Investment Incentives in Tradable Emissions Markets with Price Floors*

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Abstract

Emissions uncertainty has led regulators to include price controls in many cap-and-trade markets. We study how these controls affect firms' incentives to invest in new abatement technologies in a model with abatement cost uncertainty. Price floors increase investment incentives because they raise the expected benefits from lowering abatement costs. We also report a market experiment that features abatement cost uncertainty and the opportunity for cost-reducing investment, with and without a price floor. Trade occurs through a continuous double auction market. Consistent with the theoretical model, investment is significantly greater with the price floor in place. Emissions permit prices also respond as predicted to abatement investments and emissions shocks.

Keywords: Emissions trading; Technological innovation; Price controls; Market design; Laboratory experiments

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1 Introduction

The dynamic efficiency of tradable emissions markets, that is the extent to which the price mechanism can steer and enhance investment towards energy-saving and advanced abatement technology in the long run, is a fundamental issue in market-based environmental policy. In the context of climate change, for instance, investment in developing and adopting low-carbon technologies is crucial to reducing the cost of climate mitigation. In this respect, for carbon markets to function effectively, not only should prices ideally be stable and relatively predictable, but allowance prices should also not be too low. Some markets, however, have experienced considerable emissions uncertainty and particularly some extremely low prices. For example, allowance prices in the European Union Emissions Trading System (EU ETS) were below €10 per ton from November 2011 to February 2018. Current prices exceed €30 per ton. Allowance auction clearing prices in the Regional Greenhouse Gas Initiative (RGGI) were at the very low reserve price (set at $1.86 per ton in 2008, increasing slowly to $2.26 in June 2019) for auctions conducted between June 2010 and December 2012, and has only rarely exceeded $6.00 per ton (US Congressional Research Service, 2019). Similarly, in California's cap-and-trade market for greenhouse gases, auction prices and secondary market prices have been at or close to the auction reserve price throughout the program's history (California Air Resources Board, 2021). Lower-than-expected prices can undermine investors' confidence in future market conditions, adversely affecting the expected rewards from investment strategies (Burtraw et al., 2010), and resulting in reduced investment in environmental innovation (Taylor, 2012). Introducing price floors can guard against the threat of (too) low allowance prices, and the potential for under-investment in abatement technology (Philibert, 2009; Wood and Jotzo, 2011).[1]

However, the theoretical and empirical literature concerning the effects of price floors on investment in abatement technologies is limited, and to some degree non-integrated. Our paper tries to fill this gap. First, we develop a formal, tractable model of an emissions trading market comprising heterogeneous firms that allows us to make theoretical predictions about the firms' investment decisions, with and without a price floor. Second, we test this model's predictions in a market experiment, providing empirical evidence on investment behavior in such market conditions. This is particularly relevant in circumstances of emissions and investment uncertainty (e.g., Cason and de Vries, 2019). Our main research question is: how does the introduction of a price floor in emissions trading markets affect firms' incentives to invest in cost-saving abatement technologies?

Our theoretical model suggests that in a market with a mix of firms that invest and do not invest in a cost-reducing technology, only firms with high abatement costs will invest in the technology. The introduction of a price floor expands the set of investors to include medium-cost firms who would not invest in the absence of the price floor. The results of our experiments are

[1] Incorporating price controls in emissions markets was first suggested by Roberts and Spence (1976). Although they considered implementing both price ceilings and price floors, the first recommendations for controlling abatement cost uncertainty in carbon markets focused on price ceilings (Pizer, 2002; Jacoby and Ellerman, 2004). However, a price ceiling cannot address the problem of low-side abatement cost risk, and it has become evident that emissions markets are more often plagued by (too) low prices rather than price spikes (Burtraw et al., 2010).

consistent with these hypotheses. The main policy lesson is clear: a price floor in an emissions market can motivate increased investment in technologies that reduce firms' abatement costs. In turn, this additional demand for cost-reducing technologies can spur additional innovation in abatement technologies.

Our work contributes to the theoretical and experimental literature on price controls in emissions markets. In the last decade, the theoretical literature expanded to include analyses of alternative price stabilization schemes (Fell et al., 2012; Grüll and Taschini, 2011); the relationship between price controls and banking (Fell and Morgenstern, 2010); and the optimal design of emissions markets with price controls accounting for enforcement (Stranlund and Moffitt, 2014) and co-pollutants (Stranlund and Son, 2019). A recent study by Borenstein et al. (2019) highlights the continuing importance of analyzing the design and effects of implementing price controls, because their work reveals that relatively large uncertainty in business-as-usual emissions implies that permit prices are likely to be determined by price floors and ceilings rather than permit supplies.

The experimental literature addressing price controls and other price stabilization policies is more limited than the theoretical literature. Building on the seminal work of Isaac and Plott (1981) and Smith and Williams (1981) who examined price controls in laboratory settings, the more recent experimental literature related to the design of emissions markets has mainly focused on comparing alternative schemes in terms of their ability to limit permit price risk. For example, Stranlund et al. (2014) studied the effects of price controls and banking, separately and together. Holt and Shobe (2016) examined alternative price and quantity controls motivated by the market stability reserve of the EU ETS. Perkis et al. (2016) examined hard and soft price ceilings, while Friesen et al (2019) examined soft price ceilings with an alternative design for auctioned permits.[2] Friesen et al. (2020) investigated the use of dual allowance reserves and trigger prices. Finally, Salant et al. (2020) studied the impact of non-binding hard and soft floors on permit prices in a dynamic setting with permit banking. In contrast to these studies of alternative mechanisms to stabilize permit prices, we examine the effects of a hard price floor on investments in a cost-saving abatement technology under uncertainty.

None of the aforementioned papers is concerned with the effects of price controls on investments in cost-reducing abatement technologies. To our knowledge, only Weber and Neuhoff (2010) and Brauneis et al. (2013) address technology investments and price controls in emissions markets. In particular, Weber and Neuhoff is a normative theoretical study of the optimal design of an emissions market with price controls; however, they do not address how price controls affect firms' investments in reducing their abatement costs. Brauneis et al. employ a simulation model in conjunction with a real options approach to determine the optimal carbon price floor and its effect on the timing of investment in low-carbon technology in the electricity sector. In contrast to these two papers, our contribution is a positive study that examines how

[2]A *hard* price floor entails a lower absolute limit on the permit price. This can be implemented in markets where allowances are distributed for free and where the government commits to buy back any unused allowances at the floor price. This is the case that we consider here. In contrast, in emissions markets where allowances are auctioned, a *soft* price floor can be implemented through a minimum reserve price for newly auctioned permits (see Murray et al., 2009).

a price floor affects the adoption of a cost-saving abatement technology, both theoretically and experimentally.

In this respect, our paper also adds to the literature on environmental policy induced technology adoption (for a survey, see Requate, 2005).[3] Under certainty about firm's abatement costs, Requate and Unold (2003) argue that a fixed emissions tax provides a greater incentive for firms to adopt a cost-saving technology than a competitive emissions market with a fixed number of emissions permits. The reason is that a significant number of adopters will lower the permit price in a market, which in turn reduces the adoption incentive and the number of adopters. We show, both theoretically and experimentally, that adding a price floor to an emissions market under uncertainty about firms' abatement costs can increase the adoption incentives in the market and increase the number of adopters of a new technology. This occurs because the price floor truncates the lower range of potential permit prices when abatement costs are uncertain.

The paper is structured as follows. In Section 2 we develop the theory and derive the main propositions. The experimental design, implementation and hypotheses are described in Section 3, followed by the analyses and discussion of results in Section 4. Conclusions are drawn in Section 5.

2 Theoretical Framework

Our experiment is based on a theoretical model of n heterogeneous risk-neutral competitive firms who participate in a market to control a uniformly mixed pollutant. Firm i in the market emits q^i units of a pollutant and its abatement cost function is

$$a^i(q^i, u) = \int_{q^i}^{q_0^i} (\widetilde{b}^i + u - cq^i) dq^i, \tag{1}$$

where $\widetilde{b}^i$ and c are positive constants. The random variable u affects the abatement costs of all firms, and is distributed on support $[\underline{u}, \overline{u}]$ with probability density function $g(u)$ and zero expectation.[4] Finally, q_0^i is the minimizer of $a^i(q^i, u)$; that is, $q_0^i(u) = (\widetilde{b}^i + u)/c$, with $\widetilde{b}^i > \underline{u}$ for each firm. This is commonly referred to as the firm's unregulated level of emissions.

Firms can make an investment to reduce their total and marginal abatement costs while holding the slope of the marginal abatement cost function constant.[5]

$$\widetilde{b}^i = b^i(1 - \beta x^i), \tag{2}$$

[3] Generally, our work fits into a broader literature that studies how market design can affect market performance by affecting investment decisions (Fabra et al., 2011).

[4] Due to the way in which this common shock u enters the abatement cost function, it could also be thought of as a common shock to emissions. This could arise, for example, through regional weather variation or macroeconomic shocks (such as, most dramatically, a global pandemic).

[5] Our research question is centered around the incentives to invest in the adoption of an existing cost-saving abatement technology. An alternative design could relate to investment in R&D and feature stochastic investment success (see Cason and de Vries, 2019). This would, however, imply a random shock at the firm level in addition to the common shock that affects the abatement costs of all firms as in our current setup (see also footnote 4). We leave investigation of this more complex design for future research.

where $x^i = [0,1]$ is an irreversible dichotomous investment choice, b^i is a positive constant that varies across firms on the interval $[b^{min}, b^{max}]$, and $\beta \in (0,1)$ is a constant that does not vary across firms. Combining equations (1) and (2) allows us to rewrite the firm's abatement cost function as

$$a^i(q^i, x^i, u) = \frac{(b^i(1-\beta x^i)+u)^2}{2c} - (b^i(1-\beta x^i)+u)q^i + \frac{c(q^i)^2}{2}. \tag{3}$$

Firms are distinguished from one another by the level of the parameter b^i, which we will sometimes refer to as firm i's "type."

We analyze an emissions trading program with and without a price floor with the following features. A total of L permits are distributed to the firms (free of charge), and firm i receives l_0^i permits from this initial distribution. Each permit confers the legal right to emit one unit of emissions and enforcement is assumed to be perfect, implying that firms' final permit holdings are equal to their emissions. Emissions permits trade at a competitive price p. When the market includes a price floor the government commits to buying back unused permits at a fixed price s. For the market to clear we must have $s \leq p$. Throughout we assume that the price floor has a strictly positive probability of binding.

The timing of events in our model is as follows. Given the elements of the market policy, in the first stage all firms choose whether to make their irreversible investments in reducing their abatement costs. In the second stage the value of u is revealed and, given u, firms choose their emissions, trade in the permit market (including potential sales to the government), the market clears, and the firms release their allowed levels of emissions.

2.1 A Pure Market without Price Controls

In this subsection we specify the equilibrium for a market without a price floor, starting with the second stage. Given the realization of u, a permit price (to be determined) and investments from the first stage, a firm chooses its emissions to minimize its compliance cost, consisting of its abatement cost and the value of its permit transactions:

$$\begin{aligned} c^i(q^i, x^i, u) &= a^i(q^i, x^i, u) + p(q^i - l_0^i) \\ &= \frac{(b^i(1-\beta x^i)+u)^2}{2c} - (b^i(1-\beta x^i)+u)q^i + \frac{c(q^i)^2}{2} + p(q^i - l_0^i). \end{aligned} \tag{4}$$

The familiar rule of equalizing marginal abatement cost and the permit price gives us the firm's choice of emissions,

$$q^i(x^i, p, u) = \frac{b^i(1-\beta x^i)+u-p}{c}. \tag{5}$$

Using (5) to solve the market clearing condition, $\sum_{i=1}^n q^i(x^i, p, u) = L$, the equilibrium permit price is

$$p(\boldsymbol{x}, u) = \frac{\sum_{i=1}^n b^i(1-\beta x^i) - cL}{n} + u, \tag{6}$$

where $\boldsymbol{x} = (x^1, ..., x^n)$ is the vector of individual investments in abatement cost reductions. Clearly the permit price is lower when the random variable u is lower and when more firms invest in reducing their abatement costs. (Throughout we ignore the fact that the permit price also depends on the supply of permits.)

It is convenient to write (6) as

$$p(\boldsymbol{x}, u) = p(\boldsymbol{x}) + u, \tag{7}$$

where $p(\boldsymbol{x})$ is the expected permit price (i.e., when $u = 0$), given investments $\boldsymbol{x}$. Substitute (5) and (7) into (4) to obtain a firm's equilibrium compliance cost in the second stage as a function of the first-stage investment

$$c^i(\boldsymbol{x}, u) = (p(\boldsymbol{x}) + u)\left(\frac{b^i(1-\beta x^i) + u}{c} - \frac{p(\boldsymbol{x}) + u}{2c} - l_0^i\right). \tag{8}$$

Having characterized the second-stage equilibrium emissions, permit price and firms' compliance costs, we are now in a position to consider a firm's choice of investment in reducing its abatement cost in the first stage. We begin by calculating a firm's expected benefit of investment, given the investment choices of the other firms. Given a realization of u, the change in firm i's compliance cost if it invests in the first stage is

$$\Delta c^i(\boldsymbol{x}, u) = c^i(x^i = 1, x^{-i}, u) - c^i(x^i = 0, x^{-i}, u), \tag{9}$$

where $x^{-i} = \boldsymbol{x}\backslash(x^i)$. It is possible that a single firm's investment in reducing its abatement cost in the first stage can influence the equilibrium permit price in the second stage, and this in turn can have an indirect effect on its decision to invest. To investigate this possibility, write $p(x^i, x^{-i}, u) = p(\boldsymbol{x}, u)$ and use (6) to calculate the change in the equilibrium permit price with i's investment,

$$\Delta^i p = p(x^i = 1, x^{-i}, u) - p(x^i = 0, x^{-i}, u) = -\frac{b^i\beta}{n} < 0. \tag{10}$$

We can see that the effect of a firm's investment on the equilibrium permit price will be negligible in a market with a relatively large number of participants, as in most real emissions markets. To model these cases we set $\Delta^i p = 0$. The propositions that we derive below and the corresponding experimental hypotheses are based on this case. However, experimental emissions markets typically have a small number of participants, as do some emissions markets in practice.[6] Therefore, we will also address the small-number case when $\Delta^i p < 0$.

Define a firm's expected reduction in its compliance cost from its investment in the first stage as

$$r^i(\boldsymbol{x}) = -\mathbb{E}\left(\Delta c^i(\boldsymbol{x}, u)\right), \tag{11}$$

where $\mathbb{E}$ denotes the expectation operator. In Appendix A we show that

$$\Delta c^i(\boldsymbol{x}, u) = \Delta^i p\left(\frac{b^i - p(x^i = 0, x^{-i})}{c} - l_0^i - \frac{\Delta^i p}{2c}\right) - \frac{(p(x^i = 1, x^{-i}) + u)b^i\beta}{c}. \tag{12}$$

Taking the expectation of (12) and multiplying by -1 gives us the expected reduction in the firm's compliance cost from investing in reducing its abatement cost:

$$r^i(\boldsymbol{x}) = \frac{p(x^i = 1, x^{-i})b^i\beta}{c} - \Delta^i p\left(\frac{b^i - p(x^i = 0, x^{-i})}{c} - l_0^i - \frac{\Delta^i p}{2c}\right). \tag{13}$$

[6] For example, permit markets for effluent emissions to waterways sometimes have a small number of large emitters, as discussed in Cason et al. (2003).

The firm's expected benefit from investment (13) is made up of two effects. The first term on the right side of (13) is the direct effect of the firm's investment, while the second term is an indirect price effect that the firm experiences only when there is a small enough number of firms in the market. That the direct effect is strictly positive indicates that, holding the permit price constant, the firm's investment in reducing its abatement cost decreases its expected compliance cost when there is a large number of firms in the market. However, the firm's expected compliance cost may not fall from its investment if the number of firms is small enough so that a single firm's investment changes the permit price. Since $\Delta^i p < 0$ in the small-numbers case, the sign of the indirect price effect of the firm's investment depends on the sign of

$$\frac{b^i - p(x^i = 0, x^{-i})}{c} - l_0^i - \frac{\Delta^i p}{2c}. \tag{14}$$

The first term of (14) is $\mathbb{E}\left(q^i(x^i = 0, p, u)\right) = (b^i - p(x^i = 0, x^{-i}))/c$. This is the firm's expected emissions (and permit demand) if it does not invest. Thus, the first two terms of (14) indicate the firm's expected permit transaction when it does not invest. Given $-\Delta^i p/2c > 0$, (14) is positive if the firm expects to buy permits, or sell fewer than $\Delta^i p/2c$ permits. In these cases, the price effect of the firm's investment is positive and it reinforces the direct effect of its investment. However, if the firm expects to sell more than $\Delta^i p/2c$ permits, (14) is negative, reducing the motivation for the firm to invest in lowering its abatement cost. Thus, the firm is less willing to invest in reducing its abatement cost if it believes that doing so will reduce the value of its permit sales. It is even possible that a firm that expects to sell a significant number of permits would find that its investment in reducing its abatement cost could actually increase its expected compliance cost (i.e., $r^i(\boldsymbol{x}) < 0$).

We are now able to characterize a firm's investment choice. Suppose that the cost of the investment is f, which does not vary across firms. We assume that if a firm is indifferent about making the investment in reducing its abatement cost then it chooses to make the investment. The firm then invests in reducing its abatement cost if and only if

$$f \leq r^i(\boldsymbol{x}); \tag{15}$$

that is, the firm invests if and only if the cost of the investment is not greater than the expected reduction in its compliance cost.

If the market comprises many firms such that a single firm's investment does not affect the permit price, $\Delta^i p = 0$ and $r^i(\boldsymbol{x}) = p(x^i = 1, x^{-i})b^i\beta/c$. Given an equilibrium vector of investments $\boldsymbol{x}^*$ that includes $x^i = 1$,

$$r^i(\boldsymbol{x}^*) = r(b^i, \boldsymbol{x}^*) = \frac{b^i\beta p(\boldsymbol{x}^*)}{c}, \tag{16}$$

where $p(\boldsymbol{x}^*)$ is the expected equilibrium permit price. We write $r^i(\boldsymbol{x}^*) = r(b^i, \boldsymbol{x}^*)$ to recognize that, given $\boldsymbol{x}^*$, $r^i(\boldsymbol{x}^*)$ differs over firms only as b^i varies. The following proposition tells us which firms will invest in reducing their abatement cost. All proposition proofs are in Appendix A.

Proposition 1. *Consider a competitive emissions market without a price floor and assume that no single firm's investment in reducing its abatement cost can affect the equilibrium permit price. Then, there exists a unique firm type, b^*, defined by*

$$f = \frac{b^* \beta p(\boldsymbol{x^*})}{c}, \tag{17}$$

such that if $b^* \in [b^{min}, b^{max}]$, then firm types $b^i \in [b^*, b^{max}]$ invest in reducing their abatement costs and firm types $b^i \in [b^{min}, b^*)$ do not. No firm invests if $b^* > b^{max}$, and every firm invests if $b^* < b^{min}$.

Proposition 1 indicates that a cut-off firm type, b^*, typically separates the investors who have higher abatement costs (i.e., $b^i \geq b^*$) from the non-investors who have lower abatement costs (i.e., $b^i < b^*$). The reason for this pattern of investment is that the expected value of investing in reducing abatement costs is higher for firms with higher abatement costs. To be complete, Proposition 1 also characterizes corner solutions at which all firms invest or no firm invests.

Proposition 1 relies on the fact that $r(b^i, \boldsymbol{x^*})$ as specified by (16) is linearly increasing in b^i. However, we stressed above how the price effect of a firm's investment to reduce its abatement cost can enhance, reduce, or eliminate its motivation to invest in reducing its abatement cost if this investment reduces the equilibrium permit price. In this case we cannot guarantee that $r^i(\boldsymbol{x})$, as specified in (13), is monotonically increasing for every firm. Therefore, in the case of a small number of firms whose individual investments can impact the permit price, equilibrium investments may not follow the simple pattern of Proposition 1.

2.2 A Market with a Price Floor

To set up the investment objective for a firm when a price floor is placed on a market we first need to specify the value of the random variable u at which the price floor and the permit market bind together. This value of u is u^s, the solution to $p(\boldsymbol{x}) + u = s$; that is,

$$u^s = s - p(\boldsymbol{x}). \tag{18}$$

To make sure that the price floor has a strictly positive probability of binding, we restrict ourselves to values of s such that $u^s \in (\underline{u}, \overline{u})$. For realizations of $u > u^s$ the permit cap binds, each firm chooses emissions equal to $q^i(x^i, p, u)$ from (5) and the permit market clears at price $p(\boldsymbol{x}, u)$ from (6). For $u < u^s$ the price floor binds so that $p = s$. In this case, from (5) a firm chooses emissions

$$q^i(x^i, s, u) = \frac{b^i(1 - \beta x^i) + u - s}{c}.$$

Moreover, we can modify (8) to write the firm's compliance cost when the price floor binds as

$$c^i(\boldsymbol{x}, s, u) = s\left(\frac{b^i(1 - \beta x^i) + u}{c} - \frac{s}{2c} - l_0^i\right). \tag{19}$$

From the perspective of the first-stage investment, a firm's expected compliance cost when it faces a price floor is

$$\int_{\underline{u}}^{u^s} c^i(\boldsymbol{x}, s, u) g(u) du + \int_{u^s}^{\overline{u}} c^i(\boldsymbol{x}, u) g(u) du,$$

and the firm's expected reduction in its compliance cost from investing in reducing its abatement cost is

$$r^i(\boldsymbol{x}, s) = -\int_{\underline{u}}^{u^s} \Delta c^i(\boldsymbol{x}, s, u) g(u) du - \int_{u^s}^{\overline{u}} \Delta c^i(\boldsymbol{x}, u) g(u) du, \tag{20}$$

where $\Delta c^i(\boldsymbol{x}, u)$ is given by (12). Using (19),

$$\Delta c^i(\boldsymbol{x}, s, u) = -\frac{sb^i\beta}{c}. \tag{21}$$

Substitute (12) and (21) into (20) and collect terms to obtain

$$\begin{aligned} r^i(\boldsymbol{x}, s) =& \frac{b^i\beta}{c}\left\{\int_{\underline{u}}^{u^s} sg(u)du + \int_{u^s}^{\overline{u}} \left(p(x^i = 1, x^{-i}) + u\right) g(u)du\right\} \\ & - \int_{u^s}^{\overline{u}} \Delta^i p \left(\frac{b^i - p(x^i = 0, x^{-i})}{c} - l_0^i - \frac{\Delta^i p}{2c}\right) g(u)du. \end{aligned} \tag{22}$$

As usual, the firm invests in reducing its abatement cost if and only if

$$f \leq r^i(\boldsymbol{x}, s), \tag{23}$$

and does not invest otherwise.

If the market comprises many firms such that no single firm's investment affects the permit price, $\Delta^i p = 0$ in (22). In this case, given an equilibrium vector of investments $\boldsymbol{x}^{**}$ that includes $x^i = 1$,

$$r^i(\boldsymbol{x}^{**}, s) = r(b^i, \boldsymbol{x}^{**}, s) = \frac{b^i\beta}{c}\left\{\int_{\underline{u}}^{u^{s**}} sg(u)du + \int_{u^{s**}}^{\overline{u}} (p(\boldsymbol{x}^{**}) + u) g(u)du\right\}, \tag{24}$$

where $u^{s**} = s - p(\boldsymbol{x}^{**})$ from (18). As with (16), we write $r^i(\boldsymbol{x}^{**}, s) = r(b^i, \boldsymbol{x}^{**}, s)$, because, given $\boldsymbol{x}^{**}$, $r^i(\boldsymbol{x}^{**}, s)$ varies across firms only as b^i varies across firms. In addition, we note that the bracketed term on the right side of (24) is the equilibrium expected permit price under the price floor, given investments $\boldsymbol{x}^{**}$. To make this explicit, denote the expected equilibrium permit price under the price floor as $\mathbb{E}(p(\boldsymbol{x}^{**}, s))$ and rewrite (24) as

$$r(b^i, \boldsymbol{x}^{**}, s) = \frac{b^i\beta\mathbb{E}(p(\boldsymbol{x}^{**}, s))}{c}. \tag{25}$$

The following proposition, which is the analogue to Proposition 1, characterizes equilibrium investment decisions in the case of a market with a price floor and a large number of firms.

Proposition 2. *Consider a competitive emissions market with a price floor and assume that no single firm's investment in reducing its abatement cost can affect the equilibrium permit price. Then, there exists a firm type, b^{**}, defined by*

$$f = \frac{b^{**}\beta\mathbb{E}(p(\boldsymbol{x}^{**}, s)}{c}, \tag{26}$$

such that if $b^{**} \in [b^{min}, b^{max}]$, then firm types $b^i \in [b^{**}, b^{max}]$ invest in reducing their abatement costs and firm types $b^i \in [b^{min}, b^{**})$ do not. No firm invests if $b^{**} > b^{max}$, and every firm invests if $b^{**} < b^{min}$.

As in Proposition 1, when there is a mix of investing and non-investing firms only high abatement-cost firms make the first-stage investment in reducing their abatement costs. However, the cut-off firm type under Proposition 2 is likely different from the cut-off firm type in Proposition 1, so it remains to be seen whether the price floor expands or contracts the set of firms that invest in reducing their abatement costs. Like the proof of Proposition 1, the proof of Proposition 2 relies on the fact that a firm's expected reduction in its compliance cost, equation (22), is monotonically increasing in b^i when the firm's investment cannot affect the permit price. In the case that a firm can affect the permit price with its investment, we cannot guarantee that (22) is monotonic for every firm, and hence, we cannot guarantee that only high abatement-cost firms invest in reducing their abatement costs.

2.3 Investment with and without a Price Floor

We are now ready to show how the set of firms that invest in reducing their abatement costs changes with the implementation of a price floor, at least when emissions markets are large enough so that a single firm's investment to reduce its abatement cost cannot affect the equilibrium permit price. Our results are contained in the following proposition.

Proposition 3. *Consider a competitive emissions market for which no single firm's investment in reducing its abatement cost can affect the equilibrium permit price. Assume that the cut-off firm types* b^* *and* b^{**} *in Propositions 1 and 2, respectively, are contained in the interval* $[b^{min}, b^{max}]$*. Then:*

(1) $b^{**} < b^*$.

(2) The price floor causes the set of firms that invest in reducing their abatement costs to expand to include firm types in the interval $[b^{**}, b^*)$*, provided that there are firm types in this interval.*

Proposition 3 is the main result of our analysis, because it gives us a prediction about how a price floor affects the pattern of investment in a technology to reduce abatement costs in a competitive emissions market with a relatively large number of firms. In cases in which there is a mix of investors and non-investors, only high abatement-cost firms invest whether an emissions market includes a price floor or not. However, a price floor will expand the set of investors (except in a special case) so that there are "intermediate" abatement-cost firms that invest when a price floor is in place, but would not invest in the absence of the price floor.

Figure 1 illustrates the main results of Propositions 1 through 3. We have graphed $r(b^i, \boldsymbol{x}^*)$ from (16), noting that it is a linearly increasing function of the firm types, given the equilibrium investments in the absence of a price floor, $\boldsymbol{x}^*$. In an equilibrium outcome with a mix of investors and non-investors, there is a firm type, b^*, such that firm types at b^* and above are the investors, and firm types below b^* do not invest in the new technology. Thus, as revealed by Proposition 1, only the high-abatement-cost firms invest in the new technology. We have also graphed $r(b^i, \boldsymbol{x}^{**}, s)$ from (24). This function is also linearly increasing in the firm types, given the equilibrium investments $\boldsymbol{x}^{**}$ in the presence of a price floor. Again, as revealed by

Proposition 2, in an equilibrium with a mix of investors and non-investors, there is a cut-off firm type b^{**} that separates the investors with higher abatement costs from the non-investors with the lower abatement costs.

Proposition 3 reveals that $b^{**} < b^{*}$ so that a price floor can expand the set of investors to include those firm types in the interval $[b^{**}, b^{*})$. The proof of Proposition 3 rests on showing that the expected permit price with a price floor that has a non-zero chance of binding is strictly greater than the expected permit price without the price floor. In fact, using (16) and (25), $r(b^i, \boldsymbol{x}^{**}, s) > r(b^i, \boldsymbol{x}^{*})$ as shown in Figure 1 is implied by $\mathbb{E}(p(\boldsymbol{x}^{**}, s)) > p(\boldsymbol{x}^{*})$. There are two effects at work here. The first is that the price floor truncates the lower part of the distribution of potential prices. Holding investments in the new abatement technology constant, truncating the lower part of the price distribution increases the expected permit price. However, increased investments in reducing abatement costs pushes the expected permit price down. This countervailing effect is not large enough to offset the effect of truncating the price distribution, so the expected permit price is higher with the price floor and, in turn, the set of investors is larger.

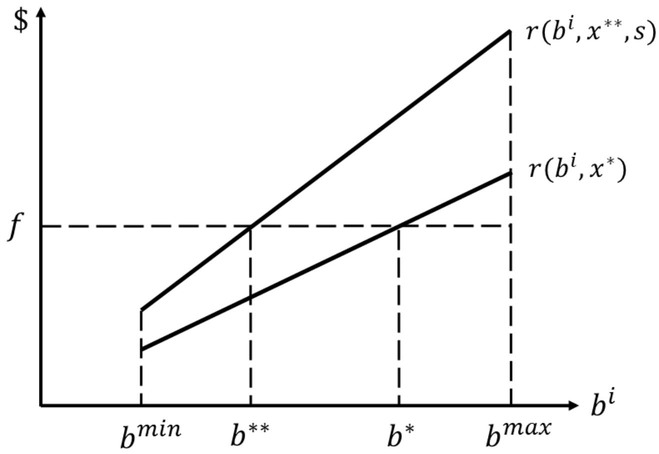

Figure 1: Impact of Price Floor on Firms' Investments in Reducing Abatement Costs

3 Experimental Design and Hypotheses

3.1 Experimental Parametrization and Trading Institution

The experimental implementation of the preceding model of abatement and investment with and without price controls required several simplifications. The quantity of emissions (q) was discretized, since emission permits are typically traded in discrete units of (e.g., tons of CO_2 equivalent). The random variable affecting abatement costs (u) was also simplified to take on a limited set of 5 equiprobable values. In this description the "firms" who make investment, abatement and trading choices were human subjects recruited to the laboratory. Their investments, abatement and permit trading decisions determined their monetary payments, which were distributed in cash at the conclusion of each experimental session.

Each market included 8 heterogeneous firms. Although it may seem relatively thin, this market size is common in laboratory studies and can result in relatively competitive pricing when trade is organized using continuous double auction rules (Smith, 1982). The double auction market used in the experiment provides a competitive environment where traders are free to submit public offers to purchase and sell permits at any prices. Those wishing to buy permits can submit bid prices to buy or accept sellers' offer prices in continuous time. Symmetrically, those wishing to sell permits can submit offer prices to sell or accept buyers' bid prices at any time.[7] This creates a centralized, multilateral negotiation process that is relatively competitive even with a small number of traders.

Firm heterogeneity arises from differences in b^i, which takes on values of $100, 200, \ldots, 800$ for the 8 different firms. The discrete shift in abatement costs due to cost-reducing investment is $\beta = 0.252$ and parameter is $c = 15$ for all firms. The mean zero random variable affecting abatement costs u is drawn each period from the set $\{-40, -20, 0, 20, 40\}$ with all values equally likely. A total of 184 emission permits are distributed equally to the 8 firms, so that each began the trading period holding 23 permits. The heterogeneity in abatement costs creates gains from trading permits. It also leads the investment incentives to differ across firms, as characterized in Propositions 1 and 2. The firms with the highest b^i have the greatest incentive to invest to reduce costs. The investment cost f was fixed at 200 Experimental Dollars for all firms.

3.2 Period Timing and Equilibrium Prices

The experiment employs stationary repetition. This means that firms make similar investment and trading decisions in a stable environment across 16 consecutive periods with firm type being fixed.[8] Such repetition is commonly employed in market experiments to allow participants to gain experience and to provide more opportunity for prices to converge to (or at least approach) equilibrium levels. New random draws occur each period for the variable affecting abatement costs (u), however, and these draws affect the equilibrium price.[9] Therefore, the equilibrium price is not stationary.

At the start of each period, traders receive fixed revenues and permits. Those firms with greater abatement costs receive greater revenues to roughly equate the equilibrium distribution of net profits across firm types. Following this allocation of fixed revenues and permits, traders make (binary) investment decisions. They make this investment decision in each of the 16 cycles of stationary repetition, in order to maximize the number of observations collected for this focus of our study. Consistent with the theoretical model developed in Section 2, this investment lowers the marginal cost for each unit abated but does not affect the slope of the marginal

[7]Throughout the trading period, firms can adjust their offers but new offers must be an improvement over previous offers. That is, any new buy offers must be higher than the current highest buy offer and any new sell offers must be lower than the current lowest sell offer.

[8]One session with two markets conducted for the no-control baseline had to be restarted due to a configuration error, so these two markets were terminated after 13 rather than the full 16 periods.

[9]Recall that the u draw each period affects all firms identically. Two sequences of u realizations were drawn before the first sessions, and these specific drawn sequences were re-used for all subsequent sessions, equally allocated across markets in both treatments. This reduces the between-session and between-treatment variability arising from the differing realizations of the random shocks.

abatement cost function. Firms make this decision simultaneously and they never learn the investment decisions of others. (Individual firms' marginal abatement costs are always their own private information.) Firms then learn the realization of the random variable affecting abatement costs (u).[10] Traders' investment decisions and this realization of u lead to a new abatement cost profile across traders of each type. Equilibrium permit prices therefore depend on investment choices and random factors affecting abatement costs, as summarized in Table 1. Equilibrium prices are a multiple of 15 due to the marginal cost parameter choice of $c = 15$.

Table 1: Equilibrium Permit Prices by Abatement Cost Shock and Number of Investors

	Abatement Cost Shock (u)				
(#) Investors	-40	-20	0	20	40
(0) None	75	90	105	135	150
(1) $b^i = 800$	45	60	75	105	120
(2) $b^i = 800, 700$	30	45	60	90	105
(3) $b^i = 800, 700, 600$	15	30	45	75	90
(4) $b^i = 800, 700, 600, 500$	0	15	30	60	75
(5) $b^i = 800, 700, 600, 500, 400$	0	0	15	45	60
(6) $b^i = 800, 700, 600, 500, 400, 300$	0	0	0	30	45
(7) $b^i = 800, 700, 600, 500, 400, 300, 200$	0	0	0	30	45
(8) $b^i = 800, 700, 600, 500, 400, 300, 200, 100$	0	0	0	30	45

Trading periods lasted for 3 minutes until period 6, when the length was reduced to 2 minutes. Prior to these 16 periods of stationary repetition, subjects first participated in 8 (paid) training periods to familiarize them with the mechanics of continuous double auction trading through the computer interface. These training periods also included an investment stage, but they employed different abatement cost parameters and permit allocations so that transaction prices were very different from the prices in the main experiment.[11] The training periods never employed price controls. The training periods and the main periods each began with one practice period without financial stakes.

3.3 Price Floor

The treatment variable in the experiment is the price floor, imposed for this chosen parameterization at 70. No offers or transactions were allowed at prices below 70; they were automatically disallowed by the market software. Obviously, this led to an excess supply of permits at the floor price when the floor was binding. Consistent with the implementation of hard price floors in emissions permit markets in practice, firms wishing to sell these excess permits were able to sell them to "the computer," analogous to the regulator standing ready to buy excess permits at the floor. In order to create a marginal incentive to sell to actual traders wishing to buy at the floor during the trading period, the computer made these purchases at the close of trading

[10] This random shock to abatement costs effectively shifted traders along their marginal abatement cost function, so it was easiest to describe to subjects as an allocation of additional permits that they all received before trading opened for the period.

[11] Equilibrium prices in the training periods ranged between 120 and 300, and had virtually no overlap with the prices shown in Table 1 for the main periods.

and at a price of 69. Firms decided how many permits to sell at this price floor, following a recommendation by the software of how many they could sell profitably at this price.

3.4 Laboratory Procedures and Power Analysis

In order to determine subjects' understanding of the investment decisions and different ways of implementing the price floor, we initially ran 3 pilot sessions.[12] These pilots generated realized effect sizes and variance estimates that were used in a power analysis to design the main experiment. These power calculations led to the conclusion that 11 markets would be sufficient to detect a difference in investment rates with power 0.80 and significance level 0.05. The power analysis also prescribed a greater allocation of markets to the price control condition due to a higher variance observed in this treatment for the pilot sessions.

We therefore collected data from a total of 11 markets, with the price floor treatment implemented in 6 markets and the no-control baseline in the other 5 markets. Each market included 8 traders as described above. The subjects were all undergraduate students at Purdue University, recruited from a database of approximately 3,000 volunteers drawn across a wide range of academic disciplines and randomly allocated to treatment conditions using ORSEE (Greiner, 2015). The z-Tree program (Fischbacher, 2007) was used for the implementation of the experiment. For the purpose of maintaining as much experimental control as possible, we used neutral framing in the experiment and did not refer to the specific environmental economics setting explicitly, since environmental framing could affect subjects' preferences differently (Cason and Raymond, 2011). In particular, tradable emission permits were referred to as "coupons," and abatement and marginal abatement cost were referred to as "production" and "production costs," respectively that firms could avoid by holding more coupons. Details are provided in the written instructions given to subjects (see Appendix B).

Each session lasted about 2 hours and after each session earnings were paid out privately in cash at a pre-announced conversion rate from the Experimental Dollars earned across all (non-practice) periods. On average, subjects earned $33.47 per person.

3.5 Testable Hypotheses

The implications of the theoretical model and corresponding experimental design allow us to test several hypotheses. We first consider the impact of price controls on investment levels. As described earlier, all eight firms make their investment choice simultaneously. The competitive equilibrium permit prices shown in Table 1 indicate that the price floor of 70 is often binding. This was a deliberate design choice so that the differences in investment incentives would be large enough to substantially change the number of equilibrium investors. As noted earlier, analysis of costs and prices in large emissions trading markets such as California's GHG market has concluded that market prices are very likely to be limited by administrative price floors or ceilings (Borenstein et al., 2019).

[12]These pilot sessions led us to add the 8 training periods described earlier, so that subjects did not have to learn the mechanics of trading at the same time they learned how permit prices depend on investment decisions

Table 2: Increase in Expected Profits from Investing in Abatement Cost Reductions, Gross of Investment Cost

Firm Investor Type	No Price Floor	Price Floor = 70
$b^i = 800$	**1788**	**1706**
$b^i = 700$	**1077**	**1105**
$b^i = 600$	**720**	**834**
$b^i = 500$	**408**	**600**
$b^i = 400$	192	**492**
$b^i = 300$	48	**350**
$b^i = 200$	45	**210**
$b^i = 100$	30	140

Notes: Amounts shown in experimental dollars, based on equiprobable likelihood of the 5 abatement cost shocks. Entries in **bold** indicate firms with incentive to invest for the investment cost used in experiment (200).

Those firms with the highest abatement costs have the greatest incentive to invest to reduce their abatement costs, as indicated by the cutoff firm types as derived in Propositions 1 and 2. For the experimental parameterization, the highest cost types (i.e., those with the greatest b^i) always have the incentive to invest and the lowest cost types never have the incentive to invest, regardless whether a price floor exists. The price floor affects the investment decision of the intermediate-cost firms. Table 2 shows that in equilibrium 4 firms have an incentive to invest without a price floor but 7 firms would invest with the price floor. This leads to our primary hypothesis in connection to Proposition 3.

Hypothesis 1 (Investment): In a competitive permit market,

(a) A price floor increases the total number of firms investing in reducing their abatement costs; and

(b) The change in investment frequency is greatest for firms with intermediate abatement costs.

The investment incentives arise through the price implications on the permit market, so a necessary condition for support of Hypothesis 1 is a correlation between prices and abatement shocks and investment. This is summarized by the second hypothesis:

Hypothesis 2 (Prices): Emission permit prices are

(a) lower on average without the price floor than with the price floor in place;

(b) lower in periods with favorable shocks that lower abatement costs for all firms; and,

(c) lower in periods in which a greater number of firms invest in reducing abatement costs.

and investment incentives depend on prices and the price floor.

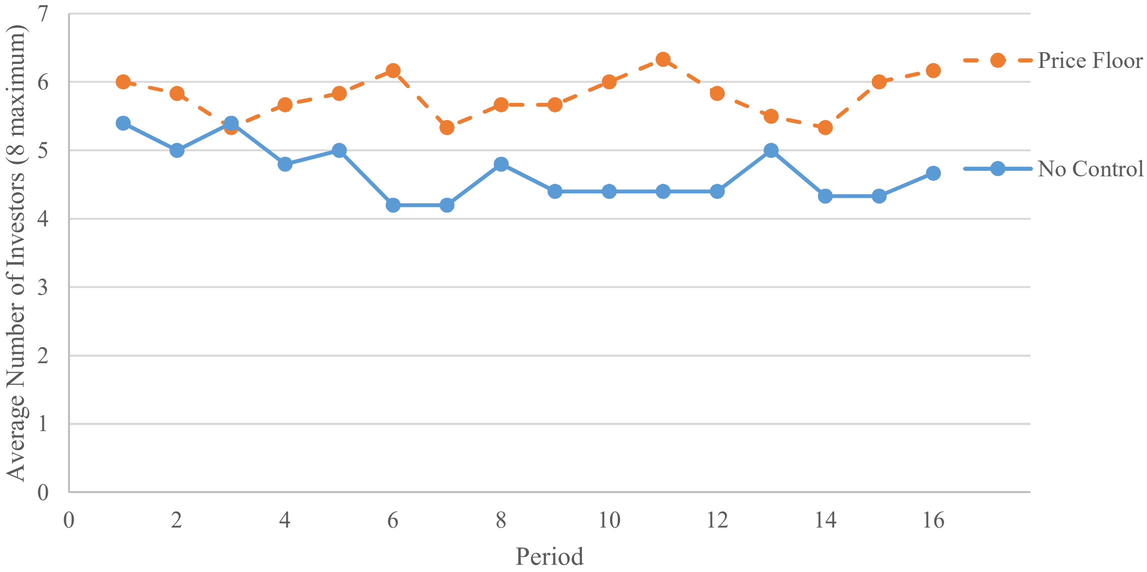

Figure 2: Mean Number of Investors, by Period

Hypothesis 2(a) is based on the primary implication of a price floor that has a non-zero chance of binding, since it truncates the lower part of the distribution of potential prices. For the other two parts of this hypothesis, Table 1 illustrates the specific amounts in equilibrium that prices change due to investment and cost shocks without the price floor. Of course, these price differences are limited by the price floor when it is imposed. When investment is sufficiently high or the abatement cost shock is favorable, the price floor will bind and parts (b) and (c) of Hypothesis 2 will not apply.

4 Experimental Results

This section is divided into two subsections, corresponding to the two hypotheses regarding cost-reducing investment and emission permit prices.

4.1 Cost-Reducing Investment

The price floor theoretically increases the number of investing firms because it helps to preserve the benefits of lower abatement costs even when favorable cost shocks cause prices to fall to low levels. For the parameters used in the experiment, 7 of the 8 firms can profitably invest in the price floor treatment, while only 4 firms can invest profitably without the price floor. Figure 2 displays the average number of investing firms across periods, pooling over all 11 markets. Although the difference in the investment frequency is similar for the first few periods, a persistent gap across treatments emerges over time. The difference is in the direction predicted in Hypothesis 1(a).

The most conservative statistical test of this hypothesis is a nonparametric test that requires no assumptions on the underlying distribution or error structure. The only requirement is that observations in the test be statistically independent, which is the case for our 11 different

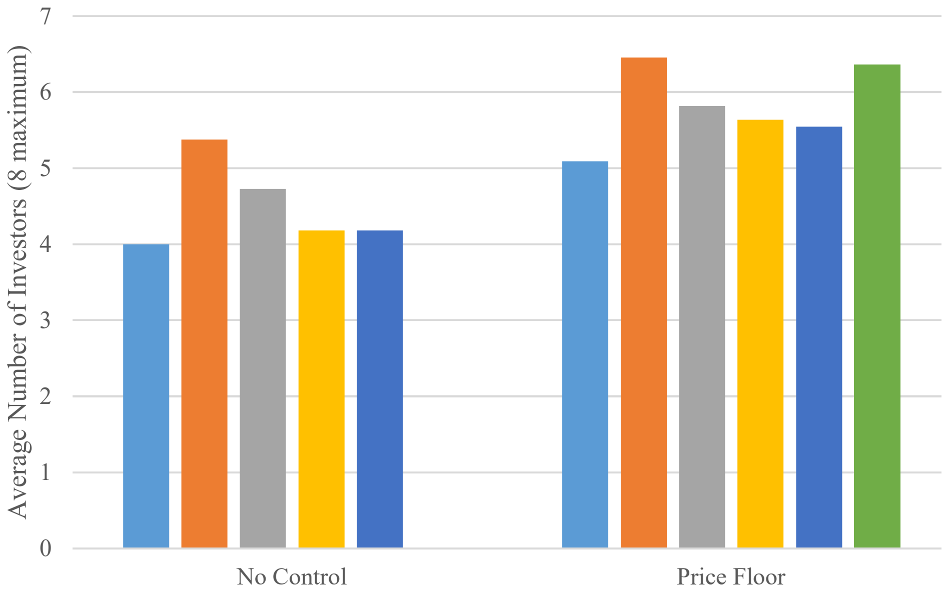

Figure 3: Mean Number of Investors, by Market (Periods 6-16 only)

markets. Figure 3 illustrates that only one market in the price floor treatment has a lower investment frequency than any market in the treatment without the price control. Since the distributions are nearly non-overlapping, a nonparametric Mann-Whitney test strongly rejects the null hypothesis of no treatment effect in favor of the directional prediction in Hypothesis 1(a) (one-tailed p-value $= 0.004, n = 11$).[13] The number of investors without the price control ranges mostly between 4 and 5, modestly exceeding the predicted number of 4 investors. The deviation below the prediction of 7 is larger for the price floor treatment, so the realized average treatment effect is smaller than the predicted level.

Hypothesis 1(b) concerns which specific firm types should change their investment choice due to the price floor. The lowest cost type ($b^i = 100$) should never invest, and the highest cost types ($b^i \geq 500$) should always invest. Only the intermediate-cost firms should change their investment decision due to the price floor.

Figure 4 shows that investment patterns are broadly consistent with this prediction. The lowest cost type invests less than 10 percent of the time, and the highest 4 types invest more than 90 percent of the time. The figure displays p-values from one-tailed nonparametric Mann-Whitney tests comparing average investments for the 3 firm types where the model predicts that the price floor increases investment incentives. Differences are statistically significant at conventional levels for 2 of these 3 types. None of the other 5 types have significantly different investment rates.[14] The variance within individual firm types across periods is not systematically different across treatments, except that type $b^i = 400$ has lower variation in investment frequency

[13]Figure 3 and this test are based on periods 6-16, after dropping the initial periods 1-5. The significance level is similar when including all periods, with a one-tailed p-value $= 0.008$.

[14]These tests employ only one observation per market ($n = 11$ for each test). They are based on periods 6-16, after dropping the initial periods 1-5. Results are similar based on all 16 periods, except that investment rates are significantly different for type $b^i = 700$ because the investment rate is exactly 100 percent in the price floor treatment.

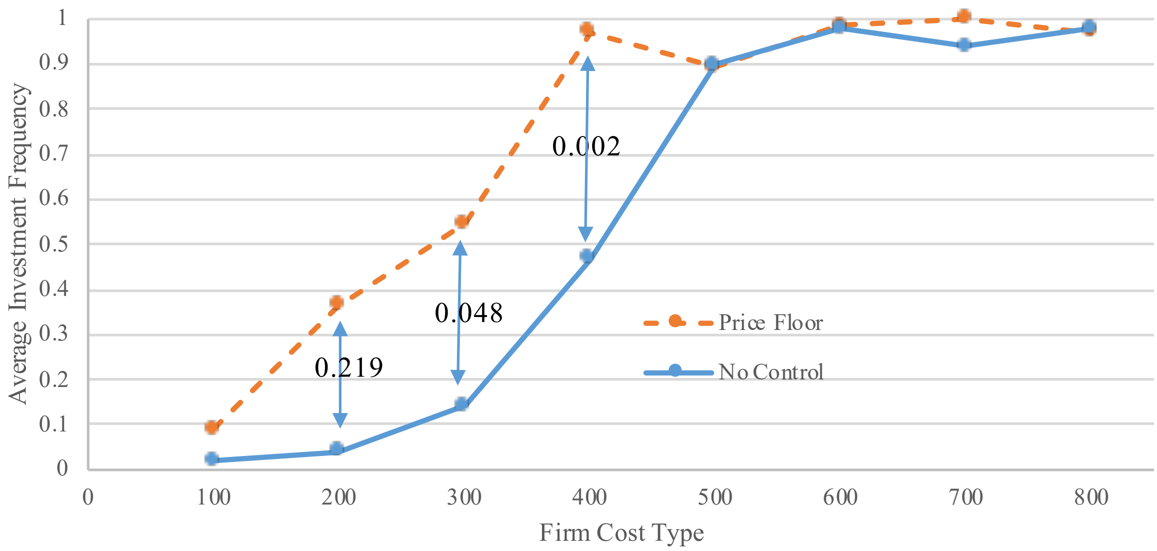

Figure 4: Mean Investment Rate, Across Firm Types (Periods 6-16 only). P-values shown for key firm types $b^i = 200, 300, 400$ where Hypothesis 1(b) predicts a significant difference.

in the price floor treatment (Mann-Whitney p-value $= 0.004$).

4.2 Emissions Permit Prices

The first and prerequisite implication of the price floor is that it raises transaction prices on average (Hypothesis 2(a)). Pooling across all periods and markets, the mean transaction price is 49.7 (se=0.58) without the price floor and is 81.7 (se=0.46) with the price floor. A nonparametric Mann-Whitney test strongly rejects the null hypothesis of no treatment effect in favor of the directional prediction in Hypothesis 2(a) (one-tailed p-value $= 0.002, n = 11$). Similar conclusions obtain when considering only the later market periods or the later transaction prices within a period. The price floor limits downward price movements, as expected.

The stronger incentives that firms have for investment in the presence of a price floor stem from the limitations imposed on price variability arising from changes in marginal abatement costs. Prices are predicted to decrease following favorable shocks to abatement costs or when additional firms invest in lowering their costs. The previous subsection provides support for these hypothesized differences in investment, which suggests that prices also vary as expected.

Realized prices in these types of experimental markets vary considerably over time. Price variation is large even within trading periods when the abatement costs are fixed and competitive equilibrium prices are unchanging. Previous experiments using this continuous double auction trading institution show that prices converge eventually when the competitive equilibrium is stable across periods. Not surprisingly, however, prices do not converge to equilibrium in an environment like this one where prices change randomly due to cost shocks and through firm-specific, cost-reducing investments.

Table 1 above indicates that equilibrium prices typically decline by 15 experimental dollars for each additional shift down to a more favorable cost shock, or when an additional firm invests in cost reduction.[15] We summarized these directional predictions above in Hypothesis 2. These price reductions are limited by the zero lower bound on prices, or limited by the price floor (70). Due to their already low abatement costs, cost reductions by firm types $b^i \leq 200$ do not impact equilibrium prices.

The early trades in each period are especially volatile and often occur far from equilibrium levels. As trades occur within a period, however, the market conveys information about underlying abatement costs (which are, recall, firms' private information). The later trading prices therefore reveal more about market conditions and become closer to equilibrium levels. For this reason we focus our analysis of the transaction prices to the later trades that occur each period.

Figure 5 displays the mean transaction prices for the baseline treatment without a price control, considering only the final 5 trades each period. Each bar corresponds to a different combination of a number of investors and abatement cost shock. Only the most common number of investors (4, 5 and 6) are displayed. Although in equilibrium prices should be 0 or 15 in nearly half of these cases (cf. rows (4) through (6) of Table 1), the displayed average prices are always 20 or greater. Average prices nevertheless tend to rise, as predicted, for more unfavorable cost shocks. The decrease in prices due to an increase in investment, moving rightward across blocks of similarly-colored bars, is less systematic.

The impact of the price floor on transaction prices is substantial, as expected. Figure 5 shows that average late period prices are always below 70 without the price floor; by contrast, Figure 6 indicates that prices are usually constrained by the floor. Average prices typically range between 70 and 80 in this treatment, and they are less sensitive to changes in cost shocks and investment choices than are prices in the treatment without the price floor.[16]

To formalize these observations, Table 3 reports a set of regressions to test Hypothesis 2. The dependent variable is the mean price across the final 5 transactions of each period (columns 1 and 3) or across the final 3 transactions of each period (columns 2 and 4). Columns 1 and 2 use data from the markets without a price control, and columns 3 and 4 are based on the price floor treatment. Panel A uses data from all periods, and panel B excludes the initial 5 periods that exhibit greater noise as traders initially trade at higher prices before later negotiating lower prices closer to equilibrium. This downward trend is reflected in the negative and sometimes significant or marginally insignificant Period Number time trend in panel A. This time trend is completely nonexistent when restricting analysis to the later periods in panel B.

The Cost Shock coefficient is predicted to be positive, and the estimates indicate that it is usually significantly greater than zero. This provides support for Hypothesis 2(b). The estimates are much larger in the baseline treatment without the price control, but even in this case they are still far below the predicted level of $15/20 = 0.75$ (cf. Table 1).[17] The coefficient on the Number

[15] The price difference is larger (30) between the 0 and 20 cost shock due to rounding.

[16] The within-period standard deviation in individual transaction prices is about 50 percent higher without the price control (9.46) than with the price floor (6.14). Although the difference is large, it is not statistically significant (Mann-Whitney test p-value $= 0.329$).

[17] Technically this simple linear function is misspecified, as the precise equilibrium impact on prices depends on the specific investors and cost shock. A full series of interactions between cost shock and investor identities would "consume" many degrees of freedom, however, so we limit ourselves to this more parsimonious approximation.

Table 3: Emission Permit Prices and Abatement Cost Shocks

Panel A: All Periods 1-16

	No Price Control		Price Floor Treatment	
Mean Price in:	Final 5	Final 3	Final 5	Final 3
	Transactions		Transactions	
	(1)	(2)	(3)	(4)
Cost Shock (-40 to 40)	0.35**	0.40**	0.07*	0.05
	(0.03)	(0.04)	(0.03)	(0.05)
Number of Investors (0 to 8)	-4.62	-4.87	-0.82	-0.54
	(3.04)	(2.72)	(1.51)	(1.99)
Period Number (1 to 16)	-1.11	-0.94	-0.79*	-0.80
	(0.54)	(0.62)	(0.26)	(0.38)
Constant	66.04*	64.63*	86.01**	84.58**
	(19.51)	(19.01)	(9.60)	(12.85)
R-squared	0.431	0.477	0.243	0.123
Observations	74	74	96	96
Clusters (Markets)	5	5	6	6

Panel B: Periods 6-16 Only

	No Price Control		Price Floor Treatment	
Mean Price in:	Final 5	Final 3	Final 5	Final 3
	Transactions		Transactions	
	(1)	(2)	(3)	(4)
Cost Shock (-40 to 40)	0.37**	0.42**	0.04**	0.04*
	(0.03)	(0.04)	(0.01)	(0.01)
Number of Investors (0 to 8)	-3.36*	-3.94*	0.03	0.28
	(1.53)	(1.17)	(1.04)	(1.22)
Period Number (6 to 16)	-0.10	-0.13	-0.09	-0.11
	(0.99)	(0.97)	(0.10)	(0.12)
Constant	48.56*	51.04*	72.61**	71.23**
	(17.16)	(14.65)	(5.83)	(6.41)
R-squared	0.423	0.477	0.079	0.093
Observations	49	49	66	66
Clusters (Markets)	5	5	6	6

Notes: Robust standard errors (clustering on markets) shown in parentheses. ** and * denote significantly different from 0 at one- and five-percent levels (one-tailed tests for only Cost Shock and the Number of Investors).

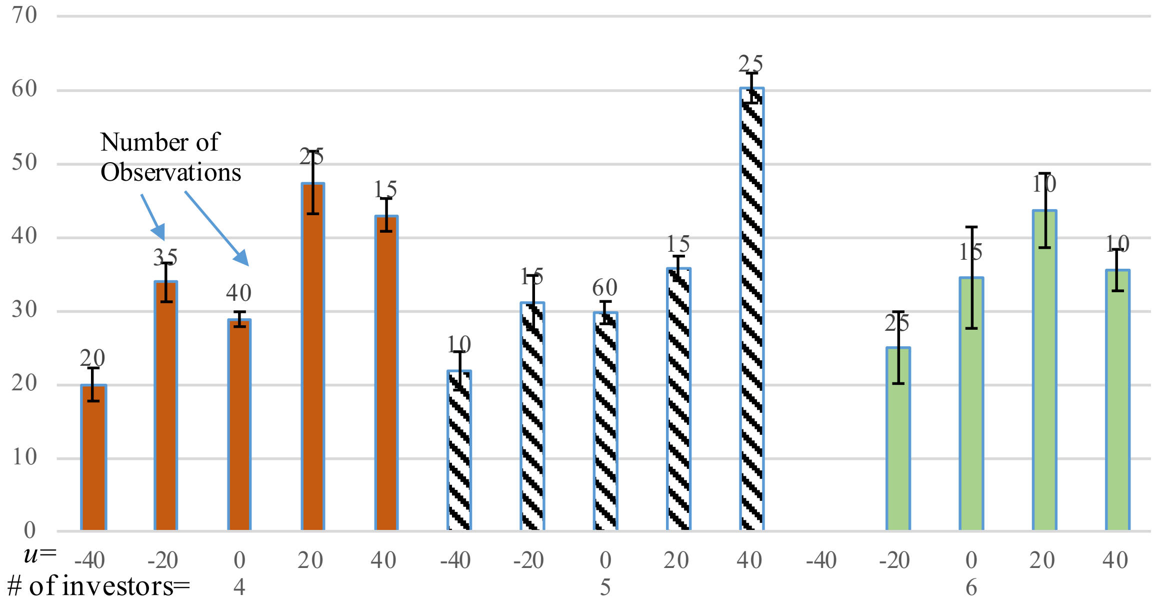

Figure 5: Mean Transaction Prices for Baseline (No Price Control) Treatment, Final 5 Trades each Period, by Cost Shock and Number of Investors. Error bars indicate standard errors.

of Investors should be negative, but it is only significantly less than zero when excluding the initial 5 periods (panel B). The evidence for Hypothesis 2(c) is therefore weak and is only seen without the price floor. These transaction price regressions establish that prices are much more sensitive to changes in abatement costs (either through the cost shock or due to investment) in the baseline treatment without the price control. In the treatment with the price floor (columns 3 and 4), Figure 6 illustrates that the floor is usually binding and so prices change little as costs shift.

4.3 Emissions

By design, emissions are limited by the total supply of permits, and the experimental environment imposed perfect compliance so the "cap" is always binding. Additional reductions below the permit supply cap do occur in the experiment, however, for a couple of reasons. First, the hard price control require permits to be purchased by the regulator to support the price floor. This encourages abatement up to the marginal cost level of the floor, and the unused permits are not used to cover emissions. Thus, the price floor mechanically reduces emissions when it binds. A second reason that emissions can fall below the cap is (low cost) sellers do not sell excess permits when prices are very low. This can occur especially in the treatment without price controls, where prices sometimes fell below the lowest marginal cost of abatement. These unused permits also lead to lower emissions.

On balance, the reduction of emissions due to the price control incentivizing greater abatement is stronger empirically for our experimental parameterization. The maximum emissions is 184, as 23 permits were allocated to each of the 8 firms. The unused permits in the no control treatment result in an emissions average of 177.6 (se=0.60), compared to 153.9 (se=1.11) for

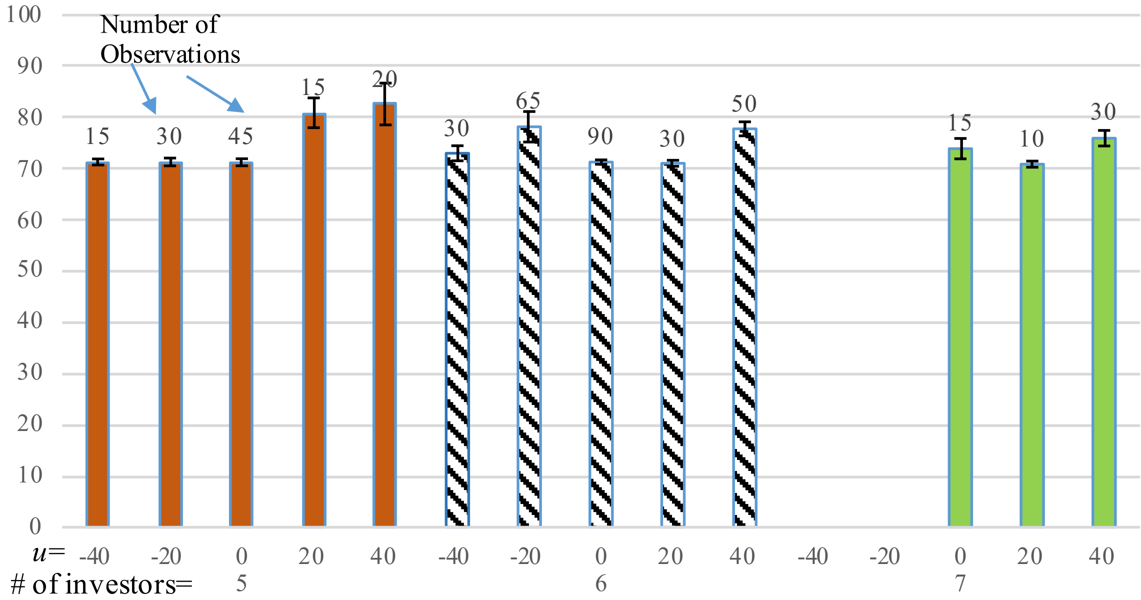

Figure 6: Mean Transaction Prices for Price Floor Treatment, Final 5 Trades each Period, by Cost Shock and Number of Investors. Error bars indicate standard errors.

the price floor treatment. This difference is highly significant (Mann-Whitney p-value = 0.004). The price floor therefore leads to greater investment, lower price volatility, more abatement and less emissions.

5 Conclusion

This paper develops a theoretical model that identifies firms' investment incentives in abatement technology for emissions trading markets characterized by cost uncertainty and regulated by price floors. The establishment of a price floor is pivotal in mitigating permit price uncertainty and limits market prices from becoming too low, which impedes investment and undermines the dynamic efficiency of markets. A price floor acts as an implicit subsidy for firms, as it increases the expected benefits from investment in lower abatement cost technology.

In a model featuring abatement cost uncertainty and a set of heterogeneous firms that interact in a competitive emissions trading market, our model reveals that, compared to an unregulated market, investment incentives are stronger when price floors are in place. More specifically, in a market where there is a mix of investors and non-investors, our model predicts that the price floor expands the number of investors in equilibrium. This key result is also supported empirically in a laboratory market experiment, which also indicates how transaction prices are sensitive to cost shocks and the number of investors. The policy lesson to be drawn from this is that abatement cost savings can be achieved through the implementation of a price floor, which can promote innovation and development of advanced abatement technology.

The experiment, of course, must impose a specific numerical parameterization for the laboratory market, and so we do not claim to provide broad empirical conclusions that can apply generally to the wide range of current and potential markets for emissions permits in the field.

The experiment's structure is guided closely by the theoretical model, however, and we believe it captures the important economic forces that cause price floors to promote abatement cost-reducing investment. The identification of clear causal channels with direct theoretical support helps promote confidence in external validity. When the price floor has a positive probability of binding, which is commonly the case for many emissions markets in practice (discussed in the Introduction), investment is likely to increase when the market is composed of a mixture of heterogeneous firms who invest at different levels.

Appendix A: Model Derivations and Proofs

Derivation of Equation (12)

Start with

$$\Delta c^i(\boldsymbol{x}, u) = c^i(x^i = 1, x^{-i}, u) - c^i(x^i = 0, x^{-i}, u).$$

To conserve notation, let $p(1) = p(x^i = 1, x^{-i})$ and $p(0) = p(x^i = 0, x^{-i})$. Moreover, define $\Delta^i p = (p(1) + u) - (p(0) + u)$. Then,

$$\begin{aligned}
\Delta c^i(\boldsymbol{x}, u) =& (p(1) + u)\left(\frac{b^i(1-\beta) + u}{c} - \frac{p(1) + u}{2c} - l_0^i\right) - (p(0) + u)\left(\frac{b^i + u}{c} - \frac{p(0) + u}{2c} - l_0^i\right) \\
=& \Delta^i p\left(\frac{b^i}{c} - l_0^i - \frac{p(1) + p(0)}{2c}\right) - \frac{(p(1) + u)b^i\beta}{c}
\end{aligned}$$

Since $p(1) = p(0) + \Delta^i p$,

$$\Delta c^i(\boldsymbol{x}, u) = \Delta^i p\left(\frac{b^i - p(0)}{c} - l_0^i - \frac{\Delta^i p}{2c}\right) - \frac{(p(1) + u)b^i\beta}{c},$$

which is equation (12).

Proposition 1

Proof. Note that $r(b^i, \boldsymbol{x^*})$, given by (16), is linearly increasing in b^i. Therefore, b^* defined by (17) is unique. Moreover, $f \leq r(b^i, \boldsymbol{x^*})$ and $x^i = 1$ for firm types $b^i \geq b^*$, and $f > r(b^i, \boldsymbol{x^*})$ and $x^i = 0$ for firm types $b^i < b^*$. If $b^* \in [b^{min}, b^{max}]$, then $f \leq r(b^i, \boldsymbol{x^*})$ and $x^i = 1$ for firm types $b^i \in [b^*, b^{max}]$, and $f > r(b^i, \boldsymbol{x^*})$ and $x^i = 0$ for firm types $b^i \in [b^{min}, b^*)$. If $b^* > b^{max}$, then $f < r(b^i, \boldsymbol{x^*})$ and $x^i = 1$ for all firms; if $b^* < b^{min}$, then $f > r(b^i, \boldsymbol{x^*})$ and $x^i = 0$ for all firms. □

Proposition 2

Proof. Proposition 2 is proved in the same way as Proposition 1. First note that $r(b^i, \boldsymbol{x^{**}}, s)$, given by (24), is linearly increasing in b^i. Therefore, b^{**} defined by (26) is unique. Moreover, $f \leq r(b^i, \boldsymbol{x^{**}}, s)$ and $x^i = 1$ for firm types $b^i \geq b^{**}$, and $f > r(b^i, \boldsymbol{x^{**}}, s)$ and $x^i = 0$ for firm types $b^i < b^{**}$. If $b^{**} \in [b^{min}, b^{max}]$, then $f \leq r(b^i, \boldsymbol{x^{**}}, s)$ and $x^i = 1$ for firm types $b^i \in [b^{**}, b^{max}]$, and $f > r(b^i, \boldsymbol{x^{**}}, s)$ and $x^i = 0$ for firm types $b^i \in [b^{min}, b^{**})$. If $b^{**} > b^{max}$, then $f < r(b^i, \boldsymbol{x^{**}}, s)$ and $x^i = 1$ for all firms; if $b^{**} < b^{min}$, then $f > r(b^i, \boldsymbol{x^{**}}, s)$ and $x^i = 0$ for all firms. □

Proposition 3

Proof. To prove part (1) of the proposition, first note that (17) and (26) imply

$$b^* p(\boldsymbol{x^*}) = b^{**}\mathbb{E}(p(\boldsymbol{x^{**}}, s)). \tag{27}$$

Subtracting $b^{**}p(\boldsymbol{x^*})$ from both sides of (27) allows us to obtain

$$sgn(b^* - b^{**}) = sgn\left\{\mathbb{E}(p(\boldsymbol{x^{**}}, s)) - p(\boldsymbol{x^*})\right\}. \tag{28}$$

Thus, what happens to the equilibrium set of investors when a price floor is imposed depends on what happens to the expected permit price.

We have

$$\mathbb{E}(p(\boldsymbol{x}^{**}, s)) = \int_{\underline{u}}^{u^{s**}} sg(u)du + \int_{u^{s**}}^{\overline{u}} (p(\boldsymbol{x}^{**}) + u)g(u)du. \tag{29}$$

From (18), $s = p(\boldsymbol{x}^{**}) + u^{s**}$. Substitute this into (29) to obtain

$$\mathbb{E}(p(\boldsymbol{x}^{**}, s)) = p(\boldsymbol{x}^{**}) + u^{s**} \int_{\underline{u}}^{u^{s**}} sg(u)du + \int_{u^{s**}}^{\overline{u}} ug(u)du. \tag{30}$$

Note that $p(\boldsymbol{x}^{*})$ can be written as

$$\begin{aligned} p(\boldsymbol{x}^{*}) &= \int_{\underline{u}}^{u^{s**}} (p(\boldsymbol{x}^{*}) + u)g(u)du + \int_{u^{s**}}^{\overline{u}} (p(\boldsymbol{x}^{*}) + u)g(u)du. \\ &= p(\boldsymbol{x}^{*}) + \int_{\underline{u}}^{u^{s**}} ug(u)du + \int_{u^{s**}}^{\overline{u}} ug(u)du. \end{aligned} \tag{31}$$

Subtract (31) from (30) to obtain

$$\mathbb{E}(p(\boldsymbol{x}^{**}, s) - p(\boldsymbol{x}^{*}) = p(\boldsymbol{x}^{**}) - p(\boldsymbol{x}^{*}) + \int_{\underline{u}}^{u^{s**}} (u^{s**} - u)g(u)du. \tag{32}$$

Toward signing (32), first note that our assumption that there is a strictly positive probability that the price floor will bind implies $u^{s**} > \underline{u}$, which in turn implies

$$\int_{\underline{u}}^{u^{s**}} (u^{s**} - u)g(u)du > 0. \tag{33}$$

To determine the relationship between $p(\boldsymbol{x}^{**})$ and $p(\boldsymbol{x}^{*})$, use the price equation (6) to write

$$\begin{aligned} p(\boldsymbol{x}^{**}) - p(\boldsymbol{x}^{*}) &= \frac{\sum_{j=1}^{n} b^j(1 - \beta x^{j**}) - cL}{n} - \frac{\sum_{j=1}^{n} b^j(1 - \beta x^{j*}) - cL}{n} \\ &= \left(\frac{1}{n}\right) \left(\sum_{j=1}^{n} b^j \beta x^{j*} - \sum_{j=1}^{n} b^j \beta x^{j**} \right), \end{aligned} \tag{34}$$

where x^{j**} and x^{j*} are equilibrium investment choices by firm j, with and without a price floor, respectively. Given $b^j\beta > 0$ for all firm types, (34) implies

$$sgn\left(p(\boldsymbol{x}^{**}) - p(\boldsymbol{x}^{*})\right) = sgn\left(\sum_{j=1}^{n} x^{j*} - \sum_{j=1}^{n} x^{j**} \right). \tag{35}$$

Let the equilibrium set of investors in the absence of a price floor be I^* and let the set of investors with the price floor be I^{**}. In addition, let $|I^*|$ and $|I^{**}|$ denote the cardinality (i.e., number of elements) of I^* and I^{**}, respectively. Note that

$$|I^*| = \sum_{j=1}^{n} x^{j*} \text{ and } |I^{**}| = \sum_{j=1}^{n} x^{j**}.$$

Then,

$$sgn\left(p(\boldsymbol{x}^{**}) - p(\boldsymbol{x}^{*})\right) = sgn\left(|I^*| - |I^{**}|\right). \tag{36}$$

Toward a contradiction of $b^* > b^{**}$ in the Proposition, suppose instead that $b^* \leq b^{**}$. From (28), this would imply $\mathbb{E}(p(\boldsymbol{x}^{**}, s)) - p(\boldsymbol{x}^*) \leq 0$. However, from (32) and (33), $\mathbb{E}(p(\boldsymbol{x}^{**}, s)) - p(\boldsymbol{x}^*) \leq 0$ requires $p(\boldsymbol{x}^{**}) - p(\boldsymbol{x}^*) < 0$, which from (36) implies $|I^*| < |I^{**}|$. However, $|I^*| < |I^{**}|$ requires $b^* > b^{**}$, which contradicts $b^* \leq b^{**}$. Since $b^* \nleq b^{**}$, we have $b^* > b^{**}$.

Part (2) of Proposition 3 follows directly from Propositions 1, 2 and part (1) of Proposition 3. □

Appendix B: Experiment Instructions

Note: Text that is shown only for price floor treatment is displayed in **bold font.**

5.1 General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of 1000 Experimental Dollars = 1 real Dollar. Notice that the more Experimental Dollars you earn, the more cash that you receive at the end of the experiment. Everyone will also receive a fixed participation payment of $5 that will be added to this total.

At your seat you have a sheet labeled Personal Record Sheet, which will help you keep track of how your decisions impact your earnings. You also have a sheet indicating your trading values for coupons (costs avoided when purchasing or additional costs incurred by selling). You are not to reveal this information to anyone. It is your own private information.

In each period you will produce units of a good. For every unit of the good that you produce, you will incur a production cost which will take away from your earnings. In order to avoid these costs, you may wish to purchase "coupons." Each coupon allows you to produce 1 less unit of the good, and avoid those production costs.

At the beginning of each period you will receive cash in the form of a Fixed Period Revenue, which will be labelled as Cash on your investment and trading screens. You will also have the opportunity to make an investment which can lower your production costs. Afterwards everyone will receive a small number of additional coupons, with the amount determined randomly. There will then be a time for you to sell or purchase coupons to and from other participants. At the end of each period you will pay your production costs, which will depend on how many coupons you hold. Your earnings each period are determined as follows:

Earnings = Fixed Period Revenue – Total Production Costs – Investment Cost (if any)

+ Sale Proceeds from Selling Coupons – Amount Spent when Buying Coupons.

Your Fixed Period Revenue does not depend on any actions you take, and does not change throughout the experiment. (In fact, it is already written on your Personal Record Sheet.) You will receive this revenue at the beginning of each period so that you have cash available with which to trade.

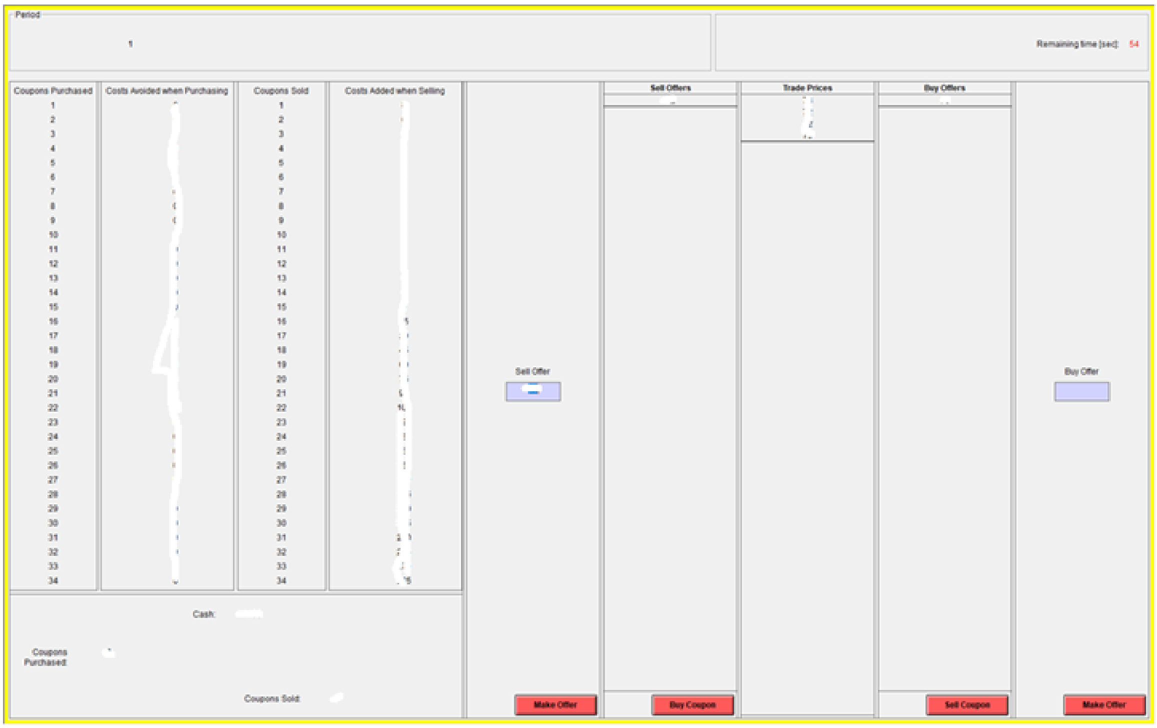

Figure 7: Coupon Trading Screen

5.2 Production Costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs are different from the costs of other participants. The production costs that you avoid by buying additional coupons, or additional production costs you must pay when selling additional coupons, are always shown on the left side of your computer screen, as illustrated in Figure 7. (The numbers on this example screen are obscured, and you won't actually learn your values until the experiment begins). Some of these values may be 0, indicating when you have enough coupons so that you do not need to produce units.

The costs shown on your screen are the extra costs associated with each additional coupon purchased or sold.

5.3 Coupons

We've already explained that your Fixed Period Revenue never changes, but your costs increase when you increase production. You can avoid production (and save on your production costs) by holding more coupons. Anyone can adjust their coupon holdings by buying and selling them in a market that will operate over the computer network. If you sell coupons your cash increases by the sale amount, but this may lead to additional production costs that you must pay. And if you buy coupons your cash decreases by the sale amount, but this may allow you to avoid some production costs. Later in these instructions we explain the rules for buying and selling coupons.

Why might you want to buy a coupon? Suppose you currently have purchased 5 coupons so far in this period, and your computer screen indicates that you can avoid incurring a cost of 300 by purchasing a 6^{th} coupon. You can increase your profit if you can buy this 6^{th} coupon for a price less than 300, since it allows you to save the production cost of 300. For example, if you bought one additional coupon for 280, you save the production cost of 300 and therefore make a profit (because of the lower production costs that you need to pay) of 300-280=20. Making such a trade will increase your profit by 20.

Why might you want to sell a coupon? Suppose that you have sold 3 coupons so far in the period, and your computer screen indicates that you will incur an additional cost of 400 if you sell a 4^{th} coupon. You can increase your profit if you can sell this additional coupon for more than 400, since these sales revenues exceed the extra production costs of this unit. For example, if you sell a coupon for 425, even if you incur the additional production cost of 400 you would still make a profit on this sale of 425-400=25. Such a trade will increase your profit by 25.

5.4 Coupon Trading Stage: How to Buy and Sell Coupons

During the trading stage, coupons can be purchased from and sold to other participants. At any time during the trading stage, everyone is free to make an offer to buy a coupon at a price they choose; likewise, everyone is free to make an offer to sell a coupon at a price they choose. Everyone is also free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best offer price specified by someone wishing to buy.

You will enter offer prices and accept prices to execute transactions using your computer. Figure 7 shows the market trading screen for the coupon trading stage. The time left in the period is shown on the upper right of the trading screen. You will have 2 or 3 minutes to buy and/or sell coupons.

Buying coupons

Participants wishing to buy can submit offer prices using the "Buy Offer" box in the right side of the screen, and then clicking on the "Make Offer" button in the lower right. This offer price is immediately displayed on all traders' computers on the upper right part of the screen, labelled "Buy Offers." Once this offer price has been submitted, anyone wishing to sell can accept this price offer by highlighting the price on this list and clicking the Sell Coupon button. This results in an immediate trade at that price. The previous trading prices in the current period are displayed in the "Trading Prices" list in the center of your computer screen.

If there are already Buy Offers displayed in the current period, then new buy offers must provide better trading terms to the sellers. Sellers prefer higher prices, so any new buy offers must be higher than the current highest buy offer. Your computer will give you an error message if you try to offer a lower price than the best price currently available.

Another way to buy coupons is with the "Buy Coupon" button. Anyone wishing to buy can accept a sell offer price by highlighting it in the Sell Offers column and clicking the "Buy Coupon" button on the bottom of that column. This results in an immediate trade at that price.

Selling Coupons

Participants wishing to sell can submit offer prices using the "Sell Offer" box in the middle of the screen, and then clicking on the "Make Offer" button below this box. This offer price is immediately displayed on all traders' computers on the upper middle part of the screen, labelled "Sell Offers." Once this offer price has been submitted, anyone wishing to buy can accept this price offer by highlighting the price on this list and clicking the Buy Coupon button.

If there are already Sell Offers displayed in the current period, then new sell offers must provide better trading terms to the buyers. Buyers prefer lower prices, so any new sell offers must be lower than the current lowest sell offer.

Another way to sell coupons is with the "Sell Coupon" button. Anyone wishing to sell can accept a buy offer price by highlighting it in the Buy Offers column and clicking the "Sell Coupon" button on the bottom of that column. This results in an immediate trade at that price.

During the experiment, there will be both a minimum and a maximum price for trading coupons. The minimum is 70 and the maximum is 999. These minimum and maximum prices will be the same for all periods.

If you submit a bid to buy or offer to sell a coupon that is greater than the maximum price, then you will receive an error message reminding you of this upper limit. In the same way, if you submit an offer to buy or sell at below the minimum price, you will receive an error message.

Regardless of how you buy or sell coupons, your net number of Coupons Purchased or Coupons Sold, and Cash total, will be updated at the time of purchase or sale. You can always find these totals in the lower left of the screen.

5.5 Period Structure

This part of the experiment will consist of 16 paid periods, following one unpaid practice period. Each period is identical and will include the following steps in Figure 8.

5.6 Investment Stage

At the start of each period, you will indicate whether you want to make an investment at a total fixed cost of 200 Experimental Dollars. If you make this investment, your costs will decrease from the amounts shown on the left side of your hardcopy coupon trading values sheet (labelled "Costs with No Investment") to the amounts shown on the right side of this sheet (labelled "Costs if Investing").

5.7 Random Coupons

You and all the other traders today will also receive a random number of additional coupons at the beginning of the trading stage. There are 5 different possible numbers of coupons you each might receive, and each of these 5 possibilities is equally likely to occur:

0 Coupons – OR – 1 Coupons – OR – 3 Coupons – OR – 4 Coupons – OR – 5 Coupons

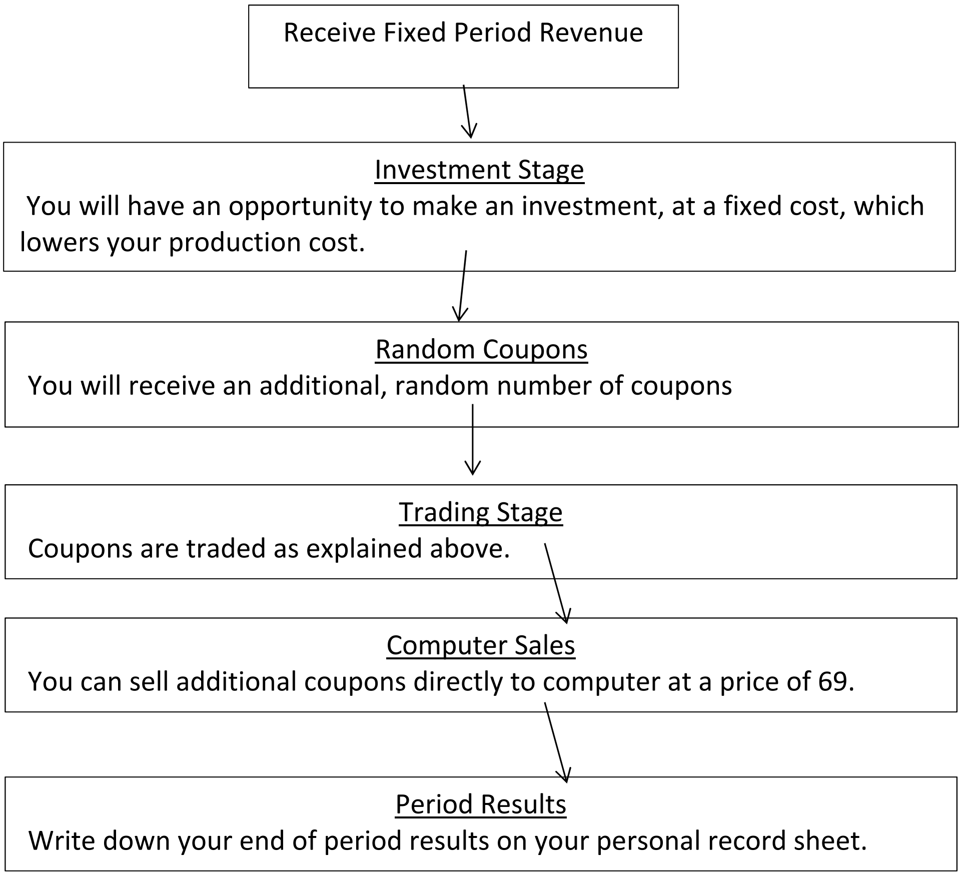

Figure 8: Period Structure

Note: This number of random coupons will typically change from period to period, but the number is the same for all participants. That is, the number of random coupons you receive is the same as the number received by each of the other traders in your market.

Note also: Your coupon trading values shown on your computer screen will adjust to reflect these random additional coupons, so they will usually not be exactly the same as the numbers shown on your hardcopy coupon trading values sheet. For example, if you receive 3 additional coupons in the random allocation, this is equivalent to moving you down the list of costs to 3 purchased coupons. The extra costs avoided by purchasing more coupons, or extra costs incurred by selling coupons, will be adjusted accordingly. Importantly, you should therefore consider the costs avoided or added ON YOUR COMPUTER SCREEN rather than on your hardcopy cost sheet while trading.

5.8 Trading Stage

After the investment stage and the random coupons are distributed in the steps described above, you may choose to buy and/or sell coupons with each other. The trading stage will last 3 minutes until period 6, when it will shorten to 2 minutes. Remember, you may wish to buy coupons if the price you pay is less than the production cost that you can avoid; or you may wish to sell coupons if the price you receive is greater than the additional production cost you must incur.

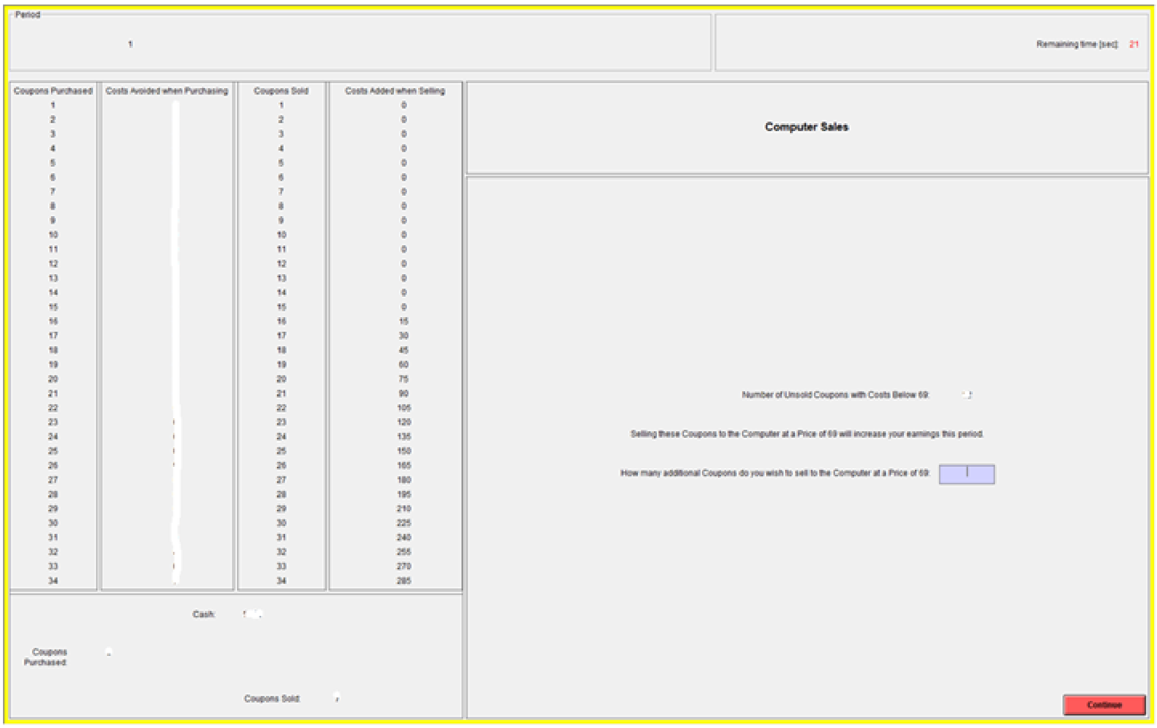

Figure 9: Computer Sales

These amounts are shown on your computer screen.

Importantly, the additional costs incurred or avoided may be different depending on how many coupons you have bought or sold in the period so far. Therefore, you should always pay close attention to this information so that you know which unit of coupons you might be buying or selling next. These total numbers of coupons purchased or sold, as well as your cash totals, will be updated immediately at the time of purchase or sale on the lower left part of your screen.

5.9 Sales to the Computer

After the market trading stage is completed, you will have a final opportunity to make sales directly to the central computer, called "Computer Sales." The software will consider your costs avoided when selling, and the number of coupons you bought or sold during the trading period, and as illustrated in Figure 9 it will indicate how many additional coupons you have with added costs less than 69. The computer will purchase any of these additional coupons you want to sell at this price. The number suggested on this screen is the total number of additional coupons you could sell to increase your earnings in the period if you sell them to the computer. This number will be 0 if you do not have additional coupons with costs lower than 69.

5.10 Period Results

Once trading has been completed, the results of the period will display on your screen, as illustrated in Figure 10. You should copy this information onto your Personal Record Sheet,

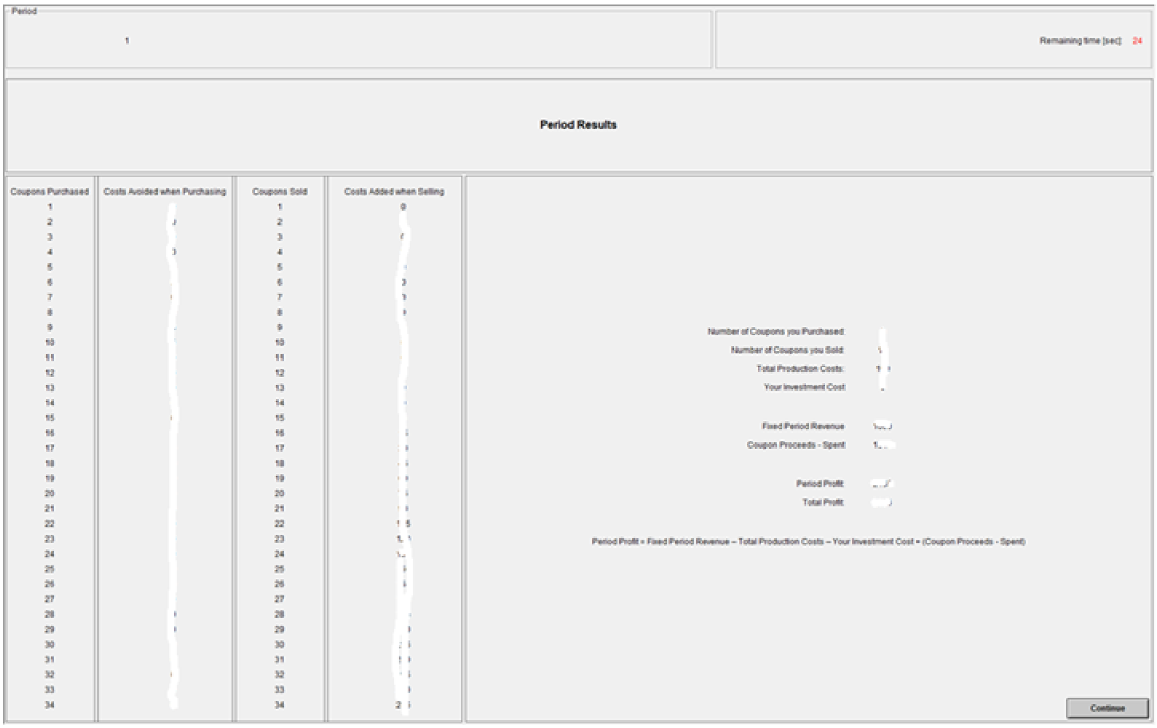

Figure 10: Computer Sales

and then click "continue" to begin the next period. Each period will progress through the stages as indicated in the flow chart of Figure 8.

5.11 Summary

1. You can avoid paying production costs by holding coupons.
2. You will receive a fixed period revenue at the start of each period.
3. Your costs shown on the left of your computer screen are the extra, additional costs avoided or incurred for each coupon that you trade.
4. At the start of each period you will decide whether to make an investment that lowers your production costs, and therefore reduces the extra costs avoided by purchasing more coupons, and reduces the extra costs incurred by selling coupons.
5. You will then receive an additional, random number of coupons. Each trader will receive the same number of random coupons, but this amount will vary randomly across periods.
6. There will be then be a 2 or 3-minute trading stage. At the end of this stage your coupons held will determine your production costs for the period.
7. Your current cash and total coupons bought or sold are always provided during trading on the lower left of your computer screen.
8. **The minimum price is 70 and the maximum price is 999 for trading coupons.**

9. **After market trading is concluded each period, you will have a final opportunity to sell additional coupons to the central computer at a fixed price of 69.**

10. Your coupon sales or purchases, final production costs, and total period profits will be provided during the Period Results stage at the end of each period. No coupons or cash will be carried over into the next period for use in trading.

    If you have any questions during the experiment, please raise your hand and I will come to your seat. Are there any questions now before we begin?

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