$\begin{cases} 0 & \text{for} \quad p \geq D'(L) \\ D'(L-R) & \text{for} \quad p < D'(L) \end{cases}$$

Kewerl shows that, in the absence of citizen participation, the simple mechanism gives firms an incentive to overstate their costs. When costs are overstated, the government issues more permits, which lowers the market price. With citizen participation, however, the permit price does not fall when firms overstate their costs because citizens purchase permits. Thus the simple mechanism is weakly incentive compatible as shown by the following proposition.

propsim **Proposition 3.** *Suppose that citizens participate in the permit market, and the government uses the simple mechanism. Then there exists a L_s (with $L_s = X^*$), such that $p(L)$ is decreasing for $L < L_s$ and equal to the constant $-C'(L_s)$ for $L \geq L_s$.*

Proposition 3 shows that $p(L)$ has a global minimum, but not a strict global minimum, at the efficient level of pollution. Firms are indifferent between telling the truth and overstating their abatement costs. The more firms overstate though, the more money citizens have to spend on permit purchases. As the name implies, the appeal of this mechanism is simplicity. The government only determines the permit endowment, it does not have to administer a subsidy program or enforce a minimum price.

5 Minimum-Price Mechanism.

By using a more complicated mechanism, we can induce a strict minimum for $p(L)$ at the efficient level of pollution, even with citizen participation. To be incentive compatible, a mechanism must keep the price of permits high when firms overstate their costs. Kwerel's mechanism uses a subsidy, but then this entices citizens to purchase to many permits. The trick is to keep the price high without inducing citizen participation. The government can do this by enforcing a minimum price in the permit market.

Minimum-Price mechanism. *The government issues an endowment of permits L. It also enforces a minimum price $\bar{p}$ in the permit market. The government selects the parameters L and $\bar{p}$ such that $D'(L) = -\hat{C}'(L) = \bar{p}$*

The endowment of permits is set in the usual way and the minimum price is equal to marginal damage at the endowment of permits.

Let $\bar{X}$ satisfy $-C'(\bar{X}) = \bar{p}$. The firms' demand for permits is

$$\begin{cases} -C'(X) & \text{for} \quad p > \bar{p} \\ -C'(\bar{X}) & \text{for} \quad p = \bar{p}. \end{cases}$$

The citizens are priced out of the market in this mechanism, as the market price is greater than or equal to marginal damage at the permit endowment.

The minimum-price mechanism is incentive compatible.

propmin **Proposition 4.** *Suppose that citizens participate in the permit market, and the government uses the minimum-price mechanism. Then there exists a L_m (with $L_m = X^*$), such that $p(L)$ attains a strict global minimum at L_m.*

Since the global minimum is strict, firms have a strict incentive to tell the truth. The government then creates the efficient endowment of permits and citizens are priced out of the market.

6 Free-Riding

In this section, we relax the assumption that citizens' demand fully captures damages. Following Smith and Yates (2003) we define the degree of free-riding by the parameter r with $0 \leq r \leq 1$. (When $r = 1$ there is no free-riding.) Let the citizens' effective damage be determined by $E(X) = rD(X)$. The citizens' demand for permits is now derived from the effective damage, rather than the actual damage. For example, under the simple mechanism, the citizens' demand for permits is $rD'(L - R)$ for the case in which $p < D'(L)$.

The propositions above describe the properties of the equilibrium price function for the case in which $r = 1$. It is straightforward to parameterize the results by r. For the Kwerel mechanism, $p(L)$ attains a strict global minimum minimum at $L_k(r)$. Proposition 2 implies that $L_k(1) < X^*$. For the simple mechanism, $p(L)$ is decreasing for $L < L_s(r)$ and a constant for $L \geq L_s(r)$. Proposition 3 implies that $L_s(1) = X^*$. For the minimum-price mechanism, $p(L)$ attains a strict global minimum at $L_m(r)$. Proposition 4 implies that $L_m(1) = X^*$.

The following proposition describes the comparative statics for r.

compstat **Proposition 5.** *Suppose that citizens participate in the permit market and the degree of free riding is described by the parameter r. Then $dL_k/dr < 0$; $dL_s/dr < 0$; and $dL_m/dr = 0$.*

As free-riding becomes more severe, the minimum point of $p(L)$ in the Kwerel mechanism increases toward X^*. So firms have a decreasing incentive to understate abatement costs. In the extreme case, we have $L_k(0) = X^*$. If citizen participation is stymied by severe free-riding, then we have conditions of Kwerel's original model and of course the Kwerel mechanism is incentive compatible. On the other hand, as free-riding becomes more severe, the minimum point of $p(L)$ for the simple mechanism increases away from X^*. So firms have an increasing incentive to overstate abatement costs. The minimum-price mechanism is robust to free-riding. Regardless of the severity of free-riding, the minimum-price mechanism gives firms the incentive to tell the truth.

7 Conclusion

Kwerel's mechanism and the simple mechanism are incentive compatible at the opposite extremes of free-riding. If free-riding is so severe it prevents any citizens from participating, then Kwerel's mechanism is incentive compatible. If free-riding does not occur at all, then the simple mechanism is incentive compatible. In contrast, the minimum-price mechanism is incentive compatible for any degree of free-riding. By enforcing a minimum price in the permit market, the government prices citizens out of the market and firms have the incentive to tell the truth about their abatement costs.

It is likely that at least some free-riding occurs in actual pollution permit markets. This suggests the minimum-price mechanism may be the preferred mechanism in policy applications.

8 Appendix

Proof of Proposition 2. Equation (2) gives the condition for citizens to be priced out of the market. Now in Kwerel's mechanism, $e = D'(L)$. So (2) becomes

$$-C'(L) \geq 2D'(L)$$

Let L_k be the value of L that satisfies this equation with equality. For $L = L_k$ we have $p = -C'(L_k)$. We also know that $L_k < X^*$. (Because $-C'(L_k) = 2D'(L_k)$ it follows that $-C'(L_k) > D'(L_k)$. Then $L_k < X^*$ follows from the definition of X^* and the fact that $D'' > 0$ and $C'' > 0$.)

For $L < L_k$, the fact that $D'' > 0$ implies $e = D'(L) < D'(L_K)$. Likewise, the fact that $C'' > 0$ implies that $-C'(L) > -C'(L_k)$. So for $L < L_k$ we have

$$D'(L) + e < 2D'(L_k) = -C'(L_k) < -C'(L).$$

It follows that citizens are priced out of the market and we have $p = -C'(L) > -C'(L_k)$.

Now for $L > L_k$ the fact that $D'' > 0$ implies that $e = D'(L) > D'(L_k)$. Likewise, fact that $C'' > 0$ implies that $-C'(L) < -C'(L_k)$. So for $L > L_k$ we have

$$D'(L) + e > 2D'(L_k) = -C'(L_k) > -C'(L).$$

It follows that citizens and firms purchase permits and the equilibrium market price is determined by equation (3). With $e = D'(L)$ equation (3) becomes

$$D'(X) + D'(L) = -C'(X).$$

Re-arranging yields

$$-C'(X) - D'(X) = D'(L). \tag{4}$$

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From the definition of L_k we have

$$-C'(L_k) - D'(L_k) = D'(L_k). \tag{5}$$

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Because $D'(L) > D'(L_k)$, it follows from (4) and (5), as well as $D'' > 0$ and $C'' > 0$, that $X < L_k$. Now, from (3), we have $p = -C'(X)$ and since $C'' > 0$ we have $p = -C'(X) > -C'(L_k)$.

In summary, for $L < L_k$, we have $p > -C'(L_k)$. For $L > L_k$, we have $p > -C'(L_k)$. And for $L = L_k$ we have $p = -C'(L_k)$. Thus $p(L)$ attains a strict global minimum at L_k, and as noted above, $L_k < X^*$.

Proof of Proposition 3. In the simple mechanism, citizens are priced out of the market if $D'(L) \leq C'(L)$. Let L_s satisfy this equation with equality. By definition of efficiency, we know $L_s = X^*$. For $L = L_s$, we have $p = -C'(L_s)$.

For $L < L_s$, citizens are priced out of the market. We have $p = -C'(L)$. Because $C'' > 0$, we know p increases as L decreases.

For $L > L_s$, firms and citizens buy permits. The equilibrium is described by

$$D'(X) = p = -C'(X).$$

The solution to this equation is $X = X^*$. So $p = -C'(X^*)$ for $L > L_s$.

Proof of Proposition 4. Citizens are always priced out of the market. Let L_m be the solution to $D'(L) = -C'(L)$. By definition of efficiency, $L_m = X^*$. For $L = L_m$, we have $p = \bar{p} = D'(X^*) = -C'(X^*)$.

For $L < L_m$, we have $\bar{p} = D'(L) < -C'(L)$. So the equilibrium price has $p = -C'(L)$ and because $C'' > 0$, we have $C'(L) > -C'(X^*)$. Thus $p > -C'(X^*)$.

For $L > L_m$, we have $\bar{p} = D'(L) > C'(L)$. So the equilibrium price is equal to the minimum price. Because $D'' > 0$ we have $\bar{p} = D'(L) > D'(X^*) = -C'(X^*)$. So the equilibrium price is greater than $C'(X^*)$.

Thus $p(L)$ attains a strict global minimum at L_m.

Proof of Proposition 5. If citizens are priced out of the market for $r = 1$, then they are priced out of the market for $r < 1$. Thus $dL_m/d_r = 0$.

In the Kwerel Mechanism, when the degree of free-riding is r, the citizens' demand for permits is described by

$$\begin{cases} 0 & \text{for} \quad p \geq rD'(L) \\ rD'(L-R)+e & \text{for} \quad p < rD'(L) \end{cases}$$

The value $L_k(r)$ is boundary value for which citizens are priced out of the market. With free-riding, the analogue of equation (2) is

$$rD'(L_k) + e = -C'(L_k).$$

The subsidy is determined by the actual, not revealed, marginal damages. So we have

$$rD'(L_k) + D'(L_k) = -C'(L_k).$$

Taking the derivative with respect to r and solving yields

$$dL_k/dr = -D'/((1+r)D'' + C'') < 0.$$

In the simple mechanism the citizens' demand for permits is described by

$$\begin{cases} 0 & \text{for} \quad p \geq rD'(L) \\ rD'(L-R) & \text{for} \quad p < rD'(L) \end{cases}$$

The value $L_s(r)$ is the boundary value for which citizens are priced out off the market. With free-riding, this equation for L_s is

$$rD'(L_s) = -C'(L_s).$$

Taking the derivative with respect to r and solving yields

$$dL_c/dr = -D'/(rD'' + C'') < 0.$$

References

1. M. Ahlheim and F. Schneider, Allowing for household preferences in emission trading, *Environ. Res. Econom.* **21**, 317–342 (2002).

2. J. Boyd and J. Conley, Fundamental nonconvexities in Arrovian markets and a Coasian solution to the problem of externalities, *J. Econom. Theory* **72**, 388–407 (1997).

3. J. Conley and S. Smith, Coasian equilibrium, *J. Math. Econom.* **41**, 687-704 (2005).

4. D. Israel, Demand for acid rain reduction: Evidence from the sulphur allowances market, Indiana State University (2002).

5. E. Kwerel, To tell the truth: imperfect information and optimal pollution control, *Rev. Econom. Stud.* **44**, 595-601 (1977).

6. D. Malueg and A. Yates, Citizen participation in pollution permit markets, to appear, *J. Environ. Econom. Manage.* (2005).

7. R. Shrestha, Uncertainty and the choice of policy instruments: a note on Baumol and Oates propositions, *Environ. Res. Econom.* **12**, 497–505 (1998).

8. S. Smith and A. Yates, Optimal pollution permit endowments in markets with endogenous emissions, *J. Environ. Econom. Manage.* **46**, 425–445 (2003).