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# An Experimental Analysis of Compliance Behavior in Emissions Trading Programs: Some Preliminary Results

JAMES J. MURPHY*
Department of Resource Economics &
Center for Public Policy and Administration
University of Massachusetts-Amherst

JOHN K. STRANLUND
Department of Resource Economics
University of Massachusetts-Amherst

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**Abstract**

While there is a substantial body of economic theory about compliance and enforcement in emissions trading programs, and readily available information about how existing emissions trading programs are enforced, there are no empirical analyses of the determinants of compliance decisions in emissions trading programs. This paper contains preliminary results from laboratory experiments designed to examine compliance behavior in emissions trading programs.

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* Correspondence to James J. Murphy, Department of Resource Economics, Stockbridge Hall, University of Massachusetts-Amherst, Amherst, MA 01003, USA. Phone: (413)545-5716, Fax: (413)545-5853, E-mail: murphy@resecon.umass.edu.

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## 1. Introduction

Emissions trading programs are an innovative approach to controlling pollution that continues to gather support from policy makers and members of the regulated community. Conceptually, emissions trading programs are quite simple, yet have very powerful implications. By exploiting the power of a market to allocate pollution control responsibilities, well-designed trading programs promise to achieve environmental quality goals more cheaply than traditional command-and-control regulations.

Despite the perceived advantages of market-based environmental policies over traditional command-and control approaches, it is clear that the efficiency gains expected of emissions trading programs will not materialize if these programs are not enforced well. In fact, the problem of enforcing market-based pollution control programs is seen by some as one of the most important barriers to the widespread implementation of emissions trading programs [Russell and Powell (1996)]. There is now a fair-sized literature that addresses certain aspects of the problem of noncompliance in emissions trading systems, most of which is theoretical in nature. Some of this literature focuses on the consequences of noncompliance [Keeler (1991), Malik (1990, 1992, 2002), and vanEgteren and Weber (1996)], while some recent work in this area is devoted to the question about how to design enforcement strategies for emissions trading programs [Stranlund and Dhanda (1999), and Stranlund and Chavez (2000)].

While the theoretical work on compliance and enforcement in emissions trading programs progressed through the 1990's, full-scale emissions trading programs were implemented; most notably the Sulfur Dioxide Allowance Trading Program—the centerpiece of the EPA's Acid Rain Program—and the Regional Clean Air Incentives Market (RECLAIM) Program of the South Coast Air Basin of California. Thus, it is now possible to compare the theory of enforcing emissions trading programs to the actual practice of doing so. [See Stranlund, Chavez, and Field (2002) for such a comparison].

While there is a substantial body of economic theory about compliance and enforcement in emissions trading programs, and readily available information about how existing emissions trading programs are enforced, there are no empirical analyses of the determinants of compliance decisions in emissions trading programs. To begin to fill this empirical gap, we have embarked on an effort to design and conduct laboratory experiments to test existing theories about compliance behavior in emissions trading programs. In this paper we report on our experimental designs and provide preliminary results from these experiments.

Over the last 40 years, laboratory experiments have provided researchers with a better understanding of markets and human behavior. Experimental research has a well-established framework that is widely accepted for testing existing theories and for the design and analysis of public policies [Smith (1982), Bjornstad *et al*. (1999)]. Although, experimental techniques have been used to evaluate many other policy initiatives, including some aspects of emissions trading programs [Cason (1995), Cason and Plott (1996), Ishikida *et al*. (1998), Isaac and Holt(1999)], and individual compliance decisions for income taxation [Beck *et al*. (1991), Alm *et al*. (1992a), Alm (1998)], to our knowledge these techniques have not yet been used to analyze compliance and enforcement of environmental policies, including emissions trading programs.

At the simplest level, enforcement of any regulation is characterized by two components: monitoring to detect violations and the assessment of sanctions if a violation is found. Conceptually, a risk-neutral firm's decisions about whether to comply with a fixed emissions quota should be determined by the relationship between its marginal costs of reducing emissions and the marginal expected penalty it faces for a violation. (The marginal expected penalty is the probability of being found in violation times the marginal sanction for the violation). The reason is simple: when facing an emissions standard, the benefit to a firm of emitting more than the standard allows is the cost it would have to incur to reduce its emissions to satisfy the standard. Therefore, a firm's marginal control costs exactly indicate its marginal benefit of non-compliance to the standard.

Firms' compliance incentives when emissions quotas are tradable are quite different. Since compliance in this setting means holding enough permits to cover emissions, a competitive firm's marginal benefit of non-compliance is what it would have to spend for permits to make sure it is compliant; that is, the prevailing permit price. Furthermore, firms in an emissions trading program are linked together through the functioning of the permit market, whereas they are largely independent under command-and-control policies. Thus, because an individual firm's compliance decision is made by comparing the prevailing permit price to the marginal expected penalty, which summarizes the regulatory enforcement strategy the firm faces, enforcement decisions and how they impact compliance behavior are important determinants of prevailing permit prices. This suggests that any analysis of compliance behavior in emissions trading programs must examine both the direct effects on individual decisions from changes in say enforcement strategies, aggregate standards, and other exogenous factors, as well as the indirect effects that work through changes in prevailing permit prices.

The rest of this paper proceeds as follows: In the next section we specify the hypotheses about market prices and compliance decisions that will be tested with the experimental data. In the third section, we lay out our experimental design. We include ten different experimental treatments that vary according enforcement strategies and aggregate emissions standards. In the fourth section, we present some preliminary results from these experiments. At this date, these experiments are incomplete and the results have not been subjected to rigorous statistical tests. Therefore, the results we present should not be taken as conclusive. However, they do suggest that a fair number of theoretical hypotheses about compliance behavior are likely to be supported by the experimental data.

## 2. Hypotheses

The results we present address several hypotheses about how prevailing permit prices and compliance choices vary with changes of an aggregate emissions standard and changes in marginal expected penalties. The comparative static analysis that generated these hypotheses are in Appendix A.

**Hypothesis 1:** *The market price for permits should be decreasing as the aggregate standard increases.*

The first hypothesis is a simple test of a basic economic prediction: all else equal, as the supply of permits increases, the price of a permit should decrease.

**Hypothesis 2:** *Aggregate violations should be decreasing as the aggregate standard increases.*

Because price is a key determinant of compliance decisions in emissions trading programs, changes in the aggregate standard will also change aggregate levels of noncompliance. A higher aggregate standard will reduce aggregate violations, because the lower permit price will reduce firms' incentives toward noncompliance.

**Hypothesis 3:** *Aggregate violations should be decreasing as the marginal expected penalty is increased.*

Of course, for a fixed aggregate standard, aggregate violations will respond to changes in the enforcement strategy as well. A higher marginal expected penalty (either a higher probability that a violation will be discovered, or increased marginal penalties for violations) implies a reduced incentive toward noncompliance.

**Hypothesis 4:** *The market price for permits should be increasing as the marginal expected penalty increases.*

Enforcement strategies will also affect firms' demands for emissions permits. Imagine an emissions trading program in which there is a fair amount of noncompliance. To reduce the amount of noncompliance, suppose that the marginal expected penalty is increased. This will motivate the noncompliant firms to demand more permits to reduce the magnitude of their violations, which will put upward pressure on the equilibrium permit price.

**Hypothesis 5:** *For two enforcement strategies that generate the same marginal expected penalty schedules, but with different monitoring probabilities and marginal penalty schedules, permit prices and rates of non-compliance should be identical.*

A basic result from the economic theory of law enforcement is that the probability of punishment and the severity of punishment are perfect substitutes for deterring noncompliance by risk-neutral agents [Becker (1968)]. However, risk-averse agents will be deterred more effectively by the severity of punishment, while the reverse is true for those who are risk seekers. Experimental results reported in Block and Gerety (1995) and Anderson and Stafford (2003) suggest that, at least in experimental settings, sanctions have a qualitatively larger effect on compliance behavior than auditing probability. Nearly all of the theory of compliance in emissions trading programs assumes risk-neutral firms.[1] We will address the issue of the relative impacts of monitoring and punishment with this hypothesis.

[1] Malik (1990) appears to be the sole exception.

**Hypothesis 6:** *Individual violations in a permit market should be identical if firms are monitored with the same probability and they face the same penalties, even though they have different marginal abatement costs.*[2]

Stranlund and Dhanda (1999) argue that the differences in the size of individual violations of risk-neutral firms that trade emissions permit competitively should be independent of differences in their abatement costs. Thus, if two firms are audited with the same probability and the same enforcement effort is applied to each, they both should have the same level of violation even though one may employ a less-advanced emissions-control technology or use a dirtier production process. This suggests that, since nothing distinguishes the compliance incentives of competitive firms in emissions trading programs, there is no reason for an enforcer to contemplate a targeted enforcement strategy. That is, provided that penalties are applied uniformly, the firms should be monitored with the same probability.[3] We will address the empirical validity of this conclusion with this hypothesis.

## 3. Experimental Design and Procedures

### *3.1 Experiment design*

The experiments are designed to test hypotheses about the different factors that might influence a firm's compliance decisions when emissions permits are tradable. During each period of the experiment, subjects simultaneously choose to produce units of a fictitious good and trade in a market for permits to produce the good. Participants can produce as many units of the good as they wish (subject to production capacity constraints) regardless of the number of permits that they own. However, at the end of the period, each individual is audited with a known probability. If an individual is audited and found to be non-compliant (i.e., total production exceeds permit holdings), then a penalty is applied. The treatment variables in this paper are the aggregate standard (or supply of permits), the probability of audit, and the marginal penalty function.

2 This result should extend to differences in initial allocations of permits as well. We plan to test this hypothesis, but have not yet run the experiments we have designed to do so.

3 This result does not hold with emission standards. Garvie and Keeler (1994) show that firms with higher marginal abatement costs should be monitored more closely, because their incentives for noncompliance are greater than firms with lower marginal abatement costs.

Subjects received a benefit from their choice of production, $q$, according to the "Earnings from Production" schedules shown below in Table 1. If $q$ is thought of as emissions, these marginal benefit functions are marginal abatement costs functions. Note that Type-A subjects have higher marginal benefit functions than Type-B subjects. Each experiment consisted of four Type-A subjects and four Type-B subjects. Subjects could choose any level of production up to a capacity constraint, which was eight units for Type-A subjects and 17 units for Type-B subjects.

To be compliant, subjects were required to possess permits, $l$, to cover their production choices. Limiting the number of permits put into circulation imposed a cap on aggregate production. We chose two aggregate standards: one high ($Q_H = 56$) and the other low ($Q_L = 28$). In the high aggregate standard experiments, each of the eight subjects in an experiment received an initial allocation of seven permits. In the low aggregate standard experiments, each of the four Type-A firms was allocated three permits, and the four Type-B firms were each given four permits.

To check for compliance, subjects' records were examined with a known probability $\pi$. If a subject was examined and was found to be non-compliant; that is, $q > l$, they were penalized according to a penalty schedule generated from a quadratic penalty function, $f = F(q-l) + (\phi/2)(q-l)^2$, where $F$ and $\phi$ are positive constants. Note that the penalty function is strictly convex, so that each additional unit of violation brings a higher penalty.

**Table 1. Earnings from production for each subject type**
(E$ for each unit permit shortfall)

| | **Earnings from Production** *(E$ for each unit produced)* | |
|---|---|---|
| **Unit Produced** | **Type-A** | **Type-B** |
| 1st | 17 | 16 |
| 2nd | 16 | 14 |
| 3rd | 15 | 12 |
| 4th | 14 | 10 |
| 5th | 13 | 8 |
| 6th | 12 | 6 |
| 7th | 11 | 4 |
| 8th | 10 | 2 |
| 9th | 9 | |
| 10th | 8 | |
| 11th | 7 | |
| 12th | 6 | |
| 13th | 5 | |
| 14th | 4 | |
| 15th | 3 | |
| 16th | 2 | |
| 17th | 1 | |

**Notes**
- Earnings from Production are expressed as marginal, not total, dollars.
- The Earnings from Production schedule is a discrete approximation to the quadratic benefit function $b(q) = \alpha q - (\beta/2)q^2$, where $\alpha$ and $\beta$ are positive constants, chosen in part to guarantee that $b(q) > 0$ for all feasible levels of production, $q$. The benefit function parameters are: $\left[(\alpha_A = 17, \beta_A = 1), (\alpha_B = 16, \beta_B = 2)\right]$. The subscripts A and B denote subject type.

By changing the parameters of the marginal expected penalty function, $\pi f' = \pi[F + \phi(q - l)]$, we developed four enforcement strategies which we labeled *High*, *Med*($\pi_H$), *Med*($\pi_L$), and *Low*. (The tag *Med* should be read "medium"). The *High* marginal expected penalty (*MEP*) function was designed to induce perfect compliance to the aggregate standards, $Q_L$ and $Q_H$, using a high monitoring probability ($\pi_H = 0.70$) and a relatively high marginal Permit Shortfall Penalty function. The treatments *Med*($\pi_H$) and *Med*($\pi_L$) generate the same marginal expected penalties, but *Med*($\pi_H$) uses the high monitoring probability and a relatively low marginal penalty function, whereas *Med*($\pi_L$) uses a low monitoring probability ($\pi_L = 0.35$) and a higher marginal penalty function. Subjects were expected to choose to be noncompliant when facing both of these medium marginal expected penalty functions. The marginal expected penalty function *Low* was constructed to be the weakest enforcement strategy, with the low monitoring probability, $\pi_L$, and a low marginal penalty function. Enforcement parameter values were chosen, in part, so that the marginal expected penalty functions are parallel to each other—each has a slope of approximately one. The parameters for each experiment are shown in Table 2.

**Table 2. Enforcement strategy parameters**

| | **Aggregate Standard** | |
|---|---|---|
| **Enforcement Strategy** | $Q_L = 28$ | $Q_H = 56$ |
| *High MEP* | $(\pi_H, \phi_1, F_1)$ | $(\pi_H, \phi_1, F_1)$ |
| *Med*($\pi_H$) *MEP* | $(\pi_H, \phi_1, F_2)$ | $(\pi_H, \phi_1, F_2)$ |
| *Med*($\pi_L$) *MEP* | $(\pi_L, \phi_2, F_3)$ | $(\pi_L, \phi_2, F_3)$ |
| *Low MEP* | $(\pi_L, \phi_2, F_4)$ | $(\pi_L, \phi_2, F_4)$ |

The enforcement parameter values are $(\pi_L,\ \pi_H) = (0.35,\ 0.70)$, $(\phi_1,\ \phi_2) = (1.43,\ 2.90)$ and $(F_1,\ F_2,\ F_3,\ F_4) = (17.5,\ 6,\ 12,\ 2)$. The values for $\phi$ and $F$ generate the Permit Shortfall Penalty schedules shown in Table 3.

**Table 3. Permit Shortfall Penalties**
(E$ for each unit permit shortfall)

| Permit Shortfall | High | *Med*($\pi_H$) | *Med*($\pi_H$) | *Low* |
|---|---|---|---|---|
| 1st unit | 18.9 | 7.4 | 14.9 | 4.9 |
| 2nd | 20.4 | 8.9 | 17.8 | 7.8 |
| 3rd | 21.8 | 10.3 | 20.7 | 10.7 |
| 4th | 23.2 | 11.7 | 23.6 | 13.6 |
| 5th | 24.7 | 13.2 | 26.5 | 16.5 |
| 6th | 26.1 | 14.6 | 29.4 | 19.4 |
| 7th | 27.5 | 16.0 | 32.3 | 22.3 |
| 8th | 28.9 | 17.4 | 35.2 | 25.2 |
| 9th | 30.4 | 18.9 | 38.1 | 28.1 |
| 10th | 31.8 | 20.3 | 41.0 | 31.0 |
| 11th | 33.2 | 21.7 | 43.9 | 33.9 |
| 12th | 34.7 | 23.2 | 46.8 | 36.8 |
| 13th | 36.1 | 24.6 | 49.7 | 39.7 |
| 14th | 37.5 | 26.0 | 52.6 | 42.6 |
| 15th | 39.0 | 27.5 | 55.5 | 45.5 |
| 16th | 40.4 | 28.9 | 58.4 | 48.4 |
| 17th | 41.8 | 30.3 | 61.3 | 51.3 |

**Notes**

- Permit Shortfall Penalties are expressed as marginal, not total, dollars.
- The Permit Shortfall Penalty schedule was the same for each subject type with the exception that since Type-B firms could only produce a maximum of eight units, only the first eight steps in the penalty function were displayed.
- The Permit Shortfall Penalty schedule is a discrete approximation to the marginal penalty function $f' = F + \phi(q - l)$.

Table 4 summarizes the experimental design in a 5×2 matrix, where *MEP* denotes Marginal Expected Penalty. Each cell in the table was repeated twice.[4] The two columns represent the different aggregate standards (or total number of permits available), while the five rows reflect the different enforcement strategies.

[4] We will be running a third repetition of each cell in the Fall. The data reported in this paper include two experiments per cell.

**Table 4. Experimental design**

| Enforcement Strategy | Aggregate Standard | |
|---|---|---|
| | $Q_L = 28$ | $Q_H = 56$ |
| *Forced Compliance* | *A* | *B* |
| *High MEP* | *C* | *D* |
| *Med*($\pi_H$) *MEP* | *E* | *F* |
| *Med*($\pi_L$) *MEP* | *H* | *I* |
| *Low MEP* | *K* | *L* |

In addition to the four *MEP* experiments that allowed non-compliance, we also ran a set of *Forced Compliance* experiments. By removing the ability to be non-compliant, and therefore any risks associated with a possible audit, these experiments provide a baseline against which the market outcomes of the other experiments can be compared. The *Forced Compliance* experiments are procedurally similar to other permit market experiments such as Cason *et al*. (1999) and Franciosi *et al*. (1999). During the period, subjects could only trade permits and did not make concurrent production decisions. Instead, production automatically occurred after the trading period ended, and production exactly equaled the minimum of the total number of permits owned or the maximum number of units that could be produced. (We permitted individuals to hold more permits than their maximum production capacity to allow for possible speculative trading). In both the *Forced Compliance* and *High MEP* treatments, firms are expected to be compliant, that is $q = l$. In the former treatment, this result is trivial since noncompliance is not possible. In the latter treatment, although the parameters are set such that a risk-neutral individual would choose to be perfectly compliant, noncompliant choices are possible. Because the competitive equilibrium outcomes in these two treatments are identical, this will allow us to draw some inferences about how permitting non-compliance affects individual decisions and market prices.

*3.2 Experiment procedures*

Table 5 summarizes the key aspects of the experiments.

**Table 5. Experiment Summary**

- Subjects
  - All subjects participated in a 2-hour training session prior to participating in real data sessions.
  - 54 University of Massachusetts students recruited from a pool of 116 trained subjects.
  - Paid $7 for participating, plus experiment earnings (mean $14, range $10-$17).
- Number and Type of Subjects
  - 8 subjects, 4 of each type
    - Type-A: High marginal abatement cost
    - Type-B: Low marginal abatement cost
- Periods and Length
  - 12 five-minute periods during which subjects could produce units and trade permits.
  - Data from first two periods were discarded.
- Production
  - Producing units generates "Earnings from Production" (i.e., redemption values).
  - Production allowed only during first four minutes of period.
  - Each unit produced sequentially; production takes 10 seconds/unit.
  - Maximum number of units a subject can produce: Type-A=17, Type-B=8.
- Permit Market
  - Permit market open for entire five-minute period.
  - Continuous double auction.
  - Permits cannot be banked for future use.
- Auditing
  - Each individual faced same probability $\pi$ of being audited.
  - Random audits occur after production and market trading period is over.
  - Permit Shortfall Penalty function applied if audited and production exceeds permit holdings. The marginal penalties are increasing in the size of the shortfall.

Participants were recruited from the student population at the University of Massachusetts, Amherst. Subjects were paid $7 for agreeing to participate and showing up on time, and were then given an opportunity to earn additional money in the experiment. These additional earnings ranged between $10 and $17, with a mean of $14. Earnings were paid in cash at the end of each experiment. Each experiment lasted about 2 hours.

The experiments were run in a computer lab using software designed in Visual Basic specifically for this research. To familiarize subjects with the experiments, we initially ran a series of training experiments. In the first stage of the trainers, students read online experiment instructions, which included interactive questions to ensure that students understood the instructions before proceeding. After everyone had completed the instructions and all questions were answered, the training experiment began. These practice rounds contained all the same features as the "real data" experiments with the exception that we used a different set of training parameters. The data from the trainers were discarded.

For the real data sessions, we recruited participants from the pool of 116 trained subjects. Subjects were allowed to participate in multiple sessions. A total of 74 subjects participated in 20 eight-person market compliance experiments. Table 6 shows the distribution of the number of experiments in which an individual participated. The median and mode were two and one experiments, respectively. The maximum number of experiments was six, and the mean was 2.2.

**Table 6. Distribution of the number of experiments in which an individual participated**

| Number of Experiments Participated In | Number of Subjects | Percent |
|---|---|---|
| 1 | 29 | 39% |
| 2 | 20 | 27% |
| 3 | 15 | 20% |
| 4 | 5 | 7% |
| 5 | 4 | 5% |
| 6 | 1 | 1% |
| Total number of subjects | 74 | 100% |

Prior to the start of the real data experiments, subjects were given a summary of the experiment instructions (see Appendix B). The experimenter read these instructions aloud and answered any questions. The review of the instructions took about 10 minutes.

Each experiment consisted of 12 identical five-minute rounds. At the start of each period, the eight subjects were each given an initial allocation of permits and E$10 in cash.[5] Data from the first two rounds of each experiment were discarded.

[5] During the experiment, subjects earned experimental dollars (E$) that were converted to US dollars at a pre-announced exchange rate.

Each unit of the good was produced sequentially by clicking on a button that initiated the production process. Production of a single unit took 10 seconds. After production of the unit was completed the "Earnings from Production" were immediately added to the individual's cash balance. Subjects were able to "plan" future production by indicating the total number of units to produce. Once production of a unit was completed, if there were any "planned" units, the 10-second production process for the next would automatically begin. Subjects could increase or decrease their "planned" production, but units that were "in progress" or "completed" were committed and could not be changed. That is, subjects could alter planning decisions about units not yet produced, but they could not undo production of a good after the 10-second production process had begun.

A unique feature of our experiments is that the production decisions and permit market trading were unbundled into two separate, but simultaneous, activities. We did this to allow for the possibility that the production level and permit holdings could differ. Often in permit market experiments, perfect compliance is assumed (i.e., production exactly equals the number of permits owned at the end of the trading period) and subjects earn income based on their final permit holdings plus any net income from permit market trading [e.g., Cason *et al*. (1999), Franciosi *et al*. (1999)]. In our experiments, permits are useful because they are an instrument for choosing compliance rates, and they could also generate capital gains from speculative trading. Therefore, during the period and concurrent with the production decision, subjects also had the ability to alter their permit holdings by trading in a continuous double auction (CDA). In the CDA, individuals could submit bids to buy or asks to sell a single permit (provided that they had a permit available to sell). The highest bid and lowest ask price were displayed on the screen. A trade occurred whenever a buyer accepted the current ask or a seller accepted the current bid. After each trade, the current bid and ask were cleared and the market opened for a new set of bids and asks. The trading price history was displayed on the screen.

Each period lasted a total of five minutes. The permit market was open for the entire period, but production had to be completed in four minutes. The four-minute production time was more than sufficient for a subject to produce up to his or her capacity constraint. We provided the additional minute of permit trading after production was completed to give subjects a final opportunity to adjust their permit holdings. The computer screen displayed the time remaining for both production and the permit market.

As soon as a period ended, random audits were conducted and penalties were assessed. All information relating to audits penalties were private and not shared with the others in the experiment.

Since it was possible for individuals to lose money either through permit trading or permit shortfall penalties, we implemented a bankruptcy rule. If an individual's cash balance ever fell below negative E$800, he or she was declared bankrupt and was no longer allowed to participate. No subjects ever sustained a significant negative cash balance, let alone approached the bankruptcy threshold. We also instituted a price ceiling of E$20 above which offers to trade permits were not allowed. This ceiling was set above the highest possible "Earnings from Production" so had anyone paid this price for a permit she or he would have lost money. This constraint was non-binding as the maximum permit price in any experiment was E$14.

**4. Results**

In this section, we present some preliminary results from the experiments. At this date, the experiments are incomplete and the results have not been subjected to rigorous statistical tests. Therefore, the results we present should not be taken as conclusive. However, they do suggest that a fair number of theoretical hypotheses about compliance behavior are likely to be supported by the experimental data. Since we are primarily interested in equilibrium behavior, data from the first two periods were discarded to minimize the effects of learning, leaving us with 10 periods per experiment. We begin by presenting some simple descriptive statistics comparing competitive equilibrium and observed outcomes. We then make some observations about the hypotheses discussed above.

The competitive equilibrium outcomes presented in Table 7 assume that subjects are risk-neutral and trade in a perfectly competitive market. Note that the competitive equilibrium outcomes in the *Forced Compliance* and *High MEP* treatments are identical, likewise the *Med*($\pi_L$) *MEP* and *Med*($\pi_H$) *MEP* have the same competitive equilibrium. Table 8 contains the average observed outcomes for each subject type and treatment. The final permit balance, production quantity, and level of violations for each subject type are the mean of 80 observations per cell (two experiments, four subjects per type, 10 periods). In Table 8, the first line of each cell is the mean outcome from the two experiments. The second line is the percent difference between the mean outcome and the corresponding competitive equilibrium outcome in Table 7; a positive value indicates that the mean observed value exceeds the competitive equilibrium value.[6]

**Table 7. Competitive Equilibrium Outcomes**

| Low Aggregate Standard ($Q_L$ = 28) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Type-A | | | Type-B | | |
| **Enforcement Strategy** | **Permit Price** | **Permits** $l_A$ | **Production** $q_A$ | **Violations** $v_A=q_A-l_A$ | **Permits** $l_B$ | **Production** $q_B$ | **Violations** $v_B=q_B-l_B$ |
| A. *Forced Compliance* | (12, 13) | 5 | 5 | not applicable | 2 | 2 | not applicable |
| C. *High MEP* | (12, 13) | 5 | 5 | 0 | 2 | 2 | 0 |
| E. *Med*($\pi_H$) *MEP* | (8, 9) | 6 | 9 | 3 | 1 | 4 | 3 |
| H. *Med*($\pi_L$) *MEP* | (8, 9) | 6 | 9 | 3 | 1 | 4 | 3 |
| K. *Low MEP* | 6 | (6, 7) | 11 | (5, 4) | (1, 0) | 5 | (4, 5) |

| High Aggregate Standard ($Q_H$ = 56) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Type-A | | | Type-B | | |
| **Enforcement Strategy** | **Permit Price** | **Permits** $l_A$ | **Production** $q_A$ | **Violations** $v_A=q_A-l_A$ | **Permits** $l_B$ | **Production** $q_B$ | **Violations** $v_B=q_B-l_B$ |
| B. *Forced Compliance* | 8 | (9, 10) | (9, 10) | not applicable | (5, 4) | (4, 5) | not applicable |
| D. *High MEP* | 8 | (9, 10) | (9, 10) | 0 | (5, 4) | (4, 5) | 0 |
| F. *Med*($\pi_H$) *MEP* | (6, 7) | 10 | 11 | 1 | 4 | 5 | 1 |
| I. *Med*($\pi_L$) *MEP* | (6, 7) | 10 | 11 | 1 | 4 | 5 | 1 |
| L. *Low MEP* | 4 | (10, 11) | 13 | (3, 2) | (4, 3) | 6 | (2, 3) |

[6] For those cases in which the competitive equilibrium is a range, we used the value in the range that was closest to the mean value, i.e., how far is the mean value from just falling into the range.

**Table 8. Average Observed Outcomes**[a]

| Low Aggregate Standard ($Q_L$ = 28) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Type-A | | | Type-B | | | |
| **Enforcement Strategy** | **Permit Price** | **Permits** $l_A$ | **Production** $q_A$ | **Violations** $v_A=q_A-l_A$ | **Permits** $l_B$ | **Production** $q_B$ | **Violations** $v_B=q_B-l_B$ |
| A. *Forced Compliance* | 12.64 | 4.81 | 4.81 | not applicable | 2.19 | 2.19 | not applicable |
| C. *High MEP* | 12.41 | 4.31 | 4.78 | 0.46 | 2.69 | 2.89 | 0.20 |
| E. *Med*($\pi_H$) *MEP* | 9.54 | 4.54 | 7.56 | 3.03 | 2.46 | 4.81 | 2.35 |
| H. *Med*($\pi_L$) *MEP* | 12.07 | 3.95 | 5.35 | 1.40 | 3.05 | 4.20 | 1.15 |
| K. *Low MEP* | 8.19 | 4.75 | 8.08 | 3.33 | 2.25 | 5.44 | 3.19 |

| High Aggregate Standard ($Q_H$ = 56) | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | Type-A | | | Type-B | | |
| **Enforcement Strategy** | **Permit Price** | **Permits** $l_A$ | **Production** $q_A$ | **Violations** $v_A=q_A-l_A$ | **Permits** $l_B$ | **Production** $q_B$ | **Violations** $v_B=q_B-l_B$ |
| B. *Forced Compliance* | 7.78 | 9.11 | 9.11 | not applicable | 4.89 | 4.89 | not applicable |
| D. *High MEP* | 7.67 | 9.00 | 9.16 | 0.16 | 5.00 | 5.09 | 0.09 |
| F. *Med*($\pi_H$) *MEP* | 6.63 | 9.29 | 10.48 | 1.19 | 4.71 | 5.64 | 0.93 |
| I. *Med*($\pi_L$) *MEP* | 6.79 | 9.49 | 10.69 | 1.20 | 4.51 | 5.20 | 0.69 |
| L. *Low MEP* | 3.59 | 8.36 | 11.83 | 3.46 | 5.64 | 7.44 | 1.80 |

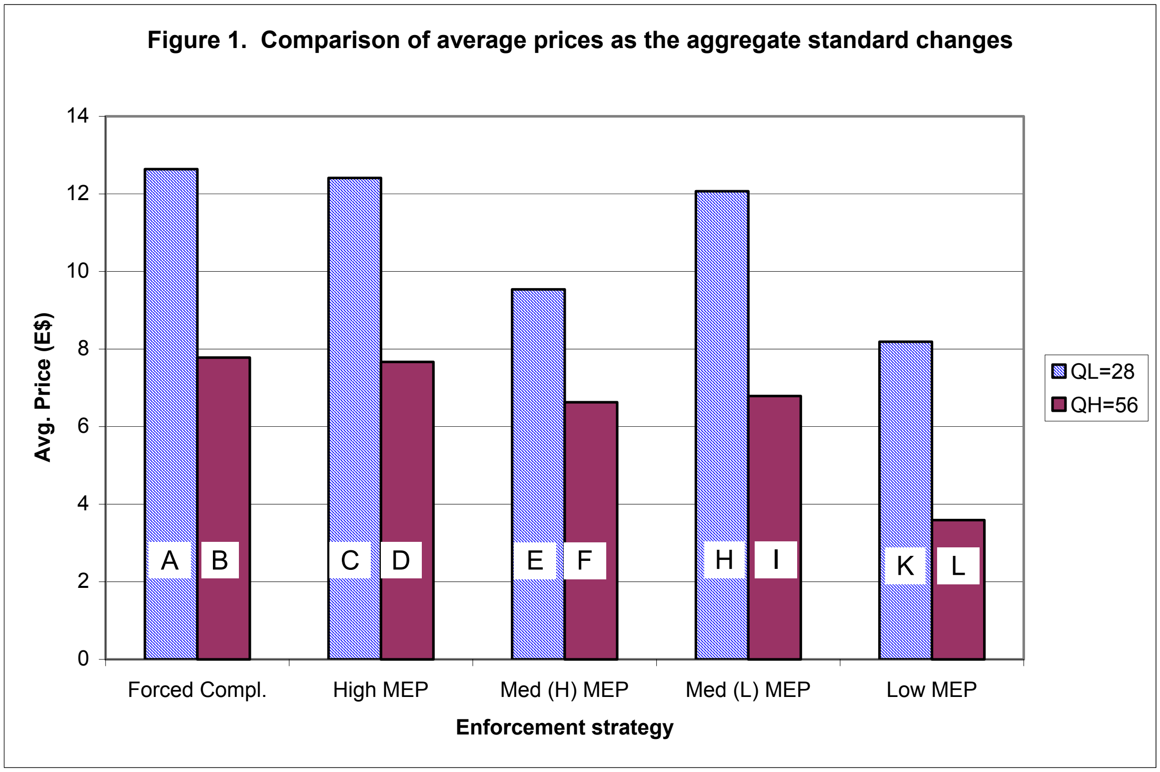
a These averages are from two experiments for each treatment. Each experiment consists of 10 periods (we ran 12 periods and dropped the first two).

In six of the twelve experiments we ran (two experiments per treatment), the average permit price approximately equaled the competitive equilibrium price, and in five experiments the average price exceeded the equilibrium price. In only one of the 12 experiments was the average permit price below the equilibrium price.

Within each experiment the observed prices were relatively stable. As a measure of price dispersion, we calculated the mean absolute percentage price difference between the individual trade prices and the mean price for the experiment. This measure of dispersion ranged between 2% and 7%. With the same measure, Newell, Sanchirico, and Kerr (2002), found average price dispersion of 2 % for the $SO_2$ market over 2001-2002; 5% for nitrogen oxide trading in the northeastern U.S. over the same period, and 28% for the RECLAIM markets over 1995-2002. They also found that for the markets that make up New Zealand's individual transferable fishing quotas (ITQs), dispersion of ITQ lease prices averaged 35% in 1987 and 25% in 2000, while the average dispersion of ITQ sales prices was about 25% in 1987, falling to 5% in 2000. It is reassuring that that average price dispersion in our experiments is in line with, and sometimes much lower than, existing markets for tradable property rights, suggesting that our experimental markets are functioning reasonably well.

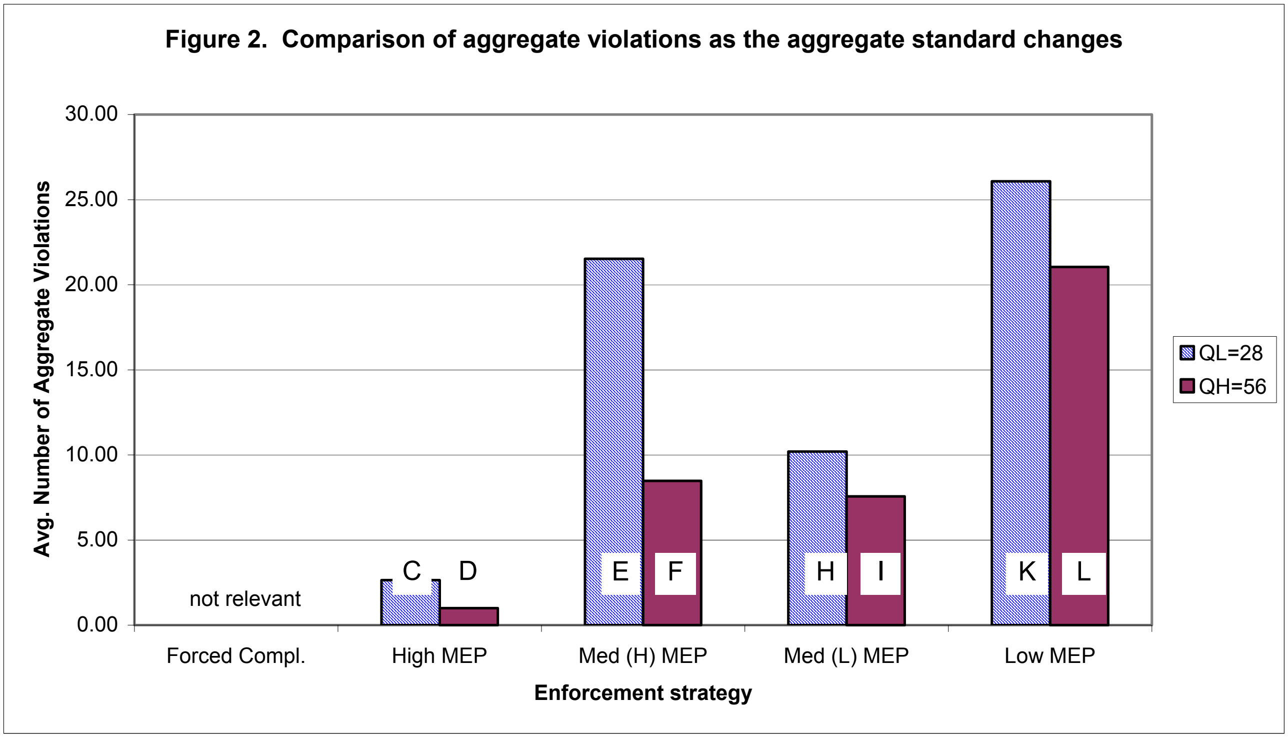
**Hypothesis 1:** *The market price for permits should be decreasing as the aggregate standard increases.*

For each enforcement strategy, Figure 1 contains a simple pairwise comparison of the mean price for low and high aggregate standard ($Q_L$ and $Q_H$) treatments. The letters on the bars (E, F, etc.) refer to the treatment cell from Table 4. Although the data in Table 8 suggest that observed prices may sometimes differ from the competitive equilibrium prices, the average price is moving in the hypothesized direction with respect to changes in the aggregate standard for all enforcement strategies—average prices are clearly lower when the aggregate standard is high ($Q_H$).




**Hypothesis 2:** *Aggregate violations should be decreasing as the aggregate standard increases.*

Table 8 indicates that in the low aggregate standard experiments ($Q_L$), average rates of non-compliance are generally lower than the competitive equilibrium. In the high aggregate standard experiments ($Q_H$), however, the results are mixed. Figure 2 compares aggregate violations as the aggregate standard changes. As hypothesized, aggregate violations are lower with the higher aggregate standard when the subjects faced the *Med*($\pi_H$) and *Low* marginal expected penalties. However, the reverse is true with the *Med*($\pi_L$) marginal expected penalty. Recall from Tables 7 and 8 that, relative to the prediction for the H treatment ($8-9), the actual average price is quite a bit higher ($12.07). Furthermore, the predicted aggregate violation (24) for the H treatment is much higher than average aggregate violations (about 10). The high average price for this treatment is consistent with the low aggregate violation—low noncompliance implies stronger demand for permits and consequently higher permit prices.




**Hypothesis 3:** *Aggregate violations should be decreasing as the marginal expected penalty is increased.*

Figure 3 is a re-formatted version of Figure 2 to highlight how average aggregate violations vary with the marginal expected penalties. As hypothesized, aggregate violations are higher with the *Low* marginal expected penalty as compared to the *Med*($\pi_H$) and *Med*($\pi_L$) marginal expected penalties. Note again the low average aggregate violation for the H treatment.

**Hypothesis 4:** *The market price for permits should be increasing as the marginal expected penalty increases.*

Given an aggregate standard, weaker enforcement and higher noncompliance implies lower permit prices. Figure 4 highlights the how average permit prices change as the marginal expected penalty decreases. Consistent with Hypothesis 4, note that average permit prices for both the low and high aggregate standards ($Q_L$ and $Q_H$) are lowest with the *Low* marginal expected penalty.

**Figure 3. Comparison of aggregate violations as the MEP changes**

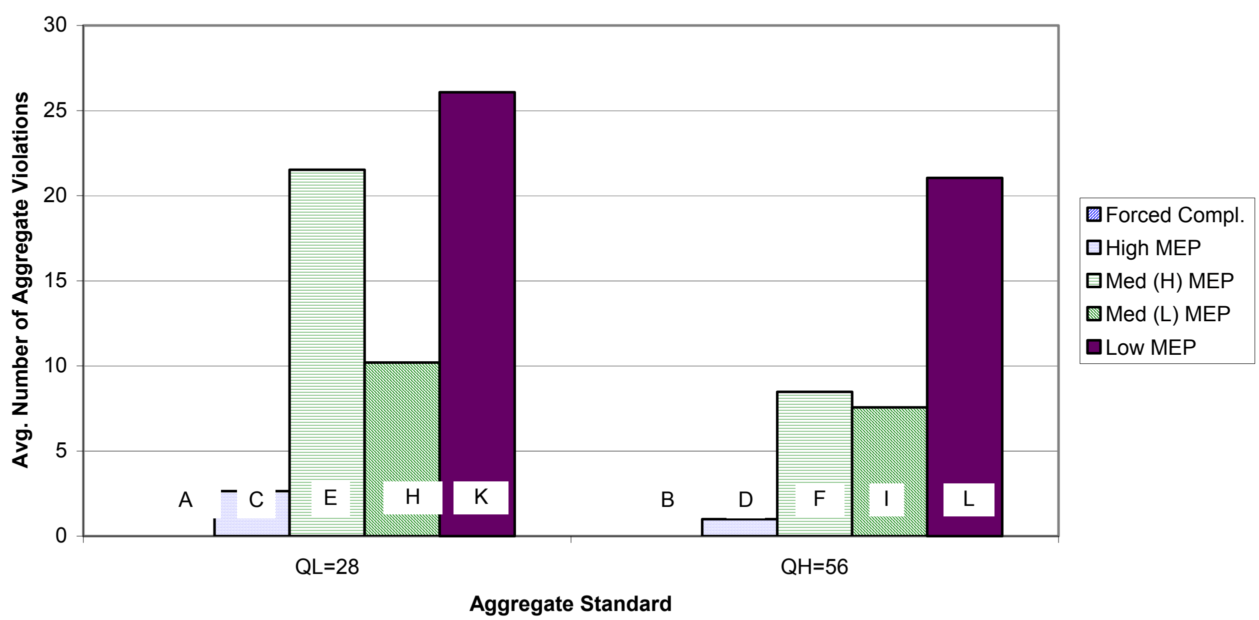
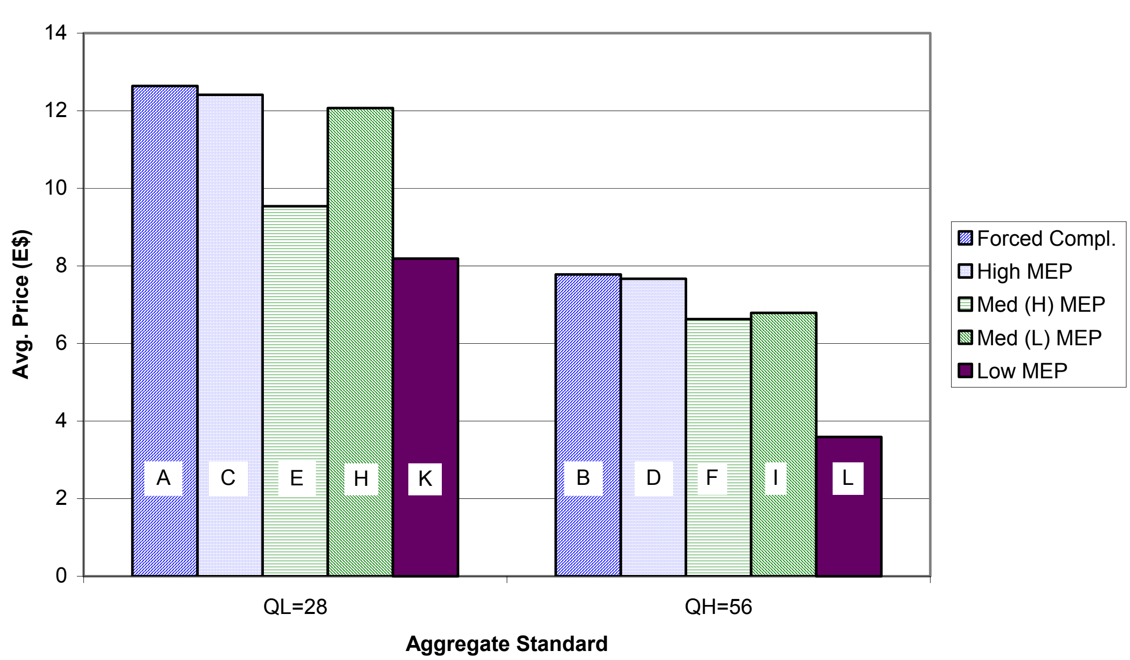



**Figure 4. Comparison of average prices as the MEP changes**



**Hypothesis 5:** *For two enforcement strategies that generate the same expected marginal penalty schedules, but with different monitoring probabilities and marginal penalty schedules, rates of non-compliance and permit prices should be identical.*

Refer to treatments E, H, F and I in Figures 3 and 4 to compare average aggregate violations and permit prices for the $Med(\pi_H)$ and $Med(\pi_L)$ marginal expected penalties. It appears that the data are not likely to support Hypothesis 5. Average aggregate violations are clearly not the same. Furthermore, violations are higher for the $Med(\pi_H)$ marginal expected penalty than the $Med(\pi_L)$ marginal expected penalty when the aggregate standard is low ($Q_L$), while they are lower when the aggregate standard is high ($Q_H$). At this stage of the research, we are unable to say anything about whether subjects' violation choices are more or less responsive to the probability of apprehension or the severity of punishment.

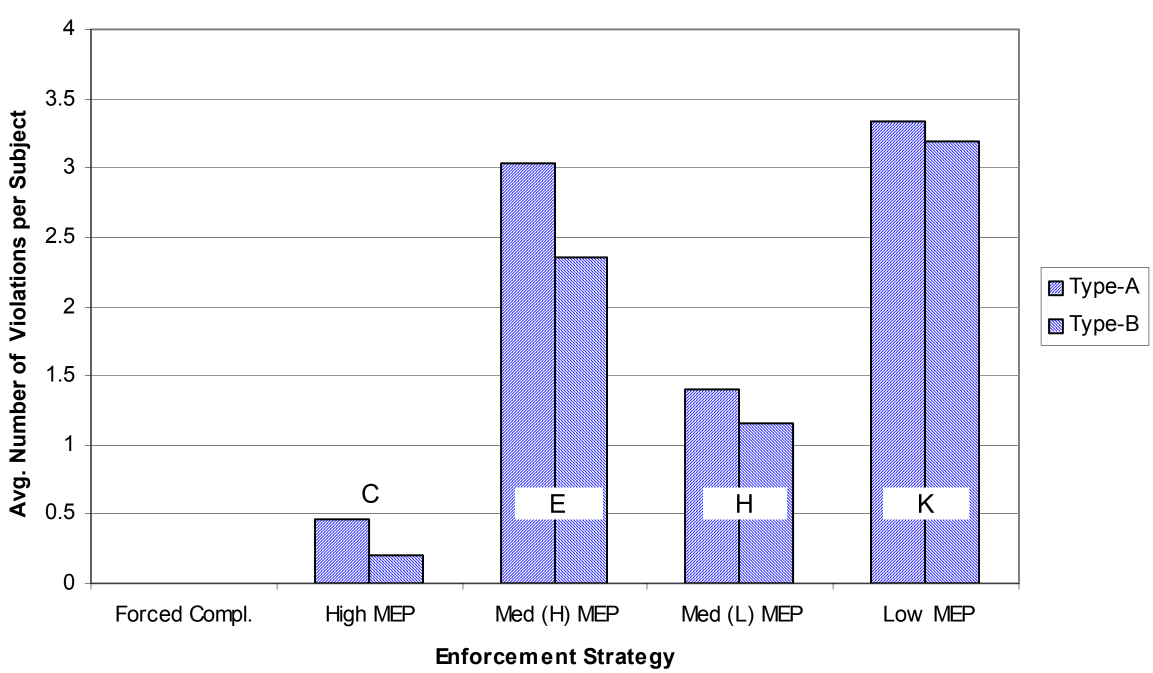
Looking now at average prices in Figure 4, we can see that there may be some support for the hypothesis in the high aggregate standard experiments ($Q_H$)—the average price in both the $Med(\pi_H)$ and $Med(\pi_L)$ marginal expected penalty treatments are about the same ($6.63 and $6.79, respectively). (These prices are within the competitive equilibrium price range of $6-7). In the low aggregate standard experiments ($Q_L$), however, the average price with the $Med(\pi_L)$ marginal expected penalty is $12.07 which is significantly higher than the average price of $9.54 with the $Med(\pi_H)$ marginal expected penalty. The competitive equilibrium price for both treatments is between $8 and $9. It is premature to speculate as to why the average permit price was so high in the two experiments with the low standard and $Med(\pi_L)$ marginal expected penalty. It is seems likely that average values mask a group-specific effect. For example, the mean prices in the two experiments with the low standard ($Q_L$) and the $Med(\pi_L)$ marginal expected penalty (cell H) were quite different: $12.97 and $9.72: with the low standard and the $Med(\pi_H)$ marginal expected penalty (cell E), the mean prices were $8.93 and $10.49. Not surprisingly, a simple t-test of the null hypothesis that the mean price of the two groups within the treatment is equal is strongly rejected at the 1% level of significance. As we subject the data to a thorough statistical analysis, we will probably need to control for group effects.

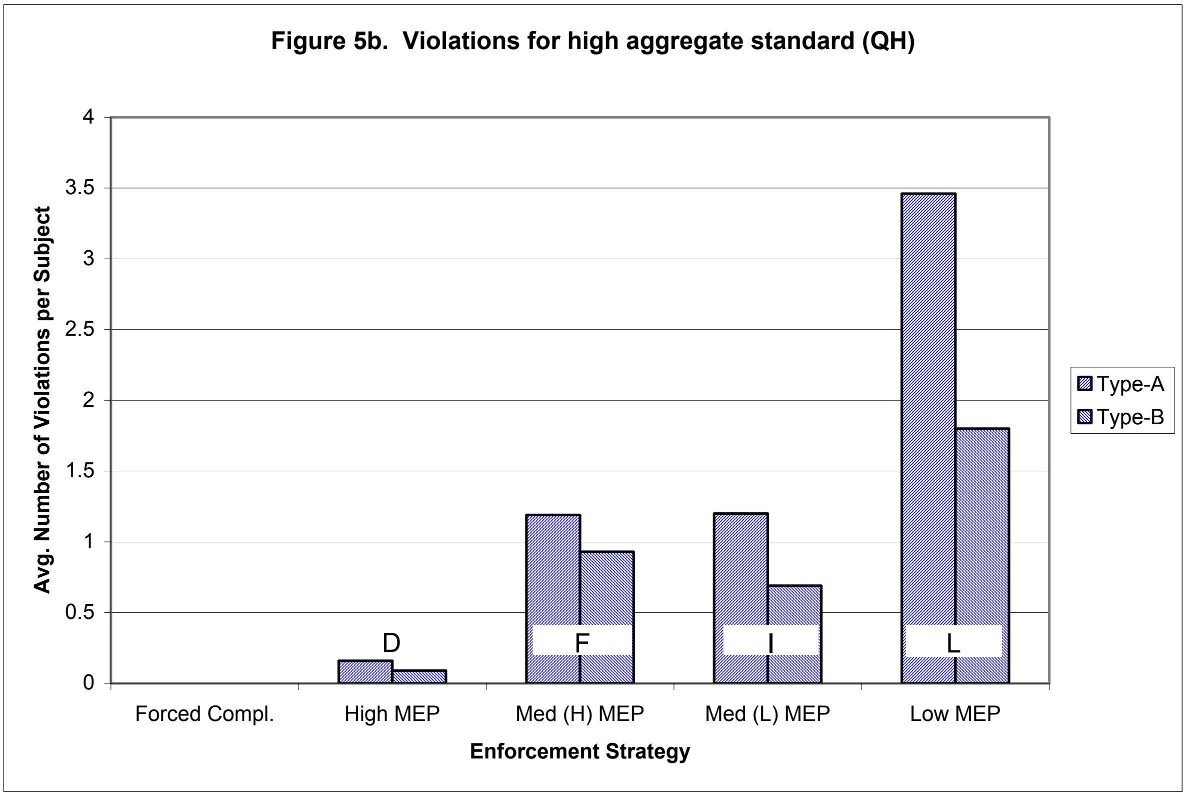
**Hypothesis 6:** *Individual violations in a permit market should be identical if firms are monitored with the same probability and they face the same penalties, even though they have different marginal abatement costs.*

Figures 5a and 5b compare average individual violations by subject type for the low ($Q_L$) and high ($Q_H$) aggregate standard, respectively. Recall from Table 6 that Type-A subjects have the higher marginal benefit functions (marginal benefit is synonymous with marginal abatement cost). These figures suggest that for all enforcement strategies and aggregate standards, the average level of violation is higher for Type-A subjects than for Type-B subjects, which is inconsistent with Hypothesis 6. However, note that for four of the six treatments reported (H, K, F, and L), these values are quite close to each other. Therefore, even if these differences turn out to be statistically significant, it is possible that they may not be "economically significant."

Concurrent with running the market experiments reported in this paper, we have also been running experiments that are identical except that permits are not tradable. We are doing so in order to compare compliance behavior with transferable permits to compliance with fixed emissions standards. Our preliminary results from these fixed standards experiments suggest that the differences in violation levels between Type-A and Type-B subjects are significantly larger than the differences in the market experiments.

**Figure 5a. Violations for low aggregate standard (QL)**






## 5. Concluding remarks

While there is a substantial body of economic theory about compliance and enforcement in emissions trading programs, and readily available information about how existing emissions trading programs are enforced, there are no empirical analyses of the determinants of compliance decisions in emission trading programs. Furthermore, there are no empirical analyses of various elements of actual or proposed enforcement designs. Toward filling these gaps, the overall objective of this research is to use laboratory experiments to test a number of hypotheses about compliance behavior and enforcement strategies for emissions trading programs.

Clearly, it is premature to draw any significant conclusions from this preliminary presentation of the results. Although the observed average prices and violations may differ from the competitive equilibrium predictions, there does appear to be general support for most of the comparative static predictions. Permit prices and aggregate violations are generally responding to changes in aggregate standard and enforcement strategies in a manner that is consistent with our hypotheses. However, the simple averages we present mask variations across periods and groups and it is also possible that risk attitudes could play an important role in individual decisions.

We expect that further analysis of this data will provide policy-makers, regulators and researchers with a more comprehensive understanding of compliance behavior and the effectiveness of various enforcement tactics in emissions trading programs than is currently available. This will lead to a better understanding of how market mechanisms and incentives in managing environmental problems should be designed, implemented, and managed to meet environmental quality goals cost-effectively.

**Appendix A: Comparative statics of compliance under competitive emissions trading**

*Basic assumptions*

Throughout we consider a fixed set of heterogeneous, risk-neutral firms that are grouped by type into a set $K$. There are $n^k$ identical firms of type $k$. We assume competitive behavior so that a single firm's choices have no affect on the equilibrium of the emissions permit market; however, we assume that there are enough firms of each type so that the aggregate choices of firms of a particular type will impact the market. At the time the firms make their choices, a fixed number of emissions permits have been allocated to the firms free-of-charge, and the enforcement authority has committed itself to a type-specific monitoring and enforcement program.

The emissions-control (abatement) costs of a $k$-type firm are summarized by $c(q^k, \alpha^k)$, which is strictly decreasing and convex in the firm's emissions $q^k$ [$c_q(q^k, \alpha^k) < 0$ and $c_{qq}(q^k, \alpha^k) > 0$; throughout subscripts denote partial derivatives in the usual manner]. Firm heterogeneity is captured by the shift parameter $\alpha^k$. We assume that total and marginal abatement costs are increasing in $\alpha^k$; that is, $c_\alpha(q^k, \alpha^k) > 0$, and $-c_{q\alpha}(q^k, \alpha^k) > 0$.

Suppose that a total of $Q$ emissions permits have been issued and that possession of a permit confers the legal right to release one unit of emissions. Let $l_0^k$ be the number of emissions permits that are initially allocated to each $k$-type firm, and let $l^k$ be the number of permits each of these firms holds after trade. Assume competitive behavior in the permit market so that trade establishes a constant price per permit $p$. If a $k$-type firm is noncompliant, its emissions exceed the number of permits it holds and the magnitude of its violation is $v^k = q^k - l^k > 0$. If a firm is compliant, $q^k - l^k \leq 0$ and $v^k = 0$.

We allow the probabilities with which firms are audited (monitoring) and penalties to vary among firm-types, but not among firms of the same type. Suppose that each $k$-type firm is audited with constant probability $\pi^k$. We have in mind here that the enforcement authority commits to auditing $\bar{n}^k < n^k$ firms of type $k$ at random so that $\pi^k = \bar{n}^k / n^k$. If a firm is found to be in violation, a penalty $f(v^k, \phi^k)$ is imposed. Assume that the penalty for a zero violation is zero but the marginal penalty for a zero violation is greater than zero [$f(0, \phi^k) = 0$ and $f_v(0, \phi^k) > 0$]. Furthermore, for a positive violation the penalty is increasing at an increasing rate in the level of the violation [$f_v(v^k, \phi^k) > 0$ and $f_{vv}(v^k, \phi^k) > 0$]. The parameter $\phi^k$ is a shift parameter with $f_\phi(v^k, \phi^k) > 0$ and $f_{v\phi}(v^k, \phi^k) > 0$.

Assume that each firm chooses positive emissions and permits, and never over-complies. Then, a $k$-type firm's problem is to choose emissions and permits to

$$\begin{aligned} &\min \quad c(q^k, \alpha^k) + p(l^k - l_0^k) + \pi^k f(q^k - l^k, \phi^k). \qquad \textbf{[1]} \\ &s.t \quad q^k - l^k \geq 0. \end{aligned}$$

The Lagrange equation for this problem is $\theta^k = c(q^k, \alpha^k) + p(l^k - l_0^k) + \pi^k f(q^k - l^k, \phi^k) - \eta^k(q^k - l^k)$ and the Kuhn-Tucker conditions are:

$$\theta_q^k = c_q(q^k, \alpha^k) + \pi^k f_v(q^k - l^k, \phi^k) - \eta^k = 0; \qquad \textbf{[2a]}$$

$$\theta_l^k = p - \pi^k f_v(q^k - l^k, \phi^k) + \eta^k \leq 0,\ \theta_l^k \times (q^k - l^k) = 0; \qquad \textbf{[2b]}$$

$$\theta_\eta^k = q^k - l^k \geq 0,\ \eta^k \geq 0,\ \eta^k \times (q^k - l^k) = 0. \qquad \textbf{[2c]}$$

Given our assumptions about abatement costs and the penalty schedule, [2a-c] are necessary and sufficient to determine the firm's optimal choices of emissions and permits uniquely.

*Individual Choices*
Whether a $k$-type firm is compliant or noncompliant, it chooses its emissions so that the price of a permit is equal to its marginal abatement cost; that is,

$$q^k(\alpha^k, p) = \{ q^k \mid c_q(q^k, \alpha^k) + p = 0\}. \quad \textbf{[3]}$$

To see this, suppose at first that the firm is noncompliant so that $q^k - l^k > 0$. Then, [2b] and [2c] require $\theta_l^k = \eta^k = 0$. In turn, [2a] becomes $c_q(q^k, \alpha^k) + \pi^k f_v(q^k - l^k, \phi^k) = 0$, and [2b] becomes $p - \pi^k f_v(q^k - l^k, \phi^k) = 0$. Taken together, [2a] and [2b] then imply $c_q(q^k, \alpha^k) + p = 0$. Now suppose that the firm is compliant. In this case its objective function reduces to $c(q^k, \alpha^k) + p(q^k - l_0^k)$, the minimization of which requires $c_q(q^k, \alpha^k) + p = 0$.

Consistent with an observation by Malik (1990, pg. 101), when the probability with which a firm is audited is constant as in the case of random audits, a firm's choice of emissions is independent of the intensity with which it is monitored and the enforcement pressure applied to it. As Malik notes, and we repeat here, this does not imply that the equilibrium distribution of emissions among the firms is independent of the particular monitoring and enforcement policy -- the policy will affect a firm's equilibrium choice of emissions, but only through its impact on the equilibrium permit price.

Turn now to the firm's demand for emissions permits. When it is compliant the number of permits it demands is simply equal to its choice of emissions; that is, $l^k(\alpha^k, p) = q^k(\alpha^k, p)$. When the firm is noncompliant its demand for emissions permits is

$$l^k(\alpha^k, \pi^k, \phi^k, p) = \{ l^k \mid p - \pi^k f_v(q^k(\alpha^k, p) - l^k, \phi^k) = 0\}. \quad \textbf{[4]}$$

To obtain [4] note from [2b] and [2c] that $q^k - l^k > 0$ implies $\eta^k = 0$ and $\theta_l^k = p - \pi^k f_v(q^k - l^k, \phi^k) = 0$. Substitution of the firm's choice of emissions $q^k(\alpha^k, p)$ into $p - \pi^k f_v(q^k - l^k, \phi^k) = 0$ yields [4]. Note that although a noncompliant firm's choice of emissions is not affected by the monitoring and enforcement effort applied to it, its demand for emissions permits is.

Having specified a firm's choice of emissions and its demand for permits, we can now turn to its choice of violation. We start with its choice of whether to be compliant or not: A $k$-type firm is compliant if and only if

$$p - \pi^k f_v(0, \phi^k) \leq 0. \quad \textbf{[5]}$$

Although this result is not new, one aspect of it has been overlooked; namely, [5] does not depend on $\alpha^k$. A firm's decision to be compliant or not depends only on the relationship between the permit price and the marginal expected penalty of a vanishingly slight violation, not on parametric characteristics of its emissions-control costs. In fact, Stranlund and Dhanda (1999) show that this independence extends to the choice of violation by a noncompliant firm. That is, a $k$-type firm's choice of violation, including whether it is compliant or not, is independent of the abatement cost shift parameter $\alpha^k$. (We will verify this result in a moment).

Since a noncompliant firm's choice of violation does not depend on its marginal abatement costs, we can use this fact and [3] and [4], we write the firm's choice of violation

$$v^k(\pi^k, \phi^k, p) = q^k(\alpha^k, p) - l^k(\alpha^k, \pi^k, \phi^k, p). \qquad \textbf{[6]}$$

[3], [4], and [6] describe the choices of emissions, permits, and violation of a noncompliant *k*-type firm. The marginal impacts of $\alpha^k$, $\pi^k$, $\phi^k$, and $p$ on theses choices are presented in Table 1 and derived below.

Let $\beta = (\alpha^k, \pi^k, \phi^k, p)$. Then, assuming a non-compliant firm, [2a] and [2b] can be written as the following identities:

$$c_q(q^k(\beta), \alpha^k) + \pi^k f_v(q^k(\beta) - l^k(\beta), \phi^k) \equiv 0; \qquad \textbf{[7]}$$

$$p - \pi^k f_v(q^k(\beta) - l^k(\beta), \phi^k) \equiv 0. \qquad \textbf{[8]}$$

Differentiate [7] and [8] with respect to $\alpha^k$ and place in matrix form:

$$\begin{bmatrix} c_{ee} + \pi^k f_{vv} & -\pi^k f_{vv} \\ -\pi^k f_{vv} & \pi^k f_{vv} \end{bmatrix} \begin{bmatrix} q_\alpha^k \\ l_\alpha^k \end{bmatrix} = \begin{bmatrix} -c_{e\alpha} \\ 0 \end{bmatrix}, \qquad \textbf{[9]}$$

where $q_\alpha^k$ and $l_\alpha^k$ denote derivatives of $q^k$ and $l^k$ with respect to $\alpha^k$. Let *H* denote the Hessian matrix in [9]. Its determinant is

$$|H| = (c_{qq} + \pi^k f_{vv})\pi^k f_{vv} - (\pi^k f_{vv})^2 = c_{qq}\pi^k f_{vv} > 0. \qquad \textbf{[10]}$$

The solutions to [9] are

$$q_\alpha^k = \frac{1}{|H|}\begin{vmatrix} -c_{q\alpha} & -\pi^k f_{vv} \\ 0 & \pi^k f_{vv} \end{vmatrix} = \frac{-c_{q\alpha}\pi^k f_{vv}}{c_{qq}\pi^k f_{vv}} = \frac{-c_{q\alpha}}{c_{qq}} > 0,$$

and

$$l_\alpha^k = \frac{1}{|H|}\begin{vmatrix} c_{qq} + \pi^k f_{vv} & -c_{q\alpha} \\ -\pi^k f_{vv} & 0 \end{vmatrix} = \frac{-c_{q\alpha}\pi^k f_{vv}}{c_{qq}\pi^k f_{vv}} = \frac{-c_{q\alpha}}{c_{qq}} > 0.$$

As asserted earlier, $v_\alpha^k = q_\alpha^k - l_\alpha^k = 0$. This reveals that, holding monitoring, enforcement and the permit price constant, a change in some parameter that affects the abatement costs of a firm has no effect on its choice of violation. The intuition behind this result is as follows: The marginal expected benefit to a firm of a marginal reduction in its violation is the marginal expected penalty it avoids, which clearly does not depend on the firm's characteristics. To reduce its violation it may purchase the legal right to emit, the marginal cost of which is the equilibrium permit price, or it may reduce its emissions, the marginal cost of which is $-c_q(q^k, \alpha^k)$. But, the firm always chooses its emissions to equate its marginal abatement costs to the price of an emissions permit (see [3]). Hence, the marginal cost of reducing its violation is simply equal to the permit price, and therefore, independent of the firm's marginal abatement costs.

The result that $v_{\alpha}^{k} = 0$ also suggests that a difference in the violations of any two types of firms is independent of differences in their abatement costs. Thus, if two firms are audited with the same probability and they face the same penalties, they should have the same level of violation even though they may have very different marginal abatement costs.

Now differentiate [7] and [8] with respect to $\pi^k$ to obtain:

$$H\begin{bmatrix} q_{\pi}^{k} \\ l_{\pi}^{k} \end{bmatrix} = \begin{bmatrix} -f_v \\ f_v \end{bmatrix}. \qquad \textbf{[11]}$$

The solutions to [11] are

$$q_{\pi}^{k} = \frac{1}{|H|}\begin{vmatrix} -f_v & -\pi^k f_{vv} \\ f_v & \pi^k f_{vv} \end{vmatrix} = \frac{-f_v \pi^k f_{vv} + f_v \pi^k f_{vv}}{c_{qq}\pi^k f_{vv}} = 0,$$

and

$$l_{\pi}^{k} = \frac{1}{|H|}\begin{vmatrix} c_{qq} + \pi^k f_{vv} & -f_v \\ -\pi^k f_{vv} & f_v \end{vmatrix} = \frac{f_v (c_{qq} + \pi^k f_{vv} - \pi^k f_{vv})}{c_{qq}\pi^k f_{vv}} = \frac{f_v}{\pi^k f_{vv}} > 0,$$

Furthermore, $v_{\pi}^{k} = q_{\pi}^{k} - l_{\pi}^{k} = -f_v / \pi^k f_{vv} < 0.$ We have already noted that a firm's choice of emissions is independent of the monitoring and enforcement effort applied to it (see [3]); therefore, its choice of violation is affected by monitoring and enforcement only through induced changes in the number of permits it chooses to hold. For example, if a *k*-type firm is monitored more intensely, then noncompliance is a relatively less attractive strategy. Hence, it is motivated to reduce its violation ($v_{\pi}^{k} < 0$) by purchasing more permits ($l_{\pi}^{k} > 0$), not by reducing its emissions ($q_{\pi}^{k} = 0$).

Now differentiate [7] and [8] with respect to $\phi^k$ to obtain:

$$H\begin{bmatrix} q_{\phi}^{k} \\ l_{\phi}^{k} \end{bmatrix} = \begin{bmatrix} -\pi^k f_{v\phi} \\ \pi^k f_{v\phi} \end{bmatrix}. \qquad \textbf{[12]}$$

The solutions to [12] are

$$q_{\pi}^{k} = \frac{1}{|H|}\begin{vmatrix} -\pi^k f_{v\phi} & -\pi^k f_{vv} \\ \pi^k f_{v\phi} & \pi^k f_{vv} \end{vmatrix} = \frac{(\pi^k)^2[-f_{v\phi} f_{vv} + f_{v\phi} f_{vv}]}{c_{qq}\pi^k f_{vv}} = 0,$$

and

$$l_{\phi}^{k} = \frac{1}{|H|}\begin{vmatrix} c_{qq} + \pi^k f_{vv} & -\pi^k f_{v\phi} \\ -\pi^k f_{vv} & \pi^k f_{v\phi} \end{vmatrix} = \frac{\pi^k f_{v\phi}(c_{qq} + \pi^k f_{vv} - \pi^k f_{vv})}{c_{qq}\pi^k f_{vv}} = \frac{f_{v\phi}}{f_{vv}} > 0.$$

Furthermore, $v_\phi^k = e_\phi^k - l_\phi^k = -f_{v\phi}/f_{vv} < 0.$ The effects of increasing marginal penalties are qualitatively the same as increased monitoring.

Lastly, differentiate [7] and [8] with respect to *p* to obtain

$$H\begin{bmatrix} q_p^k \\ l_p^k \end{bmatrix} = \begin{bmatrix} 0 \\ -1 \end{bmatrix}. \qquad \textbf{[13]}$$

The solutions to [13] are

$$q_p^k = \frac{1}{|H|}\begin{vmatrix} 0 & -\pi^k f_{vv} \\ -1 & \pi^k f_{vv} \end{vmatrix} = \frac{-\pi^k f_{vv}}{c_{ee}\pi^k f_{vv}} = -\frac{1}{c_{ee}} < 0,$$

and

$$l_p^k = \frac{1}{|H|}\begin{vmatrix} c_{qq} + \pi^k f_{vv} & 0 \\ -\pi^k f_{vv} & -1 \end{vmatrix} = \frac{-(c_{qq} + \pi^k f_{vv})}{c_{qq}\pi^k f_{vv}} < 0.$$

From these obtain

$$v_p^k = q_p^k - l_p^k == \frac{-\pi^k f_{vv} + c_{qq} + \pi^k f_{vv}}{c_{qq}\pi^k f_{vv}} = \frac{1}{\pi^k f_{vv}} > 0.$$

A higher permit price implies that purchasing the legal right to emit is a relatively less attractive option than reducing emissions, so a firm is motivated to hold fewer permits and reduce its emissions ($q_p^k < 0$ and $l_p^k < 0$). In addition, a higher permit price makes noncompliance a relatively more attractive option so that a firm is motivated to increase its violation ($v_p^k > 0$).

| | ***Emissions* ($q^k$)** | ***Permits* ($l^k$)** | ***Violation* ($v^k$)** |
|---|---|---|---|
| $\alpha^k$ | $q_\alpha^k = \frac{-c_{e\alpha}}{c_{ee}} > 0$ | $q_\alpha^k = l_\alpha^k > 0$ | $v_\alpha^k = 0$ |

| | | | |
|---|---|---|---|
| $\boldsymbol{\pi^k}$ | $q_\pi^k = 0$ | $l_\pi^k = \dfrac{f_v}{\pi^k f_{vv}} > 0$ | $v_\pi^k = -l_\pi^k < 0$ |
| $\boldsymbol{\phi^k}$ | $q_\phi^k = 0$ | $l_\phi^k = \dfrac{f_{v\phi}}{f_{vv}} > 0$ | $v_\phi^k = -l_\phi^k < 0$ |
| $\boldsymbol{p}$ | $q_p^k = -\dfrac{1}{c_{ee}} < 0$ | $l_p^k = \dfrac{-(c_{qq} + \pi^k f_{vv})}{c_{qq}\pi^k f_{vv}} < 0$ | $v_p^k = \dfrac{1}{\pi^k f_{vv}} > 0$ |

**Table 1: Comparative statics of a firm's choices of emissions, permits and level of violation.**

*Equilibrium comparative statics*

We turn now to characterizing the equilibrium of an emissions permit market with noncompliant firms. Define the vectors $\boldsymbol{\alpha} = (\alpha^k)_{k \in K}$, $\boldsymbol{\pi} = (\pi^k)_{k \in K}$, and $\boldsymbol{\phi} = (\phi^k)_{k \in K}$. Given that a total of $Q$ permits are issued to the firms, and the enforcement authority has committed itself to a type-specific monitoring and enforcement program $[\boldsymbol{\pi}, \boldsymbol{\phi}]$, the equilibrium permit price is $\bar{p} = \bar{p}(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q)$. Using [4], the equilibrium permit price must equate aggregate demand for permits to aggregate supply; that is, $\bar{p}$ must satisfy

$$\sum n^k l^k (\alpha^k,\ \pi^k,\ \phi^k, \bar{p}) \equiv Q. \qquad \textbf{[14]}$$

(Summations throughout are taken over the entire set $K$). Combining [14] with [3], [4], and [6] gives us equilibrium emissions, permits, and violations:

$$\bar{q}^k(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q) = q^k(\alpha^k,\ \bar{p}(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q));$$

$$\bar{l}^k(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q) = l^k(\alpha^k, \pi^k, \phi^k,\ \bar{p}(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q));$$

$$\bar{v}^k(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q) = v^k(\pi^k, \phi^k,\ \bar{p}(\boldsymbol{\alpha}, \boldsymbol{\pi}, \boldsymbol{\phi}, Q)). \qquad \textbf{[15]}$$

Let us first examine the equilibrium effects of a change in the aggregate supply of permits. (The qualitative directions of the equilibrium comparative statics are summarized in Table 2). From [14] obtain

$$\partial\bar{p}/\partial Q = 1\Big/\sum n^k l_p^k < 0. \qquad \textbf{[16]}$$

The sign follows from $l_p^k < 0$ (refer to Table 1), and indicates that the equilibrium price is decreasing in the supply of permits. Using [15] and [16] obtain:

$$\partial\bar{q}^k/\partial Q = q_p^k \bar{p}_Q > 0;$$
$$\partial\bar{l}^k/\partial Q = l_p^k \bar{p}_Q > 0;$$
$$\partial\bar{v}^k/\partial Q = v_p^k \bar{p}_Q < 0.$$

More permits induce a lower permit price. Firms respond to the lower price by increasing their emissions and permit holdings, while decreasing their violations. Note that aggregate emissions are increasing in the supply of permits, while aggregate violations are decreasing the supply of permits.

Now turn to the equilibrium effects of a change in the monitoring of *h*-type firms, holding the monitoring of the other types constant. From [14] obtain

$$\partial \overline{p} \big/ \partial \pi^h = -n^h l_\pi^h \big/ \sum n^k l_p^k > 0 . \qquad \textbf{[17]}$$

The sign of [17] follow from $l_\pi^h > 0$ and $l_p^k < 0$ (Table 1). Intuitively, increased monitoring of noncompliant firms of a particular type motivates them to purchase more permits ($l_\pi^h > 0$) to reduce the magnitude of their violations ($v_\pi^h < 0$). This increased demand for permits then puts upward pressure on the equilibrium permit price. From [15] obtain:

$$\partial q^k \big/ \partial \pi^h = \begin{cases} q_\pi^h + q_p^h \partial \overline{p} / \partial \pi^h = q_p^h \partial \overline{p} / \partial \pi^h < 0, \text{ for } k = h; \\ q_p^k \partial \overline{p} / \partial \pi^h < 0, \text{ for } k \neq h. \end{cases} \qquad \textbf{[18]}$$

[18] indicates that emissions of all firms fall as one type is monitored more closely, because this increased monitoring puts upward pressure on the equilibrium permit price.

To examine the effect of increased monitoring on equilibrium violations, it is convenient to begin with aggregate violations,

$$\sum n^k \overline{v}^k (\alpha, \pi, \phi, Q) = \sum n^k v^k (\pi^k, \phi^k, \overline{p}(\alpha, \pi, \phi, Q))..$$

Differentiate this with respect to $\pi^h$ to obtain

$$\frac{\partial}{\partial \pi^h} \left[ \sum \overline{v}^k \right] = n^h v_\pi^h + \partial \overline{p} \big/ \partial \pi^h \sum v_p^k.$$

Substitute for $\partial \overline{p} \big/ \partial \pi^h$ from [17] and use $v_\pi^h = -l_\pi^h$ from Table 1 to write this last as

$$\frac{\partial}{\partial \pi^h} \left[ \sum \overline{v}^k \right] = n^h v_\pi^h \left[ 1 + \frac{\sum n^k v_p^k}{\sum n^k l_p^k} \right] \qquad \textbf{[19]}$$

To sign [19], first recall from Table 1 that $v_p^k = e_p^k - l_p^k > 0$. This along with $e_p^k < 0$ and $l_p^k < 0$ implies $| l_p^k | > v_p^k$. Consequently, the bracketed term of [19] is positive. Since $v_\pi^h < 0$, [19] is negative, indicating that aggregate equilibrium violations fall with more intense monitoring of *h*-type firms.

Now turn to individual violations. From [15]:

$$\partial\overline{v}^k/\partial\pi^h = \begin{cases} v_\pi^h + v_p^h\,\partial\overline{p}/\partial\pi^h < 0 \text{ for } k = h; \\ v_p^k\,\partial\overline{p}/\partial\pi^h > 0 \text{ for } k \neq h. \end{cases} \qquad \textbf{[20]}$$

The sign of $\partial\overline{v}^k/\partial\pi^h$ for types $k \neq h$ follows from $v_p^k > 0$ and $\partial\overline{p}/\partial\pi^h > 0$. Finally, since aggregate violations are decreasing in $\pi^h$ and the equilibrium violations of all $k \neq h$-type firms are increasing in $\pi^h$, the equilibrium violations of $h$-type firms must be decreasing in $\pi^h$.

Although more intense monitoring of $h$-type firms leads them to reduce their equilibrium violations, this is not immediately obvious from [20]. A firm's equilibrium violation-response to more intense monitoring is made up of a two countervailing effects. Holding the permit price constant, more intense monitoring of $h$-type firms motivates each of them to reduce their violation [$v_\pi^h < 0$] by purchasing more permits [$l_\pi^h < 0$]. But as a result of their increased demand for emissions permits, the equilibrium permit price increases [$\partial\overline{p}/\partial\pi^h > 0$], which motivates each of them to increase their violation [$v_p^h < 0$]. However, the direct effect of more intense monitoring outweighs the indirect price effect so that more intense monitoring of one group of firms leads each of them to decrease their equilibrium violation. In contrast, all other firms only experience the price effect, so more intense monitoring of one group leads all of them to increase their violations. This finding should serve as a cautionary note for enforcement of emissions trading programs—efforts to induce greater compliance by one group of firms will be partially thwarted because these efforts lead all other firms to become less compliant.

Increasing the penalty for one type of firm has the same qualitative effects as increasing the monitoring of one type. Clearly, increasing the monitoring or penalties of all firms at once will lead all of them to reduce their violations.

Let us now consider the equilibrium impacts of a parametric change in the marginal abatement costs of one type of firm. Recall that a firm's choice of violation is independent of its marginal abatement costs. However, as the following proposition indicates, a change in the marginal abatement costs of one type of firm will affect the equilibrium violations of all firms through the permit price.

From [14] obtain

$$\partial\overline{p}/\partial\alpha^h = -n^h l_\alpha^h \Big/ \sum n^k l_p^k > 0,$$

the sign of which follows from $l_\alpha^h > 0$ and $l_p^h < 0$. Thus, an increase in the marginal abatement costs of one type of firm leads to an increase in the equilibrium permit price. From [15] obtain

$$\partial\overline{v}^k/\partial\alpha^h = v_p^k\,\partial\overline{p}/\partial\alpha^h > 0 \;\forall\, k \in K,$$

indicating that an increase in the marginal abatement costs of one type of firm will lead to higher violations by all firms, because of upward pressure on the equilibrium permit price. Since aggregate violations are increasing in the marginal abatement costs of a firm type, so too are aggregate emissions. That is,

$$\frac{\partial}{\partial \alpha^h}\left[\sum \overline{v}^k\right] > 0 \text{ and } \frac{\partial}{\partial \alpha^h}\left[\sum \overline{q}^k\right] > 0.$$

As for individual emissions, from [15] obtain

$$\partial \overline{q}^k / \partial \pi^h = \begin{cases} q_\alpha^k + q_p^k \partial \overline{p} / \partial \alpha^h > 0 \text{ for } k = h; \\ q_p^k \partial \overline{p} / \partial \alpha^h < 0 \text{ for } k \neq h. \end{cases}$$

The sign of $\partial \overline{q}^k / \partial \pi^h$ for types $k \neq h$ follows from $q_p^k < 0$ and $\partial \overline{p} / \partial \alpha^h > 0$. Finally, since aggregate emissions are increasing in $\alpha^h$ and the emissions of all $k \neq h$-type firms are decreasing in $\alpha^h$, the equilibrium emissions of *h*-type firms must be increasing in their marginal abatement costs.

| | $Q$ | $\pi^h$ | $\phi^h$ | $\alpha^h$ |
|---|---|---|---|---|
| **Price** $\overline{p}$ | (−) | (+) | (+) | (+) |
| **Violations** | | | | |
| Violations, type *h* | (−) | (−) | (−) | (+) |
| Violations, types $k \neq h$ | (−) | (+) | (+) | (+) |
| Aggregate violations | (−) | (−) | (−) | (+) |
| **Emissions** | | | | |
| Emissions, type *h* | (+) | (−) | (−) | (+) |
| Emissions, types $k \neq h$ | (+) | (−) | (−) | (−) |
| Aggregate emissions | (+) | (−) | (−) | (+) |

**Table 2: Equilibrium comparative statics**

**Appendix B: Instructions Summary**

Thank you for agreeing to participate in today's experiment. You have all seen a version of this experiment before. Before we begin, I would like to review the instructions for today's experiment.

It is very important to remember that although the experiment may be similar, some or all of the numbers may have changed. **Do <u>NOT</u> assume that any of the information or results from a previous experiment will be useful in helping you to make your decisions today**.

The purpose of the experiment is to give you an opportunity to earn as much money as possible. What you earn will depend on your decisions, as well as the decisions of others. As before you can produce as many units as you want regardless of the number of permits you own, but you could face a financial penalty if you do not own a permit for each unit you produce.

- During the period, you can earn money in two ways:
  1. Produce units of the fictitious good. For each unit you produce, you will earn a specified amount of money that will be added to your cash balance.
  2. Sell permits in the permit market. The selling price you receive for a permit will be added to your cash balance.
- Money will be subtracted from your cash balance if:
  1. You choose to buy additional permits. The purchase price you pay will be deducted from your cash balance.
  2. You are audited and if the total number of units you produce exceeds the number of permits you own.

*Production Highlights*

- Your Earnings from Production table tells you how many units you can produce and how much you will earn from each unit you produce. You might earn a different amount of money for each unit produced.
- Production of each unit takes a specified amount of time
- You can only produce one unit at a time.
- The Production Timer tells you how much time is left for you to produce more units.

- In order to start production of a unit, there must be sufficient time on the Production Timer to complete production of the unit.
- To start production or to place an order for additional units, click the plus (+) button. If production is idle, then production will begin immediately.
- You can cancel units that have been ordered if production has not yet begun. To do so, click the minus (–) button.
- Earnings from the units produced are automatically added to your cash balance when production is completed.
- The last row of the "Earnings from Production" table tells you the maximum number of units you are able to produce.
- Under the "Earnings from Production" table, you can see the production status of each unit (produced, in production, or planned).

*Permit Market Highlights*

- You will be given an opportunity to buy and/or sell permits in the Permit Market.
- There are 4 ways in which you can participate in the market:

1. Make an offer to buy a permit.
    a. To do so, enter your price next to the My Buying Price and click Buy.
    b. All buying prices must be GREATER than the Current Buying Price.
2. Make an offer to sell a permit.
    a. To do so, enter your price next to the My Selling Price and click Sell.
    b. All selling prices must be LOWER than the Current Selling Price.
3. Purchase a permit at the Current Selling Price.
    a. To do so, enter the Current Selling Price next to My Buying Price
    b. or click the Buy? button next to the Current Selling Price.
4. Sell a permit at the Current Buying Price.
    a. To do so, enter the Current Buying Price next to My Selling Price
    b. or click the Sell? button next to the Current Buying Price.

- After each trade is completed, your permit balance will be automatically updated. Your cash balance will automatically be updated to reflect price you paid to buy the permit, or the price you received for selling the permit. This is shown in the My Balances section of your screen.

*Auditing Highlights*

- The computer monitor always knows how many permits you own and your cash balance. The computer does not know how many units you actually produced unless you are audited.
- There is an XX% chance that you will be audited, and (1-XX)% chance you will not be audited.
- If you are audited, the computer monitor will check to see how many units you actually produced. If the number of units you produced exceeds the number of permits you own, you will receive a financial penalty. The Permit Shortfall Table lists the penalties you will face.

To summarize, your total earnings for the period will be calculated as follows:

|   |   |
|---|---|
|   | Your initial cash balance |
| + | Earnings from production of the good |
| + | Selling price for permits you sell in the permit market |
| – | Purchase price for permits you buy in the permit market |
| – | Penalties for a permit shortfall (only if you are audited and if you over produced) |
| = | Total earnings for the period |

At the end of the experiment, we will add up your total earnings for each period and you will be paid in cash for these earnings. Please raise your hand if you have any questions.

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