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Self-Reporting of Pollution and the Firm's Behavior under Imperfectly Enforceable Regulations[1]

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Motivated by the nature of U.S. laws, a model is developed for a firm that maximizes expected profit and faces imperfectly enforceable pollution standards with imperfectly enforceable reporting requirements. Some previous models of imperfectly enforceable standards and taxes are special cases of this general model. When the fine for violating the pollution standard is linear in excess pollution, the form will equate the marginal cost of control to the marginal fine rate, and thus actual pollution will be insensitive to enforcement parameters related to under-reporting. The more complex comparative statics that exist when the fine is non-linear are analyzed, and comparisons with other models are made.

Various aspects of the enforcement of pollution control laws have been examined in Martin [7], Linder and McBride [6], Downing [2], Harford [4], and Downing and Watson [3], as well as other works. These papers have examined the firm's reaction to imperfectly enforced pollution standards or taxes and some of them have examined the problem of optimal enforcement of the pollution control laws. With respect to the tax case, both Harford [4] and Linder and McBride [6] show that the expected profit maximizing firm will choose to set the marginal cost of pollution control equal to the rate of tax on pollution as long as not all of the pollution tax is evaded. Thus, relatively large variations in enforcement efforts may have no effect on a particular firm's actual emissions.[2]

On the other hand, most models of imperfectly enforceable pollution standards, including Harford's [4], generally have produced the result that the level of actual pollution is sensitive in a continuous way to the probability of being caught emitting excess pollution and the rate of penalty for such a violation. Thus, the existing literature has indicated a fundamental asymmetry in the nature of the firm's response to imperfectly enforceable versions of standards and taxes.

One of the significant results shown here is that the case of imperfectly enforceable pollution standards can exhibit a similar kind of separability between the actual pollution choice of the firm and aspects of the enforcement environment. It is also shown that this general model encompasses the imperfectly enforceable tax and the imperfectly enforceable pollution standard (with no reporting requirement) cases, as well as cases not considered in previous papers. The nature of the model forces one to recognize that a pollution tax is essentially a fine for violating a

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[2]Martin [7] has shown that this independence between self-reporting enforcement parameters and actual pollution will fail if the probability of being penalized is a function of the relative, rather than the absolute, size of the under-reporting.

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standard that allows zero pollution. While this concept is implicit in some earlier works, such as that of Roberts and Spence [8], it appears not to have been widely appreciated by those considering imperfectly enforceable pollution controls.[3]

An initial impetus for this paper is the fact that firms are largely responsible for reporting their own level of pollution and, in some cases, actually report their own violations of standards. In discussing this situation with regard to water pollution, Downing [2] states, "A possible explanation for this curious phenomenon is that the penalty for falsification of records is far greater than the penalty for violating the source's operating permit." (p. 579) An examination of the relevant Federal legislation confirms that there are separate penalties for under-reporting pollution that are in addition to penalities for violating the pollution standard itself.[4]

Accordingly, in this paper the firm faces two decisions beyond that of its output. One decision is how much pollution to generate, and therefore how large a violation of the standard to create. A second decision is how much pollution to report to the control authority, and therefore how much violation to report and how much to attempt to conceal. The penalty for the reported violation is assumed to be levied with certainty. The additional penalty for under-reporting pollution is levied only if the control authority discovers the violation of the honest reporting requirements. It is this model which encompasses both the imperfectly enforceable tax and standard cases.

In Section I we develop the objective function and the first order conditions for an interior maximum of expected profits for a firm facing the circumstances described above. Section II discusses comparative statics results regarding the firm's change in reported and actual wastes with respect to the various enforcement parameters. An Appendix contains the mathematical derivations of the comparative statics results. Section III explores the relationship of the present model to other models, and considers some policy implications of the results. A few summary remarks conclude the paper.

I. THE MODEL

It is assumed that a profit maximizing firm producing an output Q and pollution w has a revenue function $R[Q]$ and a cost function $C[Q, w]$, where $C_Q > 0$, and $C_w < 0$ hold over the range of interest. It is further presumed that $C_{QQ} > 0$ and $C_{ww} > 0$ and that C_{Qw} is less than or equal to zero. The firm faces penalties for violating a pollution standard which allows s amount of pollution in each period. The monetary penalty for reporting a level of pollution r that exceeds the standard is $F[r - s]$, which is levied with certainty.

If the actual level of pollution exceeds the reported pollution, then the firm faces a probability $p[w - r]$ of paying an under-reporting fine in an amount of $G[w - r]$,

[3] For example, the Linder and McBride [6] paper treats the firm's reactions to standards and taxes as separate cases in a manner similar to this writer in [4]. This author failed to see all the connections between the standard and tax case even though the latter paper briefly considered the possibility of some "free pollution" in the tax case.

[4] See Public Law 92-500, the Amendments to the Federal Water Pollution Control Act, Title III, Section 309, and Public Law 91-604, the Clear Air Amendments of 1970, section 113. Both pieces of legislation authorize fines up to $25,000 per day for violations of standards, and fines up to $10,000 for falsifying records related to the self-monitoring of emissions. There is also the possibility of a prison term for individuals responsible for either kind of violation.

plus an incremental fine for violating the standard of $(F[w - s] - F[r - s]) = f$, where the variables in the square brackets are arguments of the function denoted by the preceding letter. It is assumed that the penalty for under-reporting and the penalty for violating the standard are both positive functions of their arguments. The probability of detection of under-reporting is assumed to be a non-decreasing function of the amount of under-reporting.

It will be assumed that the firm maximizes its expected profits by its choices of output, actual pollution, and reported pollution. The assumption of risk neutrality can be justified either on the basis that the risk associated with non-compliance with pollution regulations is small or that such risk can be diversified away on the part of the investors in our firm.[5] Mathematically, the expected profit function can be written

$$N = R - C - F - p(G + f) = R - C - pG - pF[w - s] - (1 - p)F[r - s]. \tag{1}$$

Setting allowed pollution $s = 0$, and $F' = t$, where t is a constant, yields an objective function corresponding to that for a firm facing an imperfectly enforceable pollution tax.[6] If one imposes the constraint $r = s$, and leaves other features the same, then the size of the firm's violation of the standard and its amount of under-reporting are identical. The standards model of Harford [4] essentially corresponds to this case. In the present context, such a situation represents a type of corner solution to the firm's decision problem. Whenever the firm chooses an $r > s$, and $s > 0$, then the present objective function cannot be reduced to either of these traditional models.[7]

The first order conditions for an interior maximum of expected profit with respect to output, actual pollution and reported pollution are

$$N_Q = R_Q - C_Q = 0 \tag{2a}$$

$$N_w = -C_w - p(G' + F'[w - s]) - p'(G + f) = 0 \tag{2b}$$

$$N_r = pG' + p'(G + f) - (1 - p)F'[r - s] = 0. \tag{2c}$$

[5] Some of our main results hold under the objective of maximization of expected utility of profits, but many derivations become significantly more complicated. Since control authorities appear to be more lenient with financially troubled polluters, one may suspect that the actual enforcement practices reduce the variance in earnings of a regulated firm compared with a policy of controls which ignored the financial situation of the firm. In this case, risks might be reduced by regulation. On the other hand, if the firm's profits are being regulated, as with most electric utilities, then it is likely that revenues would be a positive function of the strictness of the standard, and the trade-offs for the firm would change significantly.

[6] It appears to be robust to view the model of a firm facing an imperfectly enforceable pollution tax as a special case of the model of a firm facing an imperfectly enforceable standard with self-reporting requirements. For example, the same translation of the firm's objective function from the standard to the tax case would work if the firm maximized expected utility of profits rather than expected profits.

[7] Since there can be uncertainty regarding the relationship between a firm's efforts to control pollution and the amount emitted, it is worthwhile to point out that this model, with only a little trouble, can be re-interpreted to apply to a situation where the firm's *effort* to control pollution, however measured, is what is being regulated. In this case, w would be re-interpreted as the actual effort to control pollution, r would be the reported effort, and s would be the legally required effort. The only mathematical differences would be that the derivatives C_w and C_{Qw} would now be positive and the arguments of the p, F, and G functions would have their signs reversed.

Equation (2a) is the usual profit maximizing condition that marginal revenue equal marginal cost. Equation (2b) indicates that the marginal cost of reducing pollution should equal the reduction in the expected penalty from under-reporting of pollution and the expected increment in the fine associated with violating the pollution standard. Equation (2c) indicates that the level of reported pollution, and thus the reported violation of the standard, should be such that the rate of change in the expected penalty for under-reporting plus the change in the expected incremental fine for standard violation should equal the (certain) rate of change in the fine on the reported level of violation.

If we add Eqs. (2b) and (2c), eliminate some terms and re-arrange, the result

$$-C_w = pF'[w - s] + (1 - p)F'[r - s] \tag{3}$$

is obtained. This equation indicates that the marginal cost of pollution control should equal the weighted average of the marginal fine rates for violations at levels $(w - s)$ and $(r - s)$ of the pollution standard, with the weights being the probabilities of being caught and not being caught under-reporting pollution, respectively.

If the marginal rate of fine for a pollution violation (discovered or reported) were a constant, then the expression above would reduce to, $-C_w = F'$. In other words, the level of pollution actually produced by an expected profit maximizing firm will be the same for a wide range of values of the level of the penalty associated purely with the under-reporting pollution. This separability result is the same as would be obtained for a model of an imperfectly enforced pollution tax. Accordingly, it is seen that an amount s of free pollution need not change the result, and that the fine rate for violating the standard plays virtually the same role in the marginal optimizing conditions as a pollution tax rate.

In this basic model, various kinds of corner solutions are possible which would make either (2b) or (2c) inequalities. If both the under-reporting penalty and the fine for violation of pollution standards increase rapidly enough so that, $N_W < 0$, and $N_r > 0$, are obtained throughout the relevant range, then both reported and actual pollution will equal the level set by the standard $(w = r = s > 0)$. If the expected penalty for under-reporting is large and increases rapidly in $(w - r)$, but the fine for reported violations of the standard is low and increases slowly in $(r - s)$, then $N_w = 0$, and $N_r > 0$, may obtain, and the firm will report the full amount of pollution which will exceed the standard $((w = r > s > 0)$. Of course, in this situation the marginal cost of pollution control will be equated to the marginal rate of fine for the actual excess pollution.

If the reverse of these latter conditions holds, then $N_w = 0$, and $N_r < 0$, may obtain throughout the relevant range, and reported pollution will equal the allowed level even though there will be pollution in excess of the standard $(w > r = s > 0)$. Under these circumstances, with appropriate notational adjustments, this model becomes equivalent to Harford's [4] model of imperfectly enforced pollution standards.[8]

[8]If $r = s$, $p(G[w - s] + F[w - s])$ becomes the (overall) expected penalty function for violating the standard as that concept was interpreted in Harford's [4] paper. In that paper, all excess pollution was assumed to be unreported and a single penalty function applied to the excess unreported pollution that was discovered.

II. COMPARATIVE STATICS

Since special cases of our present model are identical to other models, we will mainly discuss comparative statics results for those cases where $w > r > s > 0$. However, if $F' = t$, where t is a constant, certain special comparative statics results of this model are the same as those of an imperfectly enforceable pollution tax model.

In order to analyze the response of the firm to changes in the general level of p, G, and F, as well as changes in the level of the pollution standard (s), we introduce shift parameters for the first three functions, each equaling one in equilibrium. Thus it is assumed that we have the functions (up) instead of p, (hG) instead of G, (kF) instead of F, and $u = h = k = l$ initially. Given this notation we take the total differential of the equation system (2a), (2b), (2c) to obtain,

$$\begin{bmatrix} N_{QQ} & N_{Qw} & 0 \\ N_{wQ} & N_{ww} & N_{wr} \\ 0 & N_{rw} & N_{rr} \end{bmatrix} \begin{bmatrix} dQ \\ dw \\ dr \end{bmatrix} = \begin{bmatrix} -N_{Qu} & -N_{Qh} & -N_{Qk} & -N_{Qs} \\ -N_{wu} & -N_{wh} & -N_{wk} & -N_{ws} \\ -N_{ru} & -N_{rh} & -N_{rk} & -N_{rs} \end{bmatrix} \begin{bmatrix} du \\ dh \\ dk \\ ds \end{bmatrix}. \quad (4)$$

The second order conditions for an interior maximum require that the matrix on the left have a negative determinant, each second order principal minor be positive, and that the diagonal elements be negative. The expressions for all of the second order derivatives displayed above are given in the Appendix.

The signs indicated in the Appendix for the second order derivatives above will occur if p is constant, $F'' > 0$, and $G'' > 0$. We note here that if $F'' = 0$, then $N_{rs} = 0 = N_{ws}$, and that $N_{wu} = -N_{ru}$, and $N_{rr} = -N_{wr} = N_{ww} + C_{ww} < 0$. These results hold even if p is not a constant. They are helpful in obtaining comparative statics results for the case with F' constant.

As can be verified by the reader, if p is a constant, and $F'' = 0 = G''$, then $N_{rr} = 0$ and the second order conditions will not be satisfied. For p constant, either F'' or G'' must be positive for $N_{rr} < 0$ and satisfaction of the second order condition. For $F'' = 0 = G''$, p'' must be positive and p'' not too strongly negative to satisfy the second order conditions.

The comparative statics results displayed in the Appendix are generally intuitively plausible. Given a small proviso, an increase in the probability of being caught under-reporting pollution levels (increase in u) causes actual pollution to decline and reported pollution to increase. Both reactions are ways of reducing the degree of under-reporting in response to the higher probability of being caught. Indeed, the proviso on the sign of (A16) is needed because of a combination of interaction effects between the optimal actual and reported pollution, and between the optimal output and actual pollution. (See Appendix).

An increase in the allowed level of pollution causes the firm to increase both the actual and reported level of pollution. This results from the fact that the under-reporting penalty and the standards violation penalty will both be lower at the margin when the standard is relaxed, given our current assumptions. A general increase in the fine levels for under-reporting (increase in h) will cause actual pollution to fall and reported pollution to increase, with the latter result (A20) subject to a similar kind of proviso as mentioned in the last paragraph.

Finally, an increase in the fine function for violating the pollution standard (increase in k) will cause both actual and reported pollution to fall. Given this, will the amount of under-reporting increase or decrease as the fine for violating the standard is increased? To find out, we examine the rate of change of the under-reporting level $(w - r)$ with respect to the shift parameter k. The relevant partial derivative is

$$(\partial(w-r)/\partial k) = \left(N_{rk}\left(N_{QQ}N_{wr} + |H_{33}|\right) - N_{wk}N_{QQ}\left(N_{rw} + N_{rr}\right)\right)/|H|. \quad (5)$$

According to the analysis of signs given in the Appendix, (5) is ambiguous in general. However, if $F'' = 0$, then $(\partial(w-r)/\partial k) > 0$, as long as $(-N_{QQ}C_{ww} - (C_Q)^2) > 0$. This last condition is very likely to hold, and must hold for the firm under an absence of regulation or else the second order conditions for profit maximization would be violated. Thus, our results do indicate a degree of conflict between discouraging pollution and obtaining an honest reporting of the level of pollution.

In the particular case when $F'' = 0$, $G'' > 0$, and p' is non-negative, it follows that

$$(\partial w/\partial h) = (\partial w/\partial u) = (\partial w/\partial s) = (\partial r/\partial s) = 0. \quad (6)$$

In words, when the fine function for pollution standard violations is linear in the size of the violation, actual pollution is insensitive to the level of the standard, the probability of being discovered under-reporting pollution, and the general level of penalties for under-reporting. Furthermore, the level of reported pollution is insensitive to the level of standard in this case. (The signs of the other comparative statics results tend to remain the same.)

For a situation in which $p' > 0$, and $F'' > 0$, there is the possibility of ambiguity in the sign of the derivative N_{rs}, which leads to an ambiguity in at least one of our comparative statics results. It is easiest to discuss the nature of this ambiguity if we assume that the fine function F is quadratic in the difference between the known level of pollution and the pollution standard. In this case, F'' is constant, and $F' = F''(w - r)$.

With this simplication, we find that

$$N_{rs} = -p'F''(w-r)\left(1 + \left(1/E_{qv}\right)\right),$$

where $E_{qv} = -p'(w-r)/(1-p)$, which may be interpreted as the elasticity of $q = (1-p)$ with respect to $v = (w-r)$. In words, E_{qv} is the elasticity of the probability of not being caught under-reporting pollution with respect to the size of the under-reporting. The sign of E_{qv} is negative, so that $N_{rs} > 0$ requires that this elasticity be less than one in absolute value (greater than -1). However, if p' is "large" and/or $(1-p)$ is relatively small, then $E_{qv} < -1$, and $N_{rs} < 0$ becomes likely.

Not all of the comparative statics results are sensitive to the sign of N_{rs}, and of those that are, most will maintain the sign indicated in the Appendix as long as N_{rs} is not both negative and absolutely large. However, the sign of $(\partial w/\partial h)$ depends directly on the sign of N_{rs}. Recognizing that $N_{rr} + N_{wr} = -N_{rs}$, and using the fact that, $N_{rh} = -N_{wh}$, Eq. (A19) is shown to equal

$$(\partial w/\partial h) = -(N_{QQ}N_{rh}N_{rs})/|H|. \tag{7}$$

According to (7), the change in actual pollution with respect to a shift in the fine schedule for under-reporting will have the sign opposite N_{rs}. If $E_{qv} < -1$, implying $N_{rs} < 0$, then a proportional increase in the fine schedule for under-reporting pollution (G) will cause the actual level of pollution to *increase*.

This peculiar possibility arises because of the interaction that exists between reported wastes and the "average" fine rate for known violations of the pollution standard. An absolutely large value of E_{qv} implies that an increase in reported wastes will decrease p substantially (holding w constant), but it is clear that reported wastes increase with an upward shift in the fine schedule G. An increase in reported wastes thus lowers p, the weighting factor on $F'[w - s]$, and raises $(1 - p)$, the weighting factor on $F'[r - s]$, as those terms appear in equation (3). Since $F'[w - s] > F'[r - s]$, this shift in weighting tends to lower the "average" marginal fine rate to which the marginal cost of pollution control is equated. If this shift in weighting dominates the direct effect of an increase in r (causing $F'[r - s]$ to increase), then the firm will have the incentive to increase its chosen level of pollution as the penalties for under-reporting pollution become larger.

While $F'' > 0$ makes the second order conditions easier to satisfy, there is nothing in our analysis that rules out $F'' < 0$, as long as $G'' > 0$, and p is non-decreasing. In this regard, it should be noted that the results and reasoning regarding the sign of (7) are reversed if $F'' < 0$. Thus, either $F'' > 0$ and $E_{qv} < -1$, or, $F'' < 0$ and $E_{qv} > -1$, will produce the result that a proportional shift upward in the G function will cause an increase in actual pollution.

III. SOME POLICY IMPLICATIONS AND ADDITIONAL INTERPRETATIONS

In a model developed a decade ago, Roberts and Spence [8] analyzed a mixed system of perfectly enforceable pollution controls which embodied a licensing system with financial penalties and rewards for pollution above and below the licensed amount, respectively. While there are several differences between their model and this one, a comparison highlights the fact that an "unmixed" system of licenses or standards is not a possibility when controls are imperfectly enforceable. All standards or other quantity limitations must be backed up by fines or other "price-like" penalties for breaches of the limits.

Licenses, now called marketable permits, have been much discussed in recent years. They may be included in the present model by assuming that the firm is required to obtain an amount s of permits in order to legally emit amount s of pollution. If the firm could obtain all of the permits it desired at a price of m per unit, then an interior solution to the problem of maximizing expected profits with the one additional decision variable would result in the equalities,

$$-C_w = m = pF'[w - s] + (1 - p)F'[w - r], \tag{8}$$

where the fine is now for pollution beyond that allowed by the firm's permits. The result in (8) indicates that firms in a competitive permit market will equate their marginal costs of control to a common permit price even with some unlicensed pollution which faces a non-linear fine schedule. Actual pollution for a single firm might be independent of changes in its p, G, *and* F functions, but the market price of a fixed total of permits will be positively related to the average level of expected penalties for all firms.[9]

Assuming uncertainty in control costs, Watson and Ridker [10] recently analyzed the sum of pollution damage plus expected control costs under the alternatives of effluent taxes and quotas. This theoretical and empirical study, like the articles it cites, presumes perfect enforcement of quotas (standards) as well as taxes. If the presumption of perfect enforcement is dropped, the dichotomous nature of the decision disappears and a more continuous and richer set of choices emerges for the regulator.

With a linear fine for excess pollution, we have found that the actual choice of pollution depends only upon the constant marginal fine rate. It is clear that sufficiently strict standards, or a sufficiently low fine for violating them, can lead all firms to equate their marginal cost of pollution control to a common constant marginal fine rate. (If pollution damages are solely a function of the aggregate pollution emissions of all firms, then a common marginal fine rate would be appropriate.) In this circumstance, the overall reduction in pollution would seemingly be undertaken at a minimum of aggregate cost, given reasonable ancillary assumptions.

The goal of minimizing aggregate cost for a given reduction of pollution has often been the basis of support for a tax or marketable permit approach to pollution control. The usual textbook analysis argues that cost minimization under standards is extremely unlikely. (See Tietenberg [9, p. 275].) This view presumes perfect enforcement of standards which are set without the knowledge (or desire?) to achieve cost minimization. Thus, it seems that the fine rate for excess pollution has been neglected as an instrument which can be used in conjunction with a set of strict standards to promote the cost minimization goal. However, cost minimization is an incomplete efficiency criterion and imperfect enforcement adds other dimensions to the efficiency question.

Two points should be made regarding the relative efficiency of imperfectly enforceable taxes and standards. First, if the enforcement structure is exactly the same (with $F' = t$), then a firm facing the pollution tax ($s = 0$) will have higher expected average costs than an identical firm facing a pollution standard ($s = s_0$) by an amount (ts_0/Q), as long as both firms are reporting more than s_0 amount of pollution. This difference in expected average costs is the same as it would be under perfect enforcement. It implies that a competitive market equilibrium will be characterized by a smaller output under a pollution tax. This difference in equilibria reflects the standard's relative absence of an excise tax effect on output. With perfect competition and perfect enforcement, this absence of an excise tax effect makes the standard the inferior instrument of control, but this is less obvious under imperfect enforcement.

A second efficiency issue concerns variation in treatment of firms producing the same kind of output and pollution. If all firms are identical in other respects, then

[9]If some illegal pollution is being emitted by some firms, and the fine for excess pollution is linear and identical for all firms, then it is clear that the market equilibrium price of a pollution permit must equal the marginal fine rate. This result is in the same spirit as those of Roberts and Spence [8].

one could argue that it is efficient for all enforcement parameters to be the same for all firms. Variation in the enforcement parameters (the levels of p, G, and s) will cause expected average costs to vary across firms in an arbitrary way. Those firms which face the harshest enforcement will tend to go out of business more frequently than other firms. Since firms are assumed to be identical, this suggests that some enforcement effort would be wasted in such a case.

A deeper problem arises if firms vary in their costs of pollution control.[10] In the case of standards, Harford [5] has shown that relative efficiency requires that perfectly enforceable standards be set so that the equilibrium marginal cost of pollution control will be higher for those firms with the highest pollution control cost functions, ceteris paribus. This result is due to the standard's absence of an excise tax effect to properly discourage the output and pollution of high cost pollution-reducers. How imperfect enforcement affects this result is unclear. To address this question fully would require a complete specification of the heterogeneity among firms and the trade-offs facing the control authority. At this point, one can say only that the efficiency of any regulatory approach is unlikely to be separable from enforcement considerations.

IV. CONCLUSION

We have modeled the choices of firm maximizing expected profits and facing a pollution standard and a self-reporting requirement that are both imperfectly enforceable. For a firm choosing an interior solution, the actual pollution will be chosen so that the marginal cost of pollution reduction will equal a weighted average of the marginal fine rates for violating the standard by the reported margin and by the actual margin, with the weights being the probability of avoiding discovery and being discovered under-reporting pollution, respectively. In the case of a constant marginal fine rate for a violation of the standard, actual pollution is insensitive to the level of the standard, the probability of being caught under-reporting, and the general level of the penalty function for under-reporting pollution. With the marginal fine rate constant, the only real difference between the cases of an imperfectly enforced pollution tax and that of a standard is that the former allows zero amount of free pollution.

When the fine function for a violation of the standard has a convex shape with respect to the size of the violation, comparative statics results reveal that stronger enforcement of reporting requirements ordinarily will cause actual pollution to fall. A possible exception to this occurs when the probability of detecting under-reporting is highly sensitive to its amount. In this case the interaction between the choice of reported and actual pollution can cause higher levels of penalties for under-reporting to lead the firm to choose a greater level of pollution.

Greater rates of fine on reported violations of the standard, while reducing actual pollution, will tend to increase the amount of under-reporting according to our comparative statics results. This indicates a trade-off between encouraging the firm

[10] Our analysis assumes that the (subjective) probability and penalty functions are the same for all firms. Even if these functions were the same in some objective sense, the subjective views of the firms could vary significantly. In fact, it is likely to be in the interest of the monitoring authority to try to persuade firms that the expected penalties for under-reporting pollution are greater than they actually are.

to reduce pollution and encouraging it to report its amount honestly. Whether this trade-off is unavoidable depends partly upon the nature of the limitations on increasing monetary penalties for under-reporting, penalties which presumably have no social cost. The nature and implications of such limitations are a fit subject for future papers.

APPENDIX

The following are the expressions for the various second order derivatives of the expected profit function. The indicated signs are determined under the assumptions that $F'' > 0 < G''$, and p constant.

$$N_{QQ} = R_{QQ} - C_{QQ} < 0 \tag{A1}$$

$$N_{Qw} = -C_{Qw} > 0 \tag{A2}$$

$$N_{ww} = -J - C_{ww} - 2p'F'[w-s] - pF''[w-s] < 0 \tag{A3}$$

$$N_{wr} = J + p'(F'[w-s] + F'[r-s]) > 0 \tag{A4}$$

$$N_{rr} = -J - 2p'F'[r-s] - (1-p)F''[w-s] < 0, \tag{A5}$$

$$(J = 2p'G' + pG'' + p''(G+f)) \tag{A6}$$

$$N_{Qu} = N_{Qh} = N_{Qk} = N_{Qs} = N_{Qr} = 0 \tag{A7}$$

$$N_{ru} = p(G' + F'[r-s]) + p'(G+f) > 0 \tag{A8}$$

$$N_{wu} = -N_{ru} - p(F'[w-s] - F'[r-s]) < 0 \tag{A9}$$

$$N_{rs} = -p'(F'[w-s] - F'[r-s]) + (1-p)F''[r-s] > 0 \tag{A10}$$

$$N_{ws} = -N_{rs} + pF''[w-s] + (1-p)F''[r-s] > 0 \tag{A11}$$

$$N_{rh} = -N_{wh} = pG' + p'G > 0 \tag{A12}$$

$$N_{rk} = p'f - (1-p)F'[r-s] = N_{wh} < 0 \qquad \text{(by (2c))} \tag{A13}$$

$$N_{wk} = -N_{rk} - pF'[w-s] - (1-p)F'[r-s] = -N_{rk} + C_w < 0. \tag{A14}$$

Under the same conditions used to determine the signs in equation set (A1)–(A14), we can derive the comparative statics results,

$$(\partial w/\partial u) = N_{QQ}(N_{ru}N_{wr} - N_{wu}N_{rr})/|H| < 0 \tag{A15}$$

$$(\partial r/\partial u) = \left(-N_{ru}(|H_{33}|) + N_{QQ}N_{rw}N_{wu}\right)/|H| > 0^{*} \tag{A16}$$

$$(\partial w/\partial s) = N_{QQ}(N_{rs}N_{wr} - N_{ws}N_{rr})/|H| > 0 \tag{A17}$$

$$(\partial r/\partial s) = \left(-N_{rs}(|H_{33}|) + N_{QQ}N_{rw}N_{ws}\right)/|H| > 0 \tag{A18}$$

$$(\partial w/\partial h) = N_{QQ}(N_{rh}N_{wr} - N_{wh}N_{rr})/|H| < 0 \tag{A19}$$

$$(\partial r/\partial h) = \left(-N_{rh}(|H_{33}|) + N_{QQ}N_{rw}N_{wh}\right)/|H| > 0^{**} \tag{A20}$$

$$(\partial w/\partial k) = N_{QQ}(N_{rk}N_{wr} - N_{wk}N_{rr})/|H| < 0 \tag{A21}$$

$$(\partial r/\partial k) = \left(-N_{rk}(|H_{33}|) + N_{QQ}N_{rw}N_{wk}\right)/|H| < 0, \tag{A22}$$

where $|H_{33}| = (N_{QQ}N_{ww} - (N_{wQ})^2)$, the determinant of the matrix formed by deleting the third row and third column of H.

For the indicated sign of (A16) to hold, we must add the condition that $-(N_{QQ})(C_{ww} + p(F'' - f'(N_{rw}/N_{ru}))) - (N_{Qw})^2 > 0$, which is plausible, but not directly implied by our second order conditions. For the sign of (A20) to hold we must add the further condition that $-(N_{QQ})(C_{ww} + pF'')) - (N_{wQ})^2 > 0$, which appears more likely to hold than the condition offered for (A16). It is easily shown that the signs of (A16) and (A20) are assured if $N_{wr} = 0$, while maintaining the second order conditions. This requires $F'' > 0 = G'' = p' = p''$. Alternatively, if $N_{Qw} = -C_{Qw} = 0$, then the usual assumptions on the other derivatives assure the signs on (A16) and (A20). Thus, either the absence of the interaction effect between reported and actual wastes, or the absence of an output effect eliminates the potential sign ambiguities.

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