Technology Adoption under Emissions Taxes and Permit Markets with Price Collars*

Timothy N. Cason[1] John K. Stranlund[2] Frans P. de Vries[3]

[1]Department of Economics, School of Business, Purdue University, USA
[2]Department of Resource Economics, University of Massachusetts-Amherst, USA
[3]Department of Economics, Business School, University of Aberdeen, Scotland, UK

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Abstract

This study investigates the adoption and diffusion of cost-saving technologies under emissions taxes and emissions markets with and without price collars. We first develop a theoretical model of adoption and diffusion of a cost-saving technology under markets with price collars, which shows that technology diffusion depends on the collar position, in particular its midpoint, and the collar width. The model admits markets without price controls and emissions taxes as special cases and allows unambiguous rankings of the diffusion effects of the alternative policies. We also implement a laboratory market experiment to provide empirical tests of these rankings. In the experiment, traders purchase emissions permits under uncertainty about their abatement costs, or they face an emissions tax, and they can choose to adopt a costly technology that reduces their abatement costs. The results provide strong support for the main theoretical predictions of differences in technology diffusion among the alternative policy arrangements. As predicted, firms with higher abatement costs adopt the technology more frequently, market prices increase with positive shocks to abatement costs, and prices decrease in the degree of technology diffusion.

Keywords: Emissions trading; Carbon taxes; Price controls; Auctions; Experiment
JEL Classification: C91; D47; O33; Q52; Q58

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1 Introduction

The development and spread of new technologies is one of the most important determinants of progress in environmental protection. Hence, understanding the effects of alternative environmental policies on firm-level adoption and industry-wide diffusion of cost-reducing abatement technologies has been a long-standing and fundamental concern of environmental economics and policy.[1,2] While much attention has been given to the adoption and diffusion effects of emissions taxes and emissions markets (e.g., Requate (1995, 1998); Fischer et al. (2003); Requate and Unold (2001, 2003); Coria (2009); Villegas-Palacio and Coria (2010); Vidal-Meliá et al. (2022)), little research exists on the effects of emissions markets with flexible permit supplies, which are common among carbon markets (e.g., the EU ETS, California's carbon market, and the Regional Greenhouse Gas Initiative—RGGI). Emissions markets with flexible permit supplies, like those involving permit price controls in the spirit of Roberts and Spence (1976), can enhance the performance of these markets under uncertainty about firms' abatement costs by efficiently managing the resulting permit price risk and emissions risk.

In this paper, we present a theoretical model and laboratory market experiment to study policy-induced technology adoption and diffusion among polluting firms with uncertain abatement costs that operate under an emissions market with a hard price ceiling and price floor, a so-called price collar.[3] A novelty of our approach is that our model admits an emissions tax and a pure emissions market without price controls as limiting cases. This makes price-based policies directly — and more naturally — comparable in terms of technology diffusion. We therefore consider whether emissions taxes or emissions markets promote greater technology diffusion, with the addition of markets with price controls as alternative policies, and we do so with a new integrated theoretical treatment and laboratory experiment.

Another novel feature of our approach is that we examine the effects on technology diffusion of changes in the *position* and *width* of the price collar. Adjusting the width of the collar allows us to model alternative price-based policies. More specifically, increasing the width of the collar

[1]Several informative surveys review the large literature on technological change and environmental policy, including Requate (2005), Popp et al. (2010), Allan et al. (2013), and Popp (2019).

[2]Following standard terminology, *adoption* of a technology refers to a firm's investment in an existing (abatement) technology, while *diffusion* refers to the penetration of the technology in an industry or set of regulated firms. In contrast, technological *innovation* refers to the development of new technologies (Jaffe et al., 2002). Our work focuses solely on the adoption and diffusion of existing technologies.

[3]We model *hard* price controls, which are absolute limits on the price ceiling and price floor. A common way to model hard price controls in an auction framework is to assume that the government commits to selling as many additional permits as polluters desire at the price ceiling, and to limit the number of permits to the amount polluters demand if the permit price reaches the price floor. In contrast, *soft* price controls involve a limited number of extra permits for sale at the price ceiling and limiting the reduction in the number of permits removed from the auction at the price floor (Fell et al., 2012). See Table 3 in Grüll and Taschini (2011) for a succinct overview of the alternative price controls and permit supply mechanisms.

so much that there is no chance of activating either the price ceiling or floor captures a pure market (i.e., a market without price controls); decreasing the width to zero gives us an emissions tax; intermediate widths give us markets for which the permit supply, the price ceiling and the price floor all have strictly positive probabilities of being binding on the market. Varying the position of the collar, specifically its midpoint, varies the stringency of the alternative policies. That is, for a given width of a price collar, a higher collar midpoint is associated with lower expected aggregate emissions.

Our theoretical model reveals that technology diffusion is increasing in the midpoint of the collar. However, we also show that the effect of the price collar width is non-monotonic. Specifically, technology diffusion is decreasing in the width of the collar if the midpoint of the collar is above the expected price that would prevail in a pure market without controls; in contrast, technology diffusion increases with the collar width if the midpoint is below the expected price under a pure market. These results are new in the literature on the impacts on technology diffusion of alternative environmental policies, and they expand the traditional comparison of the effects of taxes versus emissions markets to include price collars. Our expanded ranking of the diffusion effects of alternative price-based policies is as follows: If the midpoint of the price collar in a market is greater than (less than) the expected price in a pure market without controls, then an emissions tax results in greater (lower) technology diffusion than a price-collared market, which in turn generates greater (lower) diffusion than a pure market. If the midpoint of the price collar and the emissions tax are equal to the expected permit price in a pure market, then all three policies result in the same technology diffusion.

We test these theoretical predictions with a laboratory market experiment in which traders purchase emissions permits while facing uncertainty about their future abatement costs, and they can choose to invest in the adoption of a technology that reduces their marginal abatement costs. A pure market acts as the baseline for our experiment and treatments involve markets with price collars whose midpoints are set above and below the expected price in the baseline, as well as emissions taxes, i.e., zero-width price collars set equal to the midpoints of these collars. The experimental results are broadly consistent with the hypotheses derived from the theoretical model. In particular, technology diffusion increases with the midpoints of the price collars, and technology diffusion is greater than (less than) under the tax relative to the corresponding price collar when the tax/collar midpoint is greater than (less than) the expected price in the baseline market.

Related Literature. Our work relates to several different strands of literature, namely the literatures concerning the effects of alternative emission control policies on the adoption and diffusion of cost-saving abatement technologies; policy implementation under uncertainty; and the implementation of emissions markets with flexible permit supplies.

The early literature on environmental policy and technology diffusion focused on generating a ranking of policy instruments in terms of their ability to promote adoption and diffusion of advanced abatement technologies (e.g., Downing and White (1986); Malueg (1989); Milliman and Prince (1989); Jung et al. (1996)). A crucial factor in establishing a ranking of policy instruments is the choice of reference point regarding policy stringency. For instance, comparing an emissions market without price controls with an emissions tax for which the expected price in the market is the same as the tax *after* all technology adoption decisions have been made will lead to the same technology diffusion under both policies. If instead the starting point is equal aggregate emissions under both the market and the tax *before* firms make their adoption decisions, then technology diffusion is lower under the market regime. This is because significant penetration of the technology will lower the price of emissions permits, thereby reducing the marginal incentive to adopt the technology relative to the fixed tax (Requate and Unold, 2003). We contribute to this literature by considering technology adoption and diffusion in emissions markets with alternative price collars, with emissions taxes and pure markets as special cases. Moreover, instead of assuming a common starting point for our alternative policies, we examine the diffusion effects of the full range of price collars in terms of both position and width, with a pure market involving a fixed permit supply as a baseline.

Incorporating price controls in emissions markets also addresses the long-standing concern of instrument choice under uncertainty about firms' abatement costs. Weitzman (1974) derived a simple rule involving the relative slopes of the marginal benefits and costs of control for determining whether a pure market or an emissions tax would be more efficient. Roberts and Spence (1976) were the first to provide a theoretical model of a market with price controls, demonstrating that a market with hard price controls can be more efficient than an emissions tax or a pure market, because price risk and emissions risk can be balanced in an efficient way. Later, concerns about price volatility in emissions markets led to suggestions to implement only price ceilings—so-called safety valves—to limit price volatility in emissions markets (Pizer, 2002; Jacoby and Ellerman, 2004). These policy suggestions were criticized for the expectation that they would discourage investment in new technologies by suppressing the permit price. Adding a price floor to create a price collar would further limit price volatility—by limiting both high-side and low-side price risk—while restoring the incentives to adopt new technologies (Burtraw et al., 2010).[4] In fact, many emissions markets for greenhouse gases include some form

[4] Approaching the December 1997 Kyoto Protocol negotiations, in a letter dated October 8th of that year, 17 environmental organizations wrote to the U.S. president: 'This proposal [of a price ceiling "relief mechanism"] would weaken, if not eliminate, any incentive for private sector innovation and investment in clean technologies that [. . .] is the key to successfully addressing the global warming problem.' See also footnote 4 in Murray et al.

of price control, or more generally, a flexible permit supply mechanism. Examples include the EU Emissions Trading System (EU ETS), the Regional Greenhouse Gas Initiative (RGGI), and California's market for greenhouse gas emissions. Using data before California's market began operations, Borenstein et al. (2019) estimated a 94.3 percent probability that the market would clear at the price floor or ceiling over the period 2013-2020.[5]

The literature concerning emissions markets with price controls has developed along with the implementation of markets with various forms of flexible permit supply. Within this domain, much research has focused on the price-stabilization role of markets with flexible permit supplies (Fell et al., 2012; Grüll and Taschini, 2011; Heijmans, 2023), including the relationship between flexible supply policies and permit banking (Fell and Morgenstern, 2010; Kollenberg and Taschini, 2016).[6] In addition to these theoretical contributions, others have explored the effects of alternative forms of flexible permit supply with laboratory experiments. Stranlund et al. (2014) examined the roles of a hard price collar and permit banking, separately and together, on limiting price risk. Holt and Shobe (2016) found that a price collar outperformed quantity controls modeled after the market stability reserve of the EU ETS. Burtraw et al. (2022) found that a price-responsive permit supply was more efficient than a fixed price and a market with a fixed permit supply. Friesen et al. (2022) examined the effects of the variable permit supply structure of the US RGGI, finding that design produces a bimodal distribution of prices. Others have employed laboratory experiments to study more restrictive permit supply schemes. For example, Perkis et al. (2016) studied hard and soft price ceilings, finding that soft price ceilings did not control high prices consistently. Salant et al. (2022, 2023) focused on hard and soft price floors, demonstrating both theoretically and experimentally that even nonbinding price floors can cause asset prices to increase.

While the literatures concerning the adoption and diffusion of abatement technologies and price controls in emissions markets are extensive, the intersection of these lines of inquiry is much more limited. To our knowledge, Weber and Neuhoff (2010) were the first to provide a theoretical model of technology investments in markets with price controls. Their approach is a normative one of optimal market design with price controls considering technology adoption.[7] In contrast,

(2009).

[5] The intuition is as follows. Imagine a pure market with a fixed permit supply with a distribution of potential equilibrium permit prices. Implementing a hard price collar truncates the lower and upper parts of the price distribution and piles the truncated parts of the distribution onto the price ceiling and price floor. The tighter the price collar and the greater the variance of the original price distribution, the more of the price distribution is stacked on the price collars, thereby increasing the probability that either the price floor or ceiling will bind. Moreover, price controls create a bimodal distribution of prices, with modes at the price controls. In a laboratory study, Friesen et al. (2022) reach a similar conclusion, although they study a market with soft price controls.

[6] Other work has examined the enforcement of markets with price controls (Stranlund and Moffitt, 2014), and instrument choice, including markets with price controls, in the presence of co-pollutants (Stranlund and Son, 2019).

[7] A recent theoretical paper by Storrøsten (2024) takes a novel approach to the problem. In this paper firms

our theoretical model is a positive one that produces behavioral and market predictions about technology diffusion over the entire range of potential hard price collars (i.e., as price collars vary in their midpoints and widths). We then test these predictions in a laboratory experiment.

The only other work that we are aware of that combines a theoretical model of technology adoption and diffusion under price-controlled markets with laboratory experiments is Cason et al. (2023), which shows both theoretically and experimentally that the introduction of a price floor in emissions markets enhances technology adoption and diffusion incentives. This earlier study considers only one-sided price controls, and so it could not examine price restrictions both above and below the pure market equilibrium without controls or the implications of price control width and emissions taxes. By considering both floors and ceilings, the present work is a substantial generalization of Cason et al. (2023).[8] Doing so allows us to extend the literature on whether emissions taxes or emissions markets provide greater incentives for technology diffusion to include markets with price collars in the comparison.

2 Model

Consider a fixed set of n heterogeneous risk-neutral competitive firms who operate under alternative pricing schemes to control a uniformly mixed pollutant. Firm $i = 1, \ldots, n$ in the market has a marginal abatement cost function

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

where q^i is the firm's emissions; $x^i = \{0, 1\}$ is an irreversible dichotomous technology adoption choice that reduces the intercept, b^i, of the firm's marginal abatement cost function by a percentage β^i; and c^i is the slope of the firm's marginal abatement cost function. The parameters b^i, β^i, and c^i may vary across firms. 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.[9]

Given a realization of u and adoption choice $x^i = \{0, 1\}$, the firm's maximum emissions,

do not adopt a discrete technology, which is the common way to model technology adoption. Instead, firms invest in the parameters of their quadratic cost functions. Moreover, the author models flexible permit supply with a smooth linear function. In actual policies these permit supply functions tend to be step functions.

[8]There is a significant literature that measures innovation, adoption, and diffusion of new technologies in existing emissions markets. See Calel (2020) for a recent example focused on the EU ETS, and a useful review of this literature. We are not aware of any empirical studies that address the specific effects of flexible permit supply measures on technological progress in existing markets.

[9]That each firm's marginal abatement cost function is linear with uncertainty in the intercept are common assumptions in the literature on instrument choice under uncertainty (e.g., Weitzman (1974); Weber and Neuhoff (2010); Fell et al. (2012); Stranlund et al. (2014); Stranlund and Son (2019)). The assumption that u is the same for all firms simplifies the analysis, but is not necessary.

$q_0^i(x^i, u)$, solve $m^i(q^i, x^i, u) = 0$, yielding

$$q_0^i(x^i, u) = \frac{b^i(1 - \beta^i x^i) + u}{c^i}. \tag{2}$$

However, in an unregulated setting a firm will not adopt the technology to reduce its abatement cost; that is, $x^i = 0$. The firm's expected unregulated emissions are

$$\widehat{q}_0^i = \mathbb{E}(q_0^i(x^i = 0, u)) = \frac{b^i}{c^i}. \tag{3}$$

($\mathbb{E}$ denotes the expectation operator throughout.) An emissions control policy will motivate the firm to reduce its emissions to some $q^i < q_0^i(x^i, u)$, and in doing so it will incur total abatement cost

$$\begin{aligned} a^i(q^i, x^i, u) &= \int_{q^i}^{q_0^i(x^i,u)} (b^i(1 - \beta^i x^i) + u - c^i q^i) dq^i, \\ &= \frac{(b^i(1 - \beta^i x^i) + u)^2}{2c^i} - (b^i(1 - \beta^i x^i) + u)q^i + \frac{c(q^i)^2}{2}. \end{aligned} \tag{4}$$

We analyze an emissions trading program with price controls that has the following features. The government offers L emissions permits at auction, which clears at the competitive price p. The market includes a hard price floor, s, and a hard price ceiling, t. For the market to clear we must have $s \leq p \leq t$. If the price floor is binding, then the government offers all permits at s, even though the firms may demand fewer than L permits. The government offers all L permits at s, even though the firms may demand fewer permits if the price floor binds.

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 technology adoption decisions. In the second stage the value of u is revealed. In the third stage the government holds the permit auction and the firms release their allowed levels of emissions.

2.1 Technology adoption

We begin by deriving a firm's decision criterion for adopting the new technology in the first stage of the game. This decision depends in large part on the expected permit price in the third stage, so we first characterize the competitive market equilibrium in this stage, given a realization of u and the adoption decisions from the first stage.

Given the realization of u, a permit price (to be determined) and the adoption decisions of all firms from the first stage, in the third stage a firm chooses its emissions to minimize its compliance cost, consisting of its abatement cost and the value of its permit holdings:

$$\begin{aligned} f^i(q^i, x^i, u) &= a^i(q^i, x^i, u) + p(q^i - l_0^i) \\ &= \frac{(b^i(1-\beta^i x^i) + u)^2}{2c^i} - (b^i(1-\beta^i x^i) + u)q^i + \frac{c^i(q^i)^2}{2} + pq^i. \end{aligned} \tag{5}$$

Equalizing the firm's marginal abatement cost and the permit price gives us its choice of emissions (i.e., its demand for permits),

$$q^i(x^i, p, u) = \frac{b^i(1-\beta^i x^i) + u - p}{c^i}. \tag{6}$$

The competitive permit price is determined from the market clearing condition, $\sum_{i=1}^n q^i(x^i, p, u) = L$. Let $\sum_{i=1}^n (1/c^i) = 1/\phi$ and use (3) to calculate

$$p(\mathbf{x}, u) = \phi\left(\sum_{i=1}^n \widehat{q}_0^i(1-\beta^i x^i) - L\right) + u, \tag{7}$$

where $\mathbf{x} = (x^1, ..., x^n)$ is the vector of individual firms' adoption decisions.[10] Clearly, the permit price is lower when the random variable u is lower and when more firms have adopted the technology. From here on we ignore the fact that the permit price depends on the supply of permits, because supply is fixed throughout. Let $\mathbb{E}(p(\mathbf{x}, u))$ be the expected competitive price under a pure market, given technology adoptions $\mathbf{x}$. Then, since $\mathbb{E}(u) = 0$, we can rewrite (7) as

$$p(\mathbf{x}, u) = \mathbb{E}(p(\mathbf{x}, u)) + u. \tag{8}$$

Imposing a price collar on this market places upper and lower bounds on $p(\mathbf{x}, u)$. It is useful to define values of the random variable, $u^t$and u^s, such that

$$\begin{aligned} \mathbb{E}(p(\mathbf{x}, u)) + u^t &= t; \\ \mathbb{E}(p(\mathbf{x}, u)) + u^s &= s. \end{aligned} \tag{9}$$

We can interpret u^t as the value of u at which the permit supply and the price ceiling bind on the market together, given technology adoptions $\mathbf{x}$. For values of $u > u^t$, the price ceiling binds and the competitive price is equal to t. Likewise, u^s is the value of u at which the permit supply and the price floor bind together. For values of $u < u^s$, the price floor binds and the price is equal to s.[11] The permit supply binds alone for values of u between u^s and u^t and the expected

[10] If we let aggregate emissions vary from L, equation (7) defines the aggregate inverse demand for emissions permits. Moreover, the aggregate inverse demand function is the minimum aggregate marginal abatement cost function for the industry.

[11] As the price controls are activated, aggregate emissions in the industry deviate from the supply of permits. If the price ceiling is activated then aggregate emissions exceed the supply of permits; if the price floor is activated

permit price is $\mathbb{E}(p(\mathbf{x}, u))$. Now, $u^t$and u^s themselves have upper and lower bounds because u varies on the interval $[\underline{u}, \overline{u}]$. Moreover, since the price ceiling cannot be below the price floor, we must have $u^s \le u^t$. Taken together,

$$\underline{u} \le u^s \le u^t \le \overline{u}. \tag{10}$$

With these constraints, the third-stage competitive permit price for a market with a price collar, given technology adoptions $\mathbf{x}$, can be characterized as

$$p(\mathbf{x}, s, t, u) = \begin{cases} t, & u \in [u^t, \overline{u}] \\ \mathbb{E}(p(\mathbf{x}, u)) + u, & u \in [u^s, u^t] \\ s, & u \in [\underline{u}, u^s]. \end{cases} \tag{11}$$

From the perspective of the first stage of the game the expected permit price is

$$\mathbb{E}(p(\mathbf{x}, s, t, u)) = \int_{\underline{u}}^{u^s} sg(u)du + \int_{u^s}^{u^t} (\mathbb{E}(p(\mathbf{x}, u)) + u)\, g(u)du + \int_{u^t}^{\overline{u}} tg(u)du. \tag{12}$$

The constraints in (10) and the corresponding alternative prices in (11) reveal important information about how our model can be used to characterize several different emissions control policies. If the inequalities in (10) are all strict inequalities (i.e., $\underline{u} < u^s < u^t < \overline{u}$) we have a price-collared market for which each element of the policy (the permit supply, the price ceiling and the price floor) has a positive probability of binding. We have a pure market if the price controls are disabled so that $u^s = \underline{u}$ and $u^t = \overline{u}$. Modeling an emissions tax, denoted τ, involves setting $s = t$ (which implies $u^s = u^t$) to reduce the price collar width to zero, and setting the tax so that $\tau = s = t$.[12]

The expected permit price plays an important role in a firm's technology adoption decision. Let a firm's expected return to technology adoption be $\mathbb{E}(r^i(\mathbf{x}, s, t, u))$. In the appendix we prove the following lemma. (All lemma and proposition proofs are in Appendix A.)

Lemma 1: Given technology adoption decisions in the industry $\mathbf{x}$, which include $x_i = 1$, firm i's expected benefit of adopting the new technology in the first stage is

$$\mathbb{E}(r^i(\mathbf{x}, s, t, u)) = \widehat{q}_0^i \beta^i \mathbb{E}(p(\mathbf{x}, s, t, u)). \tag{13}$$

aggregate emissions fall below the initial supply of permits.

[12] Although our focus in this paper is on price collars, the model also admits one-sided price controls. A market with only a price floor for which the floor and permit supply both have positive probabilities of binding has $u^s \in (\underline{u}, \overline{u})$ and $u^t = \overline{u}$ (the latter to disable the price ceiling); a market with a price ceiling has $u^t \in (\underline{u}, \overline{u})$ and $u^s = \underline{u}$ (the latter to disable the price floor).

The first term on the right-hand side, $\widehat{q}_0^i\beta^i$, is the percentage reduction in the firm's expected unregulated emissions from adopting the new technology. Multiplying this with the expected permit price gives the firm's expected return to technology adoption.

A firm's technology adoption decision in the first stage is made by simply comparing its expected benefit from adoption to the cost of adopting the technology, h^i. That is, we assume that the cost of adoption is fixed but may vary across firms. We further assume that if a firm is indifferent about the adoption decision then it chooses to adopt the technology. The firm then adopts the technology if and only if $h^i \leq \mathbb{E}(r^i(\mathbf{x}, s, t, u))$. Let

$$\theta^i = \frac{\widehat{q}_0^i\beta^i}{h^i}. \tag{14}$$

Then, using (13) and (14), firm i adopts the new technology in the first stage if and only if

$$\theta^i\mathbb{E}(p(\mathbf{x}, s, t, u)) \geq 1. \tag{15}$$

Note that θ^i is a positive constant made up of parameters that are unique to a particular firm, so we may refer to θ^i as a firm's type. In a heterogeneous industry, firm types vary in the interval $[\theta^{min}, \theta^{max}]$.

2.2 Technology diffusion

The distribution of firm types in the industry and the expected third-stage permit price determine the equilibrium diffusion of the technology in the first stage. Let $\mathbf{x}^*$ be the competitive equilibrium vector of technology adoptions. The following proposition characterizes these adoption decisions.

Proposition 1: Under a competitive emissions market with a price collar, there exists a unique value, θ^*, defined by

$$\theta^*\mathbb{E}(p(\mathbf{x}^*, s, t, u)) = 1, \tag{16}$$

such that if $\theta^* \in [\theta^{min}, \theta^{max}]$, then firm types $\theta^i \in [\theta^*, \theta^{max}]$ adopt the new technology and firm types $\theta^i \in [\theta^{min}, \theta^*)$ do not. No firm adopts the technology if $\theta^* > \theta^{max}$, and every firm adopts the technology if $\theta^* < \theta^{min}$.

Proposition 1 indicates that there is a distinct separation between adopters of the technology and non-adopters. In a heterogeneous market that comprises both adopters and non-adopters, firm types with $\theta^i \geq \theta^*$ adopt the technology while those with $\theta^i < \theta^*$ do not adopt the technology. According to (14), firms that adopt the technology tend to have higher expected unregulated emissions $\widehat{q}_0^i$ (which implies higher marginal abatement costs), technology adoption decreases their expected unregulated emissions by a greater percentage (higher β^i), or they face relatively low costs of adoption (lower h^i). Proposition 1 also characterizes corner solutions where either all or none of the firms adopt the technology. From here on, however, we will restrict our analysis to interior equilibria involving both adopters and non-adopters, that is, equilibria for which $\theta^* \in (\theta^{min}, \theta^{max})$.

Along with the distribution of firm types, the expected permit price plays a key role in determining the degree of technology diffusion in the industry. Toward determining how the expected permit price changes with variation in the collar, consider that any price collar can be characterized by both its placement and its width. Let the midpoint of a price collar be p^0 and let the width of the collar be 2α, where α is a non-negative constant. The price ceiling is then $t = p^0 + \alpha$ and the price floor is $s = p^0 - \alpha$. Note that we can characterize an emissions tax at p^0 by setting $\alpha = 0$.[13] Combine this characterization of the price collar with (9) to obtain:

$$\begin{aligned} u^s &= p^0 - \mathbb{E}(p(\mathbf{x}, u)) - \alpha, \\ u^t &= p^0 - \mathbb{E}(p(\mathbf{x}, u)) + \alpha. \end{aligned} \tag{17}$$

Recall that we must continue to maintain the constraints on u^s and u^t in (10). Proposition 2 reveals how the expected permit price under a price collar changes with the midpoint and width of the price collar.

Proposition 2: The expected permit price in a competitive emissions market with a price collar has the following characteristics:

(a) $\mathbb{E}(p(\mathbf{x}, s, t, u))$ is strictly increasing in p^0;

(b) $\mathbb{E}(p(\mathbf{x}, s, t, u)) = \mathbb{E}(p(\mathbf{x}, u))$ if and only if $p^0 = \mathbb{E}(p(\mathbf{x}, u))$;

(c) $\mathbb{E}(p(\mathbf{x}, s, t, u))$ is strictly decreasing (increasing) in α if and only if $p^0 > (<)\, \mathbb{E}(p(\mathbf{x}, u))$.

Part (a) of proposition 2 indicates that the expected permit price is increasing with the midpoint of a price collar, which is intuitive. Part (b) tells us that this effect is 'anchored' at $\mathbb{E}(p(\mathbf{x}, u))$. That is, if the price collar is centered on the expected price under a pure market, then the expected price with the price collar is the same as without it.[14] Part (c) tells us how the width of the price collar affects the expected permit price. Notice that the effect of α on the expected permit price is non-monotonic; the direction of the effect depends on whether the

[13] There are alternative ways to characterize the position of a price collar, but using the midpoint is useful as we compare alternative market designs with emissions taxes.

[14] This result is the only place in the analysis where we use the assumption that the distribution of u is symmetric. In general, $\mathbb{E}(p(\mathbf{x}, s, t, u)) \neq \mathbb{E}(p(\mathbf{x}, u))$ at $p^0 = \mathbb{E}(p(\mathbf{x}, u))$ if the distribution of u is skewed.

center of the price collar is above the expected price under a pure market or below. If the midpoint of the collar is above (below) the expected price in a pure market, then tightening the price collar reduces (increases) the expected permit price. This result helps us understand the difference between the expected price in a market with a price collar and a tax set equal to the midpoint of the collar. In particular, consider a price collar with p^0 and $\alpha > 0$ and an emissions tax $\tau = p^0$ (where $\alpha = 0$). Part (c) of Proposition 2 implies that the expected permit price with the price collar is lower (higher) than the tax if and only if $\tau = p^0$ is greater (less) than the expected price under a pure market.

Our next proposition reveals how the degree of technology diffusion is affected by changes in the price collar, where diffusion is measured by the number of firms adopting the new technology. Enhanced diffusion then implies the set of technology adopters expands, and vice versa.

Proposition 3: In a competitive emissions market with a price collar and considering an interior equilibrium involving both technology adopters and non-adopters:

(a) The set of technology adopters is weakly increasing in the midpoint of the price collar;

(b) The set of technology adopters is the same as in a pure market if the midpoint of the price collar is equal to the expected price in the pure market;

(c) The set of technology adopters is weakly decreasing (increasing) as the price collar is widened if the midpoint of the collar is above (below) the expected price of a pure market.

The set of technology adopters only *weakly* increases or decreases with changes in the price collar solely because the set of firm types is discrete. Given the distinct separation between firms that adopt and do not adopt the technology (Proposition 1), an expansion or contraction of the set of adopters will come from changes in the decisions of the firms in the 'middle' of the set of firm types.[15]

Proposition 3 characterizes technology diffusion over the entire range of price collars for a competitive emissions market. Since emissions taxes and pure markets are special cases of price-collared markets, the proposition allows us to expand the traditional comparison of the effects of taxes versus markets on technology diffusion to include markets with price collars.

[15] We have already noted that our model admits market configurations with one-sided price controls as special cases. It is straightforward to show (proofs are available from the authors) that, relative to a pure market, a market with only a price floor that has a positive probability of being activated will induce more firms to invest in technology adoption. (Cason et al. (2023) demonstrate this in a somewhat more limited model). The reason is that a price floor increases the expected permit price because it truncates the lower part of the distribution of potential prices, which increases the number of technology adopters. On the other hand, a market with only a price ceiling that has a positive probability of being activated has the opposite effects: the expected permit price is lower and there are fewer technology adopters.

The expanded rankings are contained in Proposition 4, the proof of which follows directly from Proposition 3.

Proposition 4: Consider the following emissions control policies: (1) A pure emissions market with a fixed supply of emissions permits; (2) An emissions market with the same permit supply but with a price collar with midpoint p^0, each element of which (the permit supply, price ceiling, and price floor) has a positive probability of binding; (3) An emissions tax $\tau = p^0$. Assume that the competitive equilibrium of each policy involves firms that adopt a cost-saving technology and those that do not. Then the following hold:

(a) If $\tau = p^0 > \mathbb{E}(p(\mathbf{x}, u))$, then the set of technology adopters is weakly greater under the tax than under the price-collared market, which in turn is weakly greater than under the pure market.

(b) The ranking is reversed if $\tau = p^0 < \mathbb{E}(p(\mathbf{x}, u))$. In this case, the set of technology adopters is greater under the pure market than under the price-collared market, which in turn is greater than under the emissions tax.

(c) If $\tau = p^0 = \mathbb{E}(p(\mathbf{x}, u))$, then the set of technology adopters is the same under each policy.

Proposition 4 provides clear predictions about the diffusion effects of emission taxes, pure markets, and price-collared markets. Our experiment, which we turn to next, is designed to test these predictions, along with hypotheses concerning firm-level adoption choices and market prices.

3 Experimental Design and Hypotheses

3.1 Experimental Parametrization

Although the empirical implications of price collars and emissions taxes follow directly from the model, behavioral support for these predictions could break down for several reasons. Firm earnings depend on realized permit prices, and prices and earnings both hinge upon their own and on other firms' technology adoption decisions. Firms also make adoption choices before uncertainty is resolved and prices are determined, and auction prices may not converge to competitive equilibrium levels. Moreover, costs are firms' private information so no individual has the information necessary to compute the equilibrium price. Support for the model predictions requires human subjects to overcome this incomplete information challenge and also develop an understanding of how their early stage adoption choices influence their earnings through their strategic interaction with others in an auction, which occur in later stages.

We made several simplifications for the experimental implementation of the preceding model of emissions abatement and technology adoption with and without price controls. Since emissions permits are typically traded in discrete units (e.g., tons of CO_2 equivalent), we discretized the quantity of emissions (q^i). We also simplified the random variable affecting abatement costs (u) to take on a limited set of 5 equiprobable values. Human subjects were recruited to the laboratory to take the role of 'firms' who make adoption, abatement and auction bidding choices. These decisions determined their monetary payments, which were distributed in cash at the conclusion of their experimental session.

Each market included 8 heterogeneous firms. Firm heterogeneity arises from differences in b^i, which take on values of 660, 620, 580, 560, 540, 520, 480 and 440 for the 8 different firms. We label the firms as types 1 through 8. Firm type 1 has the highest abatement cost and type 8 the lowest. The heterogeneity in abatement costs leads the technology adoption incentives to differ across firms, as characterized in Proposition 1. The firms with the highest b^i (i.e., the lowest firm type indices) have the greatest incentive to adopt the new technology to reduce costs. In terms of the fixed technology adoption costs, although the theoretical model allows for heterogeneous fixed adoption costs across firms, in the experiment this was set at $h^i = 4300$ points for all firms. The discrete shift in abatement costs due to adoption of the cost-reducing technology is $\beta^i = 0.5$ and the marginal cost parameter $c^i = 10$ for all firms. Abatement cost uncertainty, one of the key motivations for the use of price controls, is modeled through the mean zero random variable u, which is drawn each period from the set $\{-40, -20, 0, 20, 40\}$ with all values equally likely. A total of $L = 210$ emissions permits are auctioned each round.

3.2 Period Timing and Competitive Equilibrium Prices without Controls

The experiment employs stationary repetition. This means that firms make similar adoption and trading decisions in a stable environment across 20 consecutive rounds with their firm type fixed. Such repetition is commonly employed in market experiments to allow participants to gain experience and to provide more opportunity for adoption and auction bidding to converge to (or at least approach) competitive equilibrium levels. New random draws occur each period for the variable affecting abatement costs (u), however, and these draws affect the competitive price.[16]

Each round proceeded through the same three stages. In **Stage 1**, each firm made their binary choice of whether to invest 4300 points to adopt the technology to lower their abatement

[16] 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 all treatments. This reduces the between-session and between-treatment variability arising from the differing realizations of the random shocks.

Table 1: Competitive Permit Prices by Abatement Cost Shock and Number of Adopters

	Abatement Cost Shock (u)				
(#) Adopters	-40	-20	0	20	40
(0) None	250	270	290	310	330
(1) Type 1	210	230	250	270	290
(2) Type 1, 2	170	190	210	230	250
(3) Type 1, 2, 3	140	160	180	200	220
(4) Type 1, 2, 3, 4	100	120	140	160	180
(5) Type 1, 2, 3, 4, 5	70	90	110	130	150
(6) Type 1, 2, 3, 4, 5, 6	30	50	70	90	110
(7) Type 1, 2, 3, 4, 5, 6, 7	0	20	40	60	80
(8) Type 1, 2, 3, 4, 5, 6, 7, 8	0	0	20	40	60

costs. Consistent with the theoretical model developed in Section 2, adoption lowers the marginal abatement cost level but does not affect the slope of the marginal abatement cost function. Firms make this decision simultaneously and they never learn the adoption decisions of others. (Individual firms' marginal abatement costs are always their own private information.) In **Stage 2**, the shock to firms' abatement cost, which was the same across all firms, was realized and announced.[17] In **Stage 3**, firms submitted bids in a uniform price auction for emissions permits that allowed them to avoid paying abatement costs. The highest 210 bids were accepted in the auction, and all bidders paid the lowest accepted bid price. Such uniform price rules are common in auctions of emissions permits, such as for the EU ETS.[18]

Firm earnings were determined each round as follows:

$$\text{Earnings} = \text{Fixed Revenue} - \text{Total Abatement Costs} - \text{Adoption Cost (if any)} - \text{Permit Expenditure}$$

As noted in the previous subsection, firms were heterogeneous in terms of their abatement costs. Those firms with greater abatement costs receive greater fixed revenue to roughly equate the distribution of net profits across firm types. This allowed different subjects to earn similar amounts of cash regardless of their random type assignment.

Firms' adoption decisions and random variable u draws lead to a new abatement cost profile across firms of each type. Market-clearing auction permit prices therefore depend on adoption decisions and random factors affecting abatement costs, as summarized in Table 1.

[17] 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.

[18] `https://www.eex.com/en/markets/environmental-markets/eu-ets-auctions/auction-design` (accessed 17 July 2025).

Table 2: Price Control Treatments

	Collar Width	
Collar Placement	Width > 0	Width $= 0$
Low $[p^0 < \mathbb{E}(p(\boldsymbol{x}, u))]$	Low Collar	Low Tax
High $[p^0 > \mathbb{E}(p(\boldsymbol{x}, u))]$	High Collar	High Tax

3.3 Price Collars and Emissions Taxes

The experiment varied the location and width of the price collar between sessions as the treatment variables. A treatment without price controls serves as the baseline. As shown in Table 1, without price controls the competitive permit price ranges from 0 to 330 and depends on the number of firms adopting the new technology as well as the abatement cost shock. The experimental design compares the baseline no-control treatment to four price control treatments (Table 2).[19]

The **Low Collar** treatment restricted auction prices to the range [60, 140] and the **High Collar** treatment limited prices to [170, 250]. The widths of these collars are obviously identical, but their High or Low positioning differs relative to uncontrolled mean prices. They were implemented as 'hard' price controls. Whenever the floor of the price collar was binding, all bids at or greater than the floor price were filled at that minimum price, even though not all permits offered were allocated. Whenever the price ceiling was binding, all bids submitted at the maximum price were filled even when the quantity exceeded the intended supply. The computer software enforced these price controls by prohibiting bid prices outside of the collar range.

The other two treatments tightened these collars to a minimal width of zero, centered on the same ranges. As such zero-width collars are equivalent to emissions taxes, we refer to the treatment in which prices are fixed at 100 as the **Low Tax** treatment, and the treatment with prices fixed at 210 as the **High Tax** treatment. Since the price is fixed in these treatments, this simplifies the subjects' bidding problem and eliminates strategic uncertainty. They simply had to choose how much abatement to undertake to avoid paying some emissions tax. As discussed below in the hypothesis subsection, the five treatments lead to different numbers of optimally adopting firms and different permit prices.

3.4 Laboratory Procedures and Power Analysis

The main outcome variable for this study is the technology adoption frequency. As described in the next subsection, the optimal (equilibrium) number of adopting firms ranges from 0, 2, 4,

[19]None of the specific levels of the price controls we implement are set at an optimal (or second-best) level; these are not defined as we do not specify the marginal environmental damages of emissions. However, in subsection 4.3 we provide some results on emissions and social costs from the experimental data, including a brief discussion.

6 and 8 firms across the five treatments. This implies a nominal equilibrium (predicted) effect size of 2 across pairwise treatments. As discussed in our design pre-registration (AEARCTR-0013060), the standard deviation in average technology adoption across markets in an earlier related price floors study by Cason et al. (2023) ranged between 0.5 and 0.6 across treatments. For our power analysis we assume a greater standard deviation of 1.0 to be conservative, leading to a normalized effect size of 2.0 across pairwise adjacent treatments.

These assumptions lead to a required sample size of 6 markets per treatment for one-tailed tests that can detect treatment differences in the main adoption outcome at 90 percent power with 0.05 significance, for both t-tests and nonparametric Wilcoxon-Mann-Whitney tests (G*Power 3.1.9.4). One-tailed tests are justified due to theoretically-based directional hypotheses of adoption rates across treatments. Due to lower variance arising from constant permit prices, fewer sessions were required in the tax treatments. Therefore, we collected data from a total of 29, 8-person markets (232 total subjects)—5 markets in the Low Tax treatment and 6 markets in each of the other four treatments.

Subjects were all students at Purdue University (92% undergraduates), recruited from a database of approximately 5,000 volunteers drawn across a wide range of academic disciplines and randomly allocated to treatment conditions using ORSEE (Greiner, 2015). The oTree program was used to implement the experiment (Chen et al., 2016). To improve experimental control, the instructions (see Appendix B) used neutral framing and did not refer to the specific environmental economics setting explicitly.[20] For example, emission permits were referred to as 'coupons,' and abatement and marginal abatement costs were referred to as 'production' and 'production costs' that firms could avoid by buying coupons in the auction. The instructions were read aloud by a computerized voice, accompanied by graphics and key features projected on a projector screen, to promote common knowledge. Subjects also completed a 6-question quiz that required worked examples and were paid for correct answers. Two-thirds of subjects provided at least 5 correct answers.

Individual sessions typically had 24 participating subjects in the lab simultaneously (i.e., 3 separated markets) and were completed in less than 2 hours. Earnings were paid out immediately at the sessions' conclusion, privately in cash at a pre-announced exchange rate of points to U.S. dollars. (One practice round at the start of each session was unpaid.) Subjects on average earned $29.57 each, with an inter-quartile range of [$25.06, $33.75].

[20]Environmental framing could affect subjects' preferences differently, leading to a loss of control (Cason and Raymond, 2011).

3.5 Hypotheses

The theoretical model in section 2 provides clear predictions about how the placement and width of a price collar in competitive permit markets affects firms' incentives for technology adoption. The characterization of the equilibrium number of technology adopters (Proposition 1); how the expected permit price changes with the midpoint and width of the price collar (Proposition 2); and perhaps most importantly, the ranking of alternative policies in terms of technology diffusion (Proposition 4) provide the basis for the structure of our experimental design. Moreover, the theory and experiment enable us to gain insight into which types of firms have a higher propensity to invest in technology adoption. As predicted, those firms that have the highest abatement costs have the strongest incentive to adopt the new technology to reduce their abatement costs. Table 3 shows how these adoption incentives vary across the 5 treatments in the experiment according to firm type. Risk neutral, expected payoff maximizing firms will adopt the new technology if the increase in expected profits from adoption exceed the 4300 fixed technology investment cost (indicated in bold). In the Low (High) Tax treatment no (all) firms have an incentive to adopt the new abatement technology, with an intermediate range of firms adopting the technology in the Low Collar, High Collar and No Control (baseline) treatment. Finally, given the technology adoption rates and abatement cost shocks, we can assess how this affects the permit auction prices. In summary, in the case of a competitive permit market we can draw and experimentally test the following hypotheses:

Hypothesis 1. *(Technology diffusion) The policy ranking of the total number of firms adopting the cost-saving technology is*

$$\textit{High Tax} > \textit{High Collar} > \textit{No Control} > \textit{Low Collar} > \textit{Low Tax}.$$

Hypothesis 2. *(Technology adoption by firm type) Technology adoption rates are higher for firm types with higher abatement costs in the High Collar, No Control, and Low Collar treatments. All firms will adopt the technology in the High Tax treatment, and no firm will adopt the technology in the Low Tax treatment.*

Hypothesis 3. *(Auction prices) Positive shocks to abatement costs and a lower degree of technology diffusion induce higher auction prices.*

4 Results

This section is divided in three subsections. Subsection 4.1 presents the rate that firms choose to adopt the cost-reducing technology, testing Hypotheses 1 and 2. Subsection 4.2 then reports

Table 3: Increase in Expected Profits from Adopting in the New Technology, Gross of Adoption Cost

Adopter Type	Low Tax	Low Collar	No Control	High Collar	High Tax
Type 1	3300	**4620**	**9830**	**8332**	**6930**
Type 2	3100	**4340**	**8090**	**7620**	**6510**
Type 3	2900	4060	**6390**	**6308**	**6090**
Type 4	2800	4074	**5540**	**5458**	**5880**
Type 5	2700	3758	4230	**4672**	**5670**
Type 6	2600	3330	3560	**4420**	**5460**
Type 7	2400	2136	2250	4080	**5040**
Type 8	2200	1486	1192	3740	**4614**

Notes: Profit calculations are conditional on competitive permit prices, and are based on equiprobable likelihood of 5 abatement cost shocks. Entries in **bold** indicate firm types with an incentive to adopt for the adoption cost used in the experiment (4300).

average auction prices, comparing them to the equilibrium prices conditional on optimal adoption rates and testing Hypothesis 3 (see Table 1). The final subsection 4.3 presents calculations for social welfare.

4.1 Technology Adoption and Diffusion

As summarized in Hypothesis 1, the degree of technology diffusion, measured as the number of firms adopting the cost-reducing technology, should increase as the price collar rises. At the extremes of the Low (High) Tax no (all) firms should adopt in equilibrium. Figure 1 provides strong support for these predictions. The thick, red lines indicate the equilibrium number of adopting firms, which ranges from 0 to 8 across the 5 treatments. Especially for the late rounds 11-20 (Figure 2), the data clearly support both the comparative static as well as equilibrium point predictions.

Result 1. *Consistent with Hypothesis 1, the average number of adopting firms increases as the level of the price collar increases.*

Support: Nonparametric (Mann-Whitney) tests of pairwise collar treatment differences, based on independent session averages, indicate statistically significant differences in all cases except for the Low Collar to No Control comparison (p-value = 0.240). All other pairwise comparisons are significant at p-values of 0.013 or better (all rounds) or p-values of 0.004 or better (late rounds 11-20). Moreover, Wilcoxon tests indicate that in these late rounds the Low Collar (p-value = 0.094)), No Control (p-value = 0.312) and High Collar (p-value = 0.563) are

Figure 1: Average Number of Adopting Firms (All Rounds)

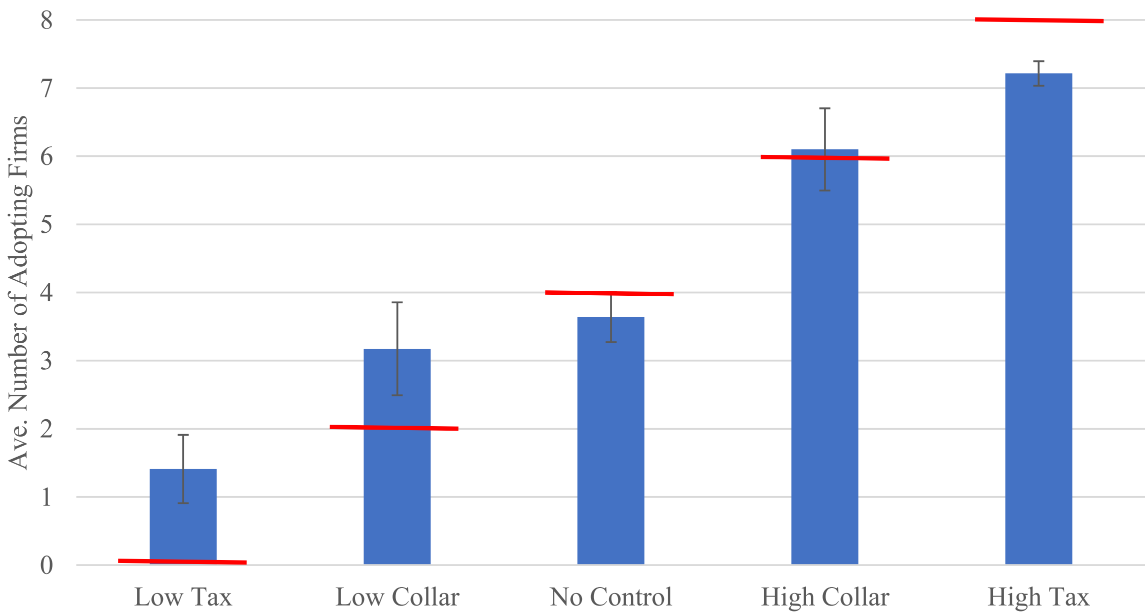
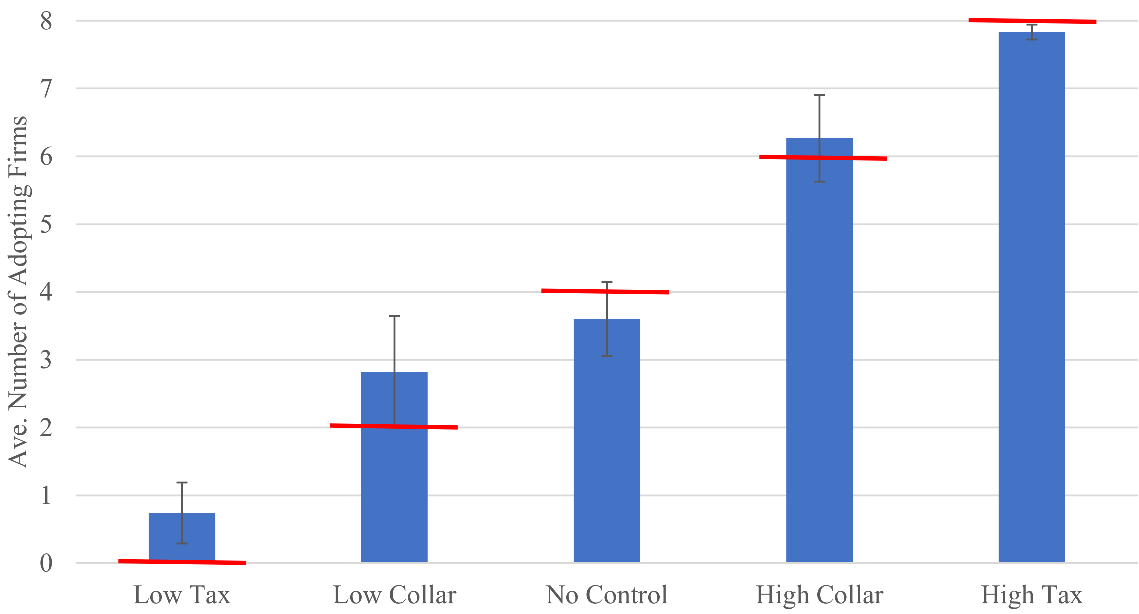


Figure 2: Average Number of Adopting Firms (Late Rounds 11-20)

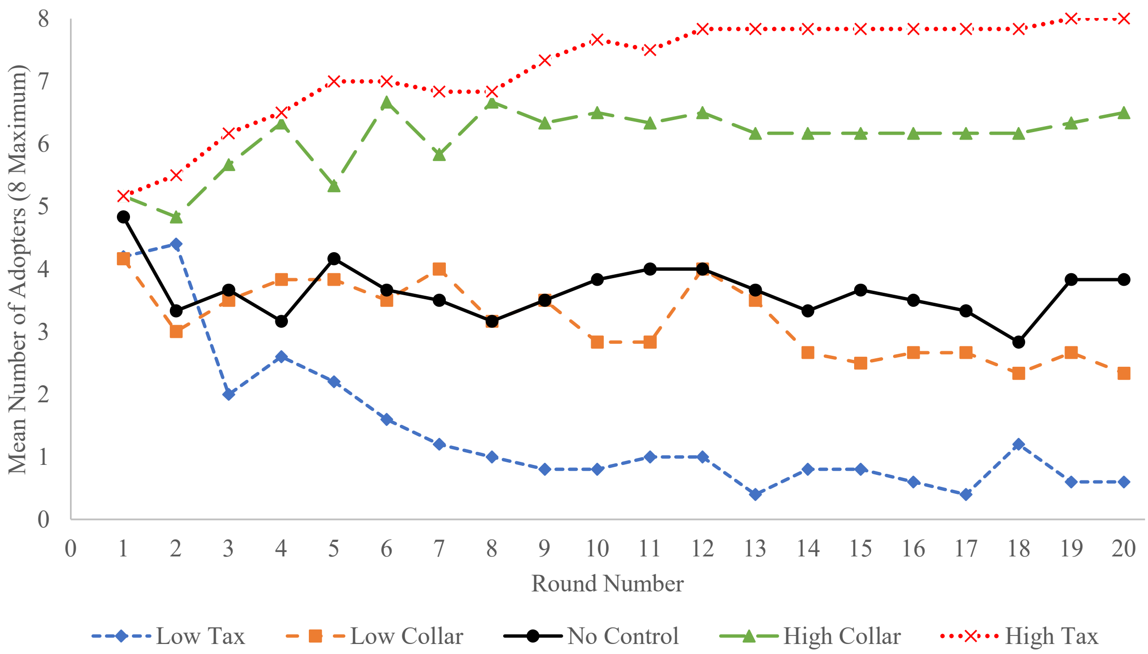


not significantly different from their theoretical predictions of 2, 4 and 6.[21]

Figure 3 illustrates the evolution of the adoption rate across rounds. All 5 treatments begin round 1 with a similar average number of adopting firms (4.17 to 5.17 out of 8 firms). The adoption frequency for the different treatments begin to separate relatively quickly, however, with substantial differences emerging across treatments in only 5 rounds. Later rounds exhibit large treatment differences, as summarized earlier in Figure 2. In all rounds the average number of adopting firms exceeds the equilibrium prediction of 2 firms for the Low Collar treatment.

[21]The tax treatments are necessarily different on average from their boundary predictions of 0 and 8.

Figure 3: Average Number of Adopting Firms, by Round



As we shall see in the next subsection, this overadoption leads auction prices to fall below competitive price predictions for this treatment.

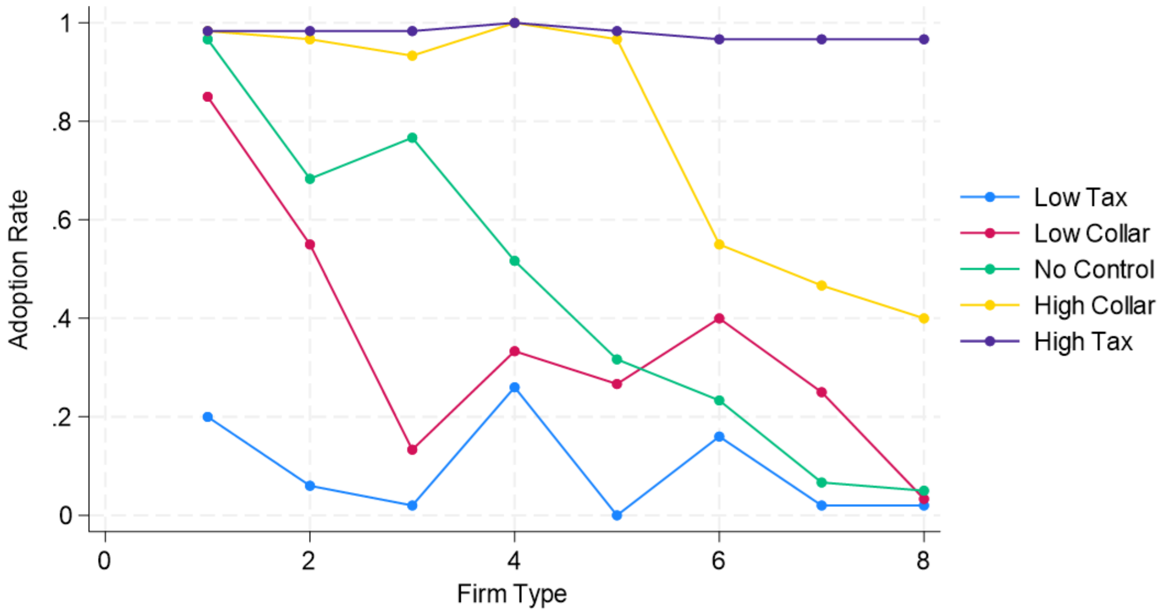
The model makes more specific predictions than simply the average number of adopting firms. In particular, it also indicates which of the heterogenous types of firms should adopt the technology depending on the location and width of the price collar (Hypothesis 2). Recall that the firm types are indexed from 1 to 8 depending on their abatement cost function, with type 1 endowed with the highest (pre-adoption) costs and type 8 with the lowest costs. For example, firm types 5 and 6 should adopt only in the High Tax and High Collar treatments, and types 3 and 4 should always adopt except in the Low Tax and Low Collar treatments.

Figure 4 summarizes the adoption rate by treatment for each of the 8 firm types, and provides support for these firm-specific equilibrium predictions.

Result 2. *Consistent with Hypothesis 2, higher cost (low firm type index) firms tend to adopt more frequently than lower cost firms. Higher cost firms adopt less frequently in the Low Tax and Low Collar treatments than the No Control baseline. Lower cost firms adopt more frequently in the High Tax and High Collar treatments than the No Control baseline.*

Support: Table 4 reports a set of linear probability models for firms' adoption decisions, estimated separately for each type. Red and blue colors with bold font highlight the coefficient estimates that should be significantly negative and positive, respectively, based on the firm type differences in adoption rates across treatments summarized in Hypothesis 2. All differences are significant as predicted except for type 4. The only unexpected and significant differences

Figure 4: Adoption Rate by Firm Type and Treatment (Rounds 11-20))



not predicted in this hypothesis concern the High Collar and High Tax treatments, which have higher adoption rates relative to the omitted No Control baseline more often than predicted.[22]

4.2 Auction Prices

Prices are, of course, fixed in the High Tax and Low Tax treatments, at 210 and 100 respectively. Auction-clearing prices could vary in the other three treatments. As noted above in Table 1, for our particular parameter choices, if the equilibrium number of firms adopt in the Low and High Collar treatments (2 and 6, respectively), then the auction should clear at a boundary of the price collars (140 and 170, respectively). This price implication for the High Collar treatment is supported. As already documented in Figures 1 through 3, the number of adopters in this treatment was around 6, as predicted, even in early rounds. Consequently, the auction in this treatment always cleared at a price of 170.

In the Low Collar treatment, however, the average number of adopting firms always exceeded the equilibrium prediction of 2 firms. This overadoption puts downward pressure on prices. Figure 5 shows that average prices in this treatment range from about 80 to 130, rising across rounds as the number of adopting firms falls across time (Figure 3).

The number of adopting firms in the No Control treatment is often similar to the number adopting in the Low Collar treatment, especially in the first half of the sessions. Correspondingly,

[22] Although not shown in this table, in a different regression we compared error rates (i.e., incorrect adoption decisions) by firm type. The highest (Type 1) and lowest (Type 8) cost types made about 7 to 8 percent fewer errors on average than those in the other types, likely because they had a simpler decision rule to nearly always or never adopt. These differences in error rates, however, are only marginally significant.

Table 4: Adoption Decisions for Different Firm Types, Rounds 11-20

	(1) Type 1	(2) Type 2	(3) Type 3	(4) Type 4
Low Tax	**-0.830*****	**-0.618*****	**-0.770*****	**-0.223***
(treatment dummy)	(0.186)	(0.135)	(0.131)	(0.125)
Low Collar	-0.127	-0.174	**-0.651*****	**-0.144**
(treatment dummy)	(0.123)	(0.203)	(0.144)	(0.129)
High Collar	-0.004	0.289*	0.153	0.419***
(treatment dummy)	(0.057)	(0.148)	(0.158)	(0.132)
High Tax	0.071	0.284**	0.200	0.484***
(treatment dummy)	(0.090)	(0.133)	(0.151)	(0.096)
Round number	-0.000	-0.001	-0.002	-0.020***
(scaled 1 to 10)	(0.002)	(0.006)	(0.006)	(0.008)
Constant	0.881***	0.838***	0.802***	0.679***
	(0.080)	(0.156)	(0.191)	(0.140)
Preference and demographic controls	Yes	Yes	Yes	Yes
Observations	290	290	290	290
Number of sessions	29	29	29	29

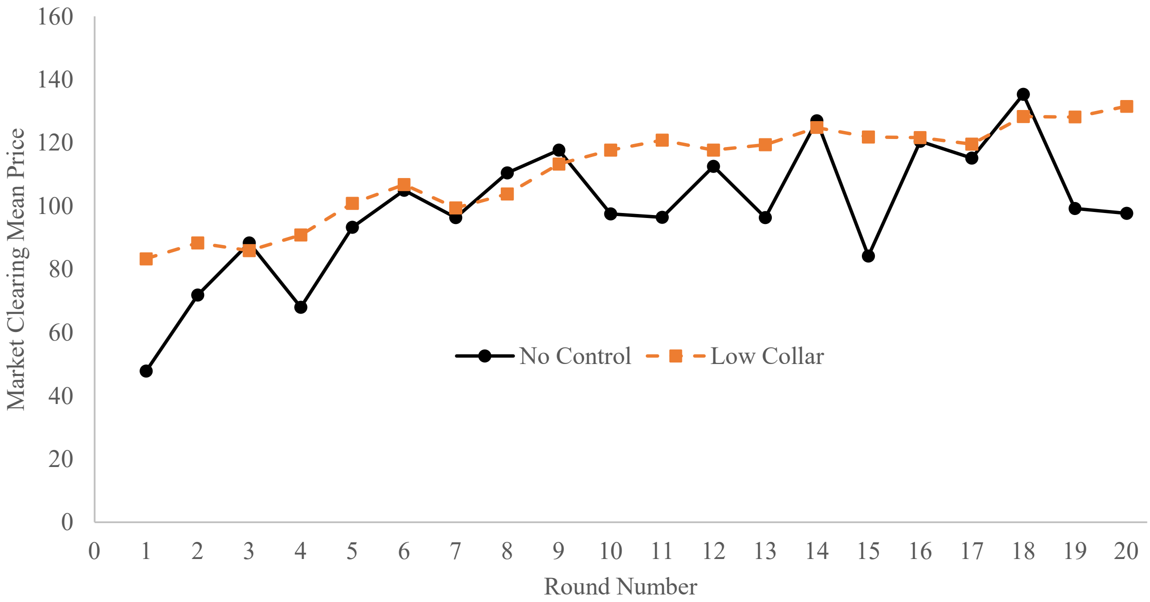
	(5) Type 5	(6) Type 6	(7) Type 7	(8) Type 8
Low Tax	-0.328**	-0.171	-0.012	-0.042
(treatment dummy)	(0.139)	(0.198)	(0.105)	(0.084)
Low Collar	-0.001	0.091	0.233*	-0.084
(treatment dummy)	(0.183)	(0.242)	(0.132)	(0.093)
High Collar	**0.657*****	**0.367****	0.474***	0.398***
(treatment dummy)	(0.129)	(0.160)	(0.175)	(0.121)
High Tax	**0.574*****	**0.733*****	**0.848*****	**0.850*****
(treatment dummy)	(0.140)	(0.138)	(0.134)	(0.078)
Round number	-0.001	-0.001	-0.005	0.001
(scaled 1 to 10)	(0.005)	(0.006)	(0.008)	(0.004)
Constant	0.476***	0.541**	0.136	0.054
	(0.177)	(0.271)	(0.188)	(0.104)
Preference and demographic controls	Yes	Yes	Yes	Yes
Observations	290	290	290	290
Number of sessions	29	29	29	29

Notes: Linear probability models with random effects on sessions and standard errors based on clustering for individual subjects (shown in parentheses). Omitted case is the No Control baseline treatment. ***, ** and * denote significantly different from 0 at one-, five- and ten-percent levels (two-tailed tests).

Figure 5 also shows that auction prices are similar in these two treatments, especially in the first half of the sessions.[23] Prices in the No Control treatment are below their predicted range of 100

[23] Average prices are actually slightly lower in the No Control than the Low Collar treatment, but this difference is not statistically significant (p-value = 0.298).

Figure 5: Average Auction Price, by Round



to 180 in early rounds. Nevertheless, our next result shows that auction prices (determined in stage 3 of each round) respond to variation in adoption rates (chosen in stage 1) and the realized abatement cost shock (realized in stage 2) as predicted.

Result 3. *Consistent with Hypothesis 3, auction prices are greater when abatement costs experience a positive shock, and when fewer firms adopt the cost-reducing technology. Both of these responses are smaller than competitive equilibrium predictions, however, and are also smaller in magnitude in the Low Collar than in the No Control treatment.*

Support: Table 5 reports a set of regressions with auction price as the dependent variable. Columns 1 and 2 employ data from the No Control treatment only. Columns 3 and 4 are based on the Low Collar treatment, the only other treatment with price variability. Columns 2 and 4 include only the late rounds 11-20. In all cases the cost shock realization is significantly positive. This coefficient is predicted to be 1.0, as each shock increase of 20 should raise price by 20. In all cases, however, the coefficient is significantly less than 1. Prices are also substantially less responsive to cost shocks in the Low Collar treatment. Conditional on the different cost shocks, prices should decline by 30 to 40 on average for each additional firm that adopts the technology. While the number of adopters coefficient is always negative and significant, it is also significantly greater than -30 in all cases and is much greater in the Low Collar treatment than the No Control treatment.[24]

[24]Table 5 reports coefficient estimates directly for the Tobit model in the Low Collar treatment. The lower sensitivity of prices in this treatment also holds for the means of the marginal effects on the expected value of the truncated price. In particular, the marginal impact of the cost shock ranges between 0.09 to 0.12, and the marginal impact of the number of adopters ranges between -1.8 to -7.6.

Table 5: Auction Price Regressions, Dependent on Adoption and Abatement Cost Shocks

	(1) No Control	(2) Late No Control	(3) Low Collar	(4) Late Low Collar
Cost shock	0.539**	0.619**	0.188**	0.147**
(-40 to 40)	(0.095)	(0.115)	(0.052)	(0.046)
Number of Adopters	-14.249**	-21.857**	-5.321**	-8.735**
(0 to 8)	(2.379)	(3.141)	(1.387)	(1.643)
Period Number	1.703**		2.471**	
(1 to 20)	(0.419)		(0.255)	
Period Number - 10		-0.280		0.448
(1 to 10, for actual 11 to 20)		(1.025)		(0.448)
Constant	133.044**	188.039**	103.929**	147.324**
	(12.378)	(13.588)	(8.700)	(6.739)
Observations	120	60	120	60
Number of sessions	6	6	6	6

Notes: Panel regression models with session random effects. Low Collar estimates employ a Tobit model due to the price controls. Standard errors shown in parentheses. ** and * denote significantly different from 0 at one- and five-percent levels (two-tailed tests).

4.3 Emissions and Social Costs

Without price controls, emissions are capped by the total supply of permits. Emissions could differ from this cap, however, due to the hard price collar. When a price floor is binding, firms have the incentive to incur additional abatement costs up to the level of the floor, and this leads to some unsold permits in the auction. A binding price floor thus mechanically reduces emissions. When a price ceiling is binding, the regulator offers additional permits at the ceiling, which leads to emissions that exceed the cap. For the case of emissions taxes (i.e, a zero-width price collar), firms optimally choose to abate up to the point where the marginal cost of abatement reaches the tax level. In all of these tax or price control conditions, emissions can differ from the cap implemented in a permit market without price controls.

Table 6 presents the average emissions (i.e., number of permits sold in the auction) per round in the five treatments of the experiment based on the later half of the sessions (rounds 11-20). Naturally, the emissions are ordered inversely with the number of technology adopting firms in each round (shown in column 3). The low tax incentivizes little abatement and results in the highest emissions, whereas the high tax induces the greatest abatement and lowest emissions. The price collars often bind in the experiment, and emissions vary accordingly. For example, the high collar binds at the floor price, so firms buy fewer permits on average (113.75) than the number offered (210). The 210 permits are always sold in the market without price controls. Thus, higher price controls and higher tax levels lead to greater adoption, more abatement and fewer emissions.

Table 6: Average Emissions, Abatement Costs and Social Costs (Rounds 11-20)

Treatment	Average Emissions (1)	Average Price (2)	Average # Adopters (3)	Ave. Total Costs (A_i) (4)	Social Costs for $d = 140$ (5)	Social Costs for $d = 160$ (6)	Social Costs for $d = 180$ (7)
Low Tax	339.86	100	0.74	8041	**55621**	62418	69216
	(3.73)	(0)	(0.09)	(490)	(435)	(476)	(524)
Low Collar	219.87	123.37	2.82	30392	61173	65571	69968
	(2.91)	(1.92)	(0.17)	(1141)	(939)	(921)	(907)
No Control	210.00	108.43	3.60	29330	58730	62930	67130
	(0)	(4.23)	(0.12)	(555)	(555)	(555)	(555)
High Collar	113.75	170	6.27	43195	59120	**61395**	63670
	(3.31)	(0)	(0.12)	(592)	(530)	(554)	(583)
High Tax	57.55	210	7.83	52471	60528	61679	**62830**
	(2.69)	(0)	(0.05)	(279)	(453)	(497)	(542)

Note: Standard errors shown in parentheses.

Whether social welfare increases due to these additional investments in abatement and technology adoption, and the resulting reduction in emissions, depends on the marginal damage function for emissions. This is unspecified in our experimental environment. However, following a procedure similar to Cason et al. (2023), we can derive a range of marginal damages for which the different price control or tax treatments lead to lower expected social costs, based on the outcomes realized in these later rounds of the experiment. For this exercise we presume that the marginal damage is a constant, d, which is a reasonable approximation for prominent cases such as carbon emissions (Pizer, 2002). Denote observed aggregate emissions in treatment i as Q_i, and the aggregate abatement costs plus costs incurred to reduce abatement costs as A_i. Expected social costs, using the constant marginal damage d, are therefore $SC_i = A_i + dQ_i$. This highlights the trade-off for social costs between higher abatement costs in the High Collar and High Tax treatments, with the higher emissions in the Low Collar and Low Tax treatment. Which is more important for welfare depends on the marginal damage weight, d.

Table 6 reports the average total costs (A_i) for each treatment in the later rounds in column 4, along with the social costs (SC_i) for three different assumed levels of the marginal damage cost. Based on the particular parameters chosen in the experiment—which, to be clear, is not calibrated for any specific country or market—social costs are lowest in the low tax treatment if marginal damages are low (column 5), but they are lowest in the high tax treatment if marginal damages are high (column 7). This is intuitive, as emissions are greatest (lowest) in the Low (High) Tax treatment. To be more precise, and based on the realized market outcomes of the experiment, social cost is lowest with the low tax when marginal damages are less than 155.5, and are lowest with the high tax when marginal damages are greater than 165. The high collar treatment has the lowest social cost for intermediate marginal damages between 155.5 and 165 (column 6). The No Control baseline treatment always has lower social costs than the Low Collar treatment, since it has lower emissions *and* lower costs on average. But this treatment without price controls always has higher social costs on average than one of the price control treatments for any positive level of marginal damages.

5 Conclusions

Regulating pollution through price-based instruments has become a cornerstone of contemporary environmental policy, as these policies promise to deliver emissions reductions across sources more cost-effectively (Baumol and Oates, 1988). Since the market for sulfur dioxide emissions in the United States demonstrated that significant cost-savings could be reaped, many other tradable permit markets have emerged across the globe to follow suit. Despite the appeal of these market mechanisms, however, prices in these markets have been prone to volatility. A major concern of volatile permit prices is that they adversely impact firms' investment incentives for adopting advanced technology to lower abatement costs. To restore price stability in tradable permit markets, policy-makers frequently propose regulatory interventions such as price collars—comprising combined price ceilings and price floors. This paper explores how firms' technology adoption incentives and the subsequent degree of technology diffusion within the market is affected by different price collar interventions.

Our theoretical model shows that, for a given initial supply of permits, technology diffusion depends on the position of the price collar relative to the expected permit price in a pure market and on the width of the price collar. Since emissions taxes can be viewed as price-collared markets when the width of the collar is zero, our theoretical results allow us to rank taxes, pure markets and price-collared markets in terms of firm-level technology adoption incentives and industry wide diffusion of the technology. In particular, if the midpoint of the price collar in a market is greater than (less than) the expected price in a pure market, then an emissions tax induces greater (lower) technology diffusion than a price-collared market, which in turn generates greater (lower) diffusion than a pure market. With a laboratory experiment, we test this ranking, as well as related hypotheses concerning firm-level technology adoption choices and permit prices. Overall, the experimental results provide substantial support for the theoretical model's predictions in terms of adoption choices by firm type, the degree of diffusion at the industry level, and prices.

Although we carefully designed the economic model and experiment, the laboratory market is implemented based on a specific numerical parameterization. This means that broad empirical conclusions must be made cautiously. However, we believe our unique experiment captures the essential economic channels to cleanly test our key hypotheses based on the theoretical model predictions. The structure of the experimental market is guided by clear economic theory, which is conducive to strengthening its external validity.

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A Proofs Appendix

Proof of Lemma 1: We begin by specifying a firm's compliance cost in the third stage given the price, $p(\mathbf{x}, s, t, u)$. To calculate the firm's compliance cost substitute (6) into (5) to obtain

$$f^i(\mathbf{x}, s, t, u) = p(\mathbf{x}, s, t, u)\left(\frac{b^i(1-\beta^i x^i)+u}{c^i} - \frac{p(\mathbf{x}, s, t, u)}{2c^i}\right). \tag{18}$$

To consider a firm's technology adoption choice in the first stage, the reduction in firm i's compliance cost if it adopts in the first stage is

$$r^i(\mathbf{x}, s, t, u) = f^i(x^i = 0, x^{-i}, s, t, u) - f^i(x^i = 1, x^{-i}, s, t, u), \tag{19}$$

where x^{-i} denotes the set $\mathbf{x} \setminus \{x^i\}$. Use (18) to calculate

$$\begin{aligned} r^i(\mathbf{x}, s, t, u) =& p(x^i = 0, x^{-i}, s, t, u)\left(\frac{b^i + u}{c^i} - \frac{p(x^i = 0, x^{-i}, s, t, u)}{2c^i}\right) \\ & - p(x^i = 1, x^{-i}, s, t, u)\left(\frac{b^i(1-\beta^i)+u}{c^i} - \frac{p(x^i = 1, x^{-i}, s, t, u)}{2c^i}\right). \end{aligned}$$

Under the assumption that a single firm's adoption of the new technology cannot change the competitive permit price so that $p(x^i = 1, x^{-i}, s, t, u) - p(x^i = 0, x^{-i}, s, t, u) = 0$,

$$r^i(\mathbf{x}, s, t, u) = \frac{b^i \beta^i p(\mathbf{x}, s, t, u)}{c^i}, \tag{20}$$

where from here on $\mathbf{x}$ includes $x^i = 1$. Taking the expectation of both sides of (20) and using (3) gives us (13). □

Proof of Proposition 1: Given equilibrium adoption decisions $\mathbf{x}^*$, $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u))$ is linearly increasing in θ^i. Therefore, θ^* defined by (16) is unique. Moreover, $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u)) \geq 1$ and $x^i = 1$ for firm types $\theta^i \geq \theta^*$, and $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u)) < 1$ and $x^i = 0$ for firm types $\theta^i < \theta^*$. If $\theta^* \in [\theta^{min}, \theta^{max}]$, then $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u)) \geq 1$ and $x^i = 1$ for firm types $\theta^i \in [\theta^*, \theta^{max}]$, and $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u)) < 1$ and $x^i = 0$ for firm types $\theta^i \in [\theta^{min}, \theta^*)$. If $\theta^* > \theta^{max}$, then $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u)) > 1$ and $x^i = 1$ for all firms; if $\theta^* < \theta^{min}$, then $\theta^i \mathbb{E}(p(\mathbf{x}^*, s, t, u)) < 1$ and $x^i = 0$ for all firms. □

Proof of Proposition 2: Our first task in this proof is to write the expected permit price in a market with a price collar in terms of the midpoint and width of the collar. Start by substituting for t and s from (9) into (12) to obtain

$$\begin{aligned} \mathbb{E}(p(\mathbf{x}, s, t, u)) \quad = \quad & \int_{\underline{u}}^{u^s} \left(\mathbb{E}(p(\mathbf{x}, u)) + u^s\right) g(u) du + \int_{u^*}^{u^t} \left(\mathbb{E}(p(\mathbf{x}, u)) + u\right) g(u) du \\ & + \int_{u^t}^{\overline{u}} \left(\mathbb{E}(p(\mathbf{x}, u)) + u^t\right) g(u) du. \end{aligned}$$

Collect terms to obtain

$$\mathbb{E}(p(\mathbf{x},s,t,u)) \quad = \quad \mathbb{E}(p(\mathbf{x},u)) + u^s \int_{\underline{u}}^{u^s} g(u)du + \int_{u^s}^{u^t} ug(u)du + u^t \int_{u^t}^{\overline{u}} g(u)du. \tag{21}$$

Since $\int_{\underline{u}}^{\overline{u}} ug(u)du = 0$,

$$\int_{u^s}^{u^t} ug(u)du = -\int_{\underline{u}}^{u^s} ug(u)du - \int_{u^t}^{\overline{u}} ug(u)du,$$

which upon substitution into (21) and collecting term yields

$$\mathbb{E}(p(\mathbf{x},s,t,u)) = \mathbb{E}(p(\mathbf{x},u)) + \int_{\underline{u}}^{u^s} (u^s - u)g(u)du + \int_{u^t}^{\overline{u}} (u^t - u)g(u)du. \tag{22}$$

Substitute (17) into (22) to obtain the characterization of the expected permit price in a market with a price collar in terms of the expected permit price under a pure market, the midpoint of the price collar and its width:

$$\begin{aligned}\mathbb{E}(p(\mathbf{x},s,t,u)) \quad &= \quad \mathbb{E}(p(\mathbf{x},u)) + \int_{\underline{u}}^{p^0-\mathbb{E}(p(\mathbf{x},u))-\alpha} \left(p^0 - \mathbb{E}(p(\mathbf{x},u)) - \alpha - u\right) g(u)du \\ &\quad + \int_{p^0-\mathbb{E}(p(\mathbf{x},u))+\alpha}^{\overline{u}} \left(p^0 - \mathbb{E}(p(\mathbf{x},u)) + \alpha - u\right) g(u)du. \end{aligned} \tag{23}$$

To prove part (a) of Proposition 2, differentiate $\mathbb{E}(p(\mathbf{x},s,t,u)$ with respect to p^0 to obtain:

$$\frac{\partial \mathbb{E}(p(\mathbf{x},s,t,u)}{\partial p^0} \quad = \quad \int_{\underline{u}}^{p^0-\mathbb{E}(p(\mathbf{x},u))-\alpha} g(u)du + \int_{p^0-\mathbb{E}(p(\mathbf{x},u))+\alpha}^{\overline{u}} g(u)du > 0. \tag{24}$$

To prove part (b), first evaluate (23) at $p^0 = \mathbb{E}(p(\mathbf{x},u))$:

$$\begin{aligned}\mathbb{E}(p(\mathbf{x},s,t,u)) \quad &= \quad \mathbb{E}(p(\mathbf{x},u)) - \int_{\underline{u}}^{-\alpha} (\alpha + u)\, g(u)du + \int_{\alpha}^{\overline{u}} (\alpha - u)\, g(u)du. \\ &= \quad \mathbb{E}(p(\mathbf{x},u)) + \alpha\left(-\int_{\underline{u}}^{-\alpha} g(u)du + \int_{\alpha}^{\overline{u}} g(u)du\right) - \int_{\underline{u}}^{-\alpha} ug(u)du - \int_{\alpha}^{\overline{u}} ug(u)du.\end{aligned}$$

Since the distribution of u is symmetric,

$$-\int_{\underline{u}}^{-\alpha} g(u)du + \int_{\alpha}^{\overline{u}} g(u)du = -\int_{\underline{u}}^{-\alpha} ug(u)du - \int_{\alpha}^{\overline{u}} ug(u)du = 0.$$

Therefore, $\mathbb{E}(p(\mathbf{x},s,t,u)) = \mathbb{E}(p(\mathbf{x},u))$ if $p^0 = \mathbb{E}(p(\mathbf{x},u))$. Since, from part (a), $\mathbb{E}(p(\mathbf{x},s,t,u))$ is strictly increasing in p^0, $\mathbb{E}(p(\mathbf{x},s,t,u)) = \mathbb{E}(p(\mathbf{x},u))$ only if $p^0 = \mathbb{E}(p(\mathbf{x},u))$.

To prove part (c), first differentiate (24) with respect to α:

$$\frac{\partial^2 \mathbb{E}(p(\mathbf{x},s,t,u))}{\partial p^0 \partial \alpha} = -g(p^0 - \mathbb{E}(p(\mathbf{x},u)) - \alpha) - g(p^0 - \mathbb{E}(p(\mathbf{x},u)) + \alpha) < 0. \tag{25}$$

Eq. (25) reveals that the rate of change of $\mathbb{E}(p(\mathbf{x}, s, t, u)$ with respect to p^0 is declining in α. Given part (b) of the proposition, (25) implies

$$\frac{\partial \mathbb{E}(p(\mathbf{x}, s, t, u))}{\partial \alpha} \begin{cases} < 0, \text{ for } p^0 > \mathbb{E}(p(\mathbf{x}, u)) \\ > 0, \text{ for } p^0 < \mathbb{E}(p(\mathbf{x}, u)). \end{cases}$$

The inequalities are strict because the sign of (25) is strict. This completes that proof of part (c), and hence of the proposition. □

Proof of Proposition 3: We first show that the expected competitive equilibrium price is declining in the number of adopters of the technology. We then use this result to show how a parametric increase (decrease) in the expected competitive price function, that for our purposes may come from a change in one or more of the parameters of the market policy, increases (decreases) the equilibrium set of technology adopters. Proposition 3 then follows directly from Proposition 2.

To show how the expected competitive permit price changes with the number of technology adopters, suppose that a subset z of the firms choose to adopt the technology when they had not before. From (7) the change in the third-stage price in a market without price controls from the new adoptions is

$$\Delta p = -\phi \sum_{z} \widehat{q}_0^i \beta^i < 0. \tag{26}$$

From (8) we see that this is also the change in the first-stage expected price under a market without price controls. Then, from (9), the change in the cut-off values $u^t$and u^s is

$$\Delta u^s = \Delta u^t = -\Delta p > 0. \tag{27}$$

We assume that $-\Delta p$ is small enough so that $u^s + \Delta u^s = u^s - \Delta p < u^t$. Let $\mathbf{x}$ be the original vector of technology adopters and let $\mathbf{x_z}$ be the new vector of adopters, that is, the vector that includes the additional set of adopters z. Then,

$$\mathbb{E}(p(\mathbf{x_z}, u)) = \mathbb{E}(p(\mathbf{x}, u)) + \Delta p. \tag{28}$$

Use (27) and (28) to modify the expected competitive price in a market with price controls (12) to include the new technology adopters:

$$\mathbb{E}(p(\mathbf{x_z}, s, t, u)) = \int_{\underline{u}}^{u^s - \Delta p} sg(u)du + \int_{u^s - \Delta p}^{u^t - \Delta p} \left(\mathbb{E}(p(\mathbf{x}, u)) + \Delta p + u\right) g(u)du + \int_{u^t - \Delta p}^{\overline{u}} tg(u)du. \tag{29}$$

Since $-\Delta p > 0$, we can write

$$\int_{\underline{u}}^{u^s - \Delta p} sg(u)du = \int_{\underline{u}}^{u^s} sg(u)du + \int_{u^s}^{u^s - \Delta p} sg(u)du; \tag{30}$$

$$\int_{u^t - \Delta p}^{\overline{u}} tg(u)du = \int_{u^t}^{\overline{u}} tg(u)du - \int_{u^t}^{u^t - \Delta p} tg(u)du. \tag{31}$$

Moreover,

$$\begin{aligned}\int_{u^s-\Delta p}^{u^t-\Delta p}\left(\mathbb{E}(p(\mathbf{x},u))+\Delta p+u\right)g(u)du &= \int_{u^s}^{u^t}\left(\mathbb{E}(p(\mathbf{x},u))+u\right)g(u)du\\ &-\int_{u^s}^{u^s-\Delta p}\left(\mathbb{E}(p(\mathbf{x},u))+u\right)g(u)du\\ &+\int_{u^t}^{u^t-\Delta p}\left(\mathbb{E}(p(\mathbf{x},u))+u\right)g(u)du\\ &+\Delta p\int_{u^s-\Delta p}^{u^t-\Delta p}g(u)du. \end{aligned} \tag{32}$$

Substitute (30) through (32) into (29), collect terms, and use (9) to calculate

$$\begin{aligned}\mathbb{E}(p(\mathbf{x_z},s,t,u))-\mathbb{E}(p(\mathbf{x},s,t,u)) &= \int_{u^s}^{u^s-\Delta p}(u^s-u)g(u)du-\int_{u^t}^{u^t-\Delta p}(u^t-u)g(u)du\\ &+\Delta p\int_{u^s-\Delta p}^{u^t-\Delta p}g(u)du, \end{aligned} \tag{33}$$

which is the change in the expected competitive permit price under a price collar with the additional technology adopters. To sign this change note first that the third term on the right side of (33) is negative because $\Delta p<0$ and $\int_{u^s-\Delta p}^{u^t-\Delta p}g(u)du>0$. The first term is also negative because

$$\int_{u^s}^{u^s-\Delta p}u^s g(u)du<\int_{u^s}^{u^s-\Delta p}ug(u)du. \tag{34}$$

However, the second term of (33) is positive because

$$\int_{u^t}^{u^t-\Delta p}u^t g(u)du<\int_{u^t}^{u^t-\Delta p}ug(u)du. \tag{35}$$

Despite this countervailing effect, $\mathbb{E}(p(\mathbf{x_z},s,t,u))-\mathbb{E}(p(\mathbf{x},s,t,u))<0$. To see this let

$$\mathbb{E}(p(\mathbf{x_z},s,t,u))-\mathbb{E}(p(\mathbf{x},s,t,u))=H, \tag{36}$$

where H is equal to the right side of (33). Now, consider the second term of H,

$$-\int_{u^t}^{u^t-\Delta p}(u^t-u)g(u)du.$$

Note that

$$\int_{u^t}^{u^t-\Delta p}ug(u)du<\int_{u^t}^{u^t-\Delta p}(u^t-\Delta p)g(u)du,$$

and, consequently

$$-\int_{u^t}^{u^t-\Delta p}(u^t-u)g(u)du<-\int_{u^t}^{u^t-\Delta p}(u^t-(u^t-\Delta p))g(u)du=-\Delta p\int_{u^t}^{u^t-\Delta p}g(u)du.$$

If we replace $-\int_{u^t}^{u^t-\Delta p}(u^t-u)g(u)du$ with $-\Delta p\int_{u^t}^{u^t-\Delta p}g(u)du$ in H to obtain $\widetilde{H}$, we have

$H < \widetilde{H}$. Moreover,

$$\begin{aligned}
\widetilde{H} &= \int_{u^s}^{u^s-\Delta p} (u^s - u)g(u)du - \Delta p \int_{u^t}^{u^t-\Delta p} g(u)du + \Delta p \int_{u^s-\Delta p}^{u^t-\Delta p} g(u)du \\
&= \int_{u^s}^{u^s-\Delta p} (u^s - u)g(u)du + \Delta p \int_{u^s-\Delta p}^{u^t} g(u)du < 0. \qquad (37)
\end{aligned}$$

The sign of $\widetilde{H}$ follows because both terms on the right side are negative. Combining (36) with $\widetilde{H}$ gives us

$$\mathbb{E}(p(\mathbf{x_z}, s, t, u)) - \mathbb{E}(p(\mathbf{x}, s, t, u)) = H < \widetilde{H} < 0. \qquad (38)$$

Thus, the expected permit price in a market with a price collar is strictly declining in the number of firms that adopt the new technology.

We now show that a parametric increase in the expected permit price will cause an increase in the equilibrium number of technology adopters. Consider a pair $(\theta^*, \mathbf{x}^*)$ that satisfies the equilibrium condition (16); that is, $\theta^* \mathbb{E}(p(\mathbf{x}^*, s, t, u)) = 1$. Our result that the expected price is declining in the number of technology adopters implies that θ^* and $\mathbb{E}(p(\mathbf{x}^*, s, t, u))$ move in the same direction. That is, a lower (higher) θ^* means the number of technology adopters is weakly greater (smaller), which implies that the expected competitive price is lower (higher). Now suppose that a parametric increase in the expected permit price produces $\mathbb{E}(\widetilde{p}(\mathbf{x}^*, s, t, u)) > \mathbb{E}(p(\mathbf{x}^*, s, t, u))$. Then, $\theta^* \mathbb{E}(\widetilde{p}(\mathbf{x}^*, s, t, u)) > 1$, so $(\theta^*, \mathbf{x}^*)$ is no longer an equilibrium. To restore the equilibrium consider another pair $(\theta^{**}, \mathbf{x}^{**})$ satisfying $\theta^{**} \mathbb{E}(\widetilde{p}(\mathbf{x}^{**}, s, t, u)) = 1$. In this equilibrium, $\theta^{**} < \theta^*$ and the number of technology adopters is greater. To see this, assume toward a contradiction that $\theta^{**} \geq \theta^*$. In this case the number of technology adopters is weakly larger than under $(\theta^*, \mathbf{x}^*)$. But this implies $\theta^{**} \mathbb{E}(\widetilde{p}(\mathbf{x}^{**}, s, t, u)) \geq \theta^* \mathbb{E}(\widetilde{p}(\mathbf{x}^*, s, t, u)) > 1$, in which case $(\theta^{**}, \mathbf{x}^{**})$ would not be an equilibrium. Therefore, $\theta^{**} < \theta^*$ and the number of technology adopters is weakly greater.

That the number of technology adopters is increasing in parametric changes in the competitive permit price implies that Proposition 3 follows directly from Proposition 2. □

B Instructions Appendix

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 points. These points will be converted to U.S. Dollars at the end of the experiment, at a rate of 2000 points = 1 Dollar. Notice that the more points you earn, the more cash that you receive. You will also take a computerized quiz at the end of these instructions, and earn $1 for each correct answer.

At your seat you have a sheet indicating your trading values for coupons, expressed as the costs avoided when purchasing coupons. 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 reduce 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 have the opportunity to make a costly investment which can lower your production costs. Afterwards everyone will receive a small number of additional coupons, with the amount determined randomly. You can then purchase more coupons in an auction. 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) − Amount Spent Buying Coupons.

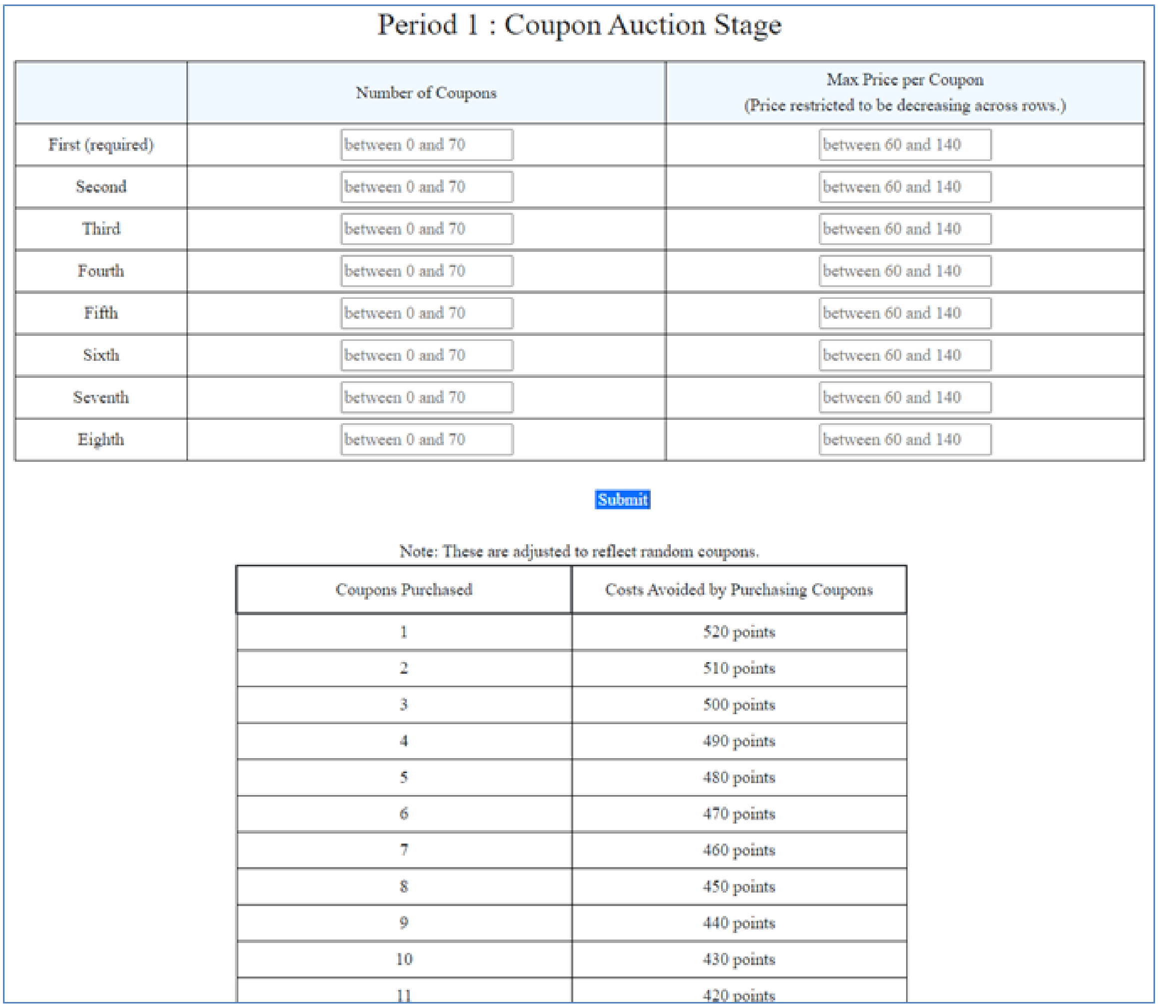
Your Fixed Period Revenue does not depend on any actions you take, and does not change throughout the experiment.

Production Costs

You must pay production costs when you produce units. The cost of each unit produced is 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 are shown on your computer screen during the coupon auction, as shown in Figure 1. (The numbers on this example screen will vary from person to person, and yours will be shown on your computer screen when the experiment begins). You must scroll down the page to see all the costs. 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 avoided with each **additional** coupon purchased. For example, consider the numbers in the column in the lower part of Figure 1 labeled "Costs Avoided by Purchasing Coupons." If, for example, you purchase 6 coupons you avoid the **sum** of the highest 6 numbers in this column: $520+510+500+490+480+470 = 2970$ points. So your total production costs can be very high if you do not buy many coupons to avoid production.

Figure 6: (Labeled Figure 1 in Instructions. Additional caption:) Note: The numbers in lower section vary from person to person, and you must scroll down to see them all



Period 1 : Coupon Auction Stage

	Number of Coupons	Max Price per Coupon (Price restricted to be decreasing across rows.)
First (required)	between 0 and 70	between 60 and 140
Second	between 0 and 70	between 60 and 140
Third	between 0 and 70	between 60 and 140
Fourth	between 0 and 70	between 60 and 140
Fifth	between 0 and 70	between 60 and 140
Sixth	between 0 and 70	between 60 and 140
Seventh	between 0 and 70	between 60 and 140
Eighth	between 0 and 70	between 60 and 140

Submit

Note: These are adjusted to reflect random coupons.

Coupons Purchased	Costs Avoided by Purchasing Coupons
1	520 points
2	510 points
3	500 points
4	490 points
5	480 points
6	470 points
7	460 points
8	450 points
9	440 points
10	430 points
11	420 points

Coupons

We just explained that your costs increase when you increase production. You can avoid production (and save on your production costs) by buying more coupons. It costs money to buy coupons, but this allows you to avoid some production costs. Later in these instructions we explain the rules for buying coupons in the auction.

Why might you want to buy a coupon? Suppose your computer screen indicates that you can avoid incurring a production cost of 520 by purchasing 1 coupon as indicated in Figure 1. You can increase your earnings if you can buy this coupon for a price less than 520, since it allows you to save the production cost of 520. For example, if you bought one additional coupon for 130 you save the production cost of 520 and therefore increase your earnings (because of the lower production costs that you need to pay) by $520 - 130 = 390$. Additional coupons that you can purchase at prices less than avoided production costs can further increase your earnings. In this example, if the price per coupon is 130 you could buy many more coupons (moving down the column in Figure 1) and increase your earnings further. For example, if you buy 6 total coupons at a price per coupon of 130 your coupon expenditures are only $6 \times 130 = 780$ points. Subtracting this from the avoided costs of 2970 summed above leads to an earnings increase of $2970 - 780 = 2190$ points. Many more coupons could be bought at this low price to further increase your earnings in this example.

If the price per coupon were higher, however, you may not want to buy as many coupons. For example, if the price were instead 495 per coupon, for the "Costs Avoided" numbers in Figure 1 it would only increase your earnings to buy 3 coupons—the ones with avoided costs greater than 495. The fourth (and lower) costs avoided are 490 and lower, so it does not increase your earnings to pay 495 for coupons to save less production cost than the coupon price.

Coupon Auction: How to Buy More Coupons

The "auctioneer" is the central computer, which seeks to sell 210 total coupons each period to the 8 people in your group. You can bid to buy coupons by filling out a "bid sheet" on your computer, shown at the top of Figure 1. This bid sheet consists of a list of numbers of coupons and a decreasing list of per-unit prices you are willing to pay. The auctioneer will sell the 210 coupons to the highest bids entered by all 8 people, but all coupons will be sold at the same, uniform price—equal to the bid amount submitted for the last (210th) coupon sold.

For example, and picking some random numbers, suppose that you submitted a bid sheet with 3 steps, as follows:

Figure 7: (No figure label or caption in the instructions)

Period 0 (Practice Period) : Coupon Auction Stage

	Number of Coupons	Max Price per Coupon (Price restricted to be decreasing across rows.)
First (required)	6	195
Second	8	133
Third	7	60
Fourth	between 0 and 70	between 0 and 59
Fifth	between 0 and 70	between 0 and 59

This bid is for a maximum of $6 + 8 + 7 = 21$ total coupons, summing the quantity bid across the three rows of the middle column. Your computer will require you to submit bid prices that are integers and that decline through the list. Here, it indicates a willingness to pay up to 195 each for the first 6 coupons, up to 133 each for the next 8 coupons, and up to 60 each for the final 7 coupons.

After everyone submits their bid sheets, the computer auctioneer will rank the bids of all 8 people in your group from highest to lowest, taking into account how many coupons are bid at each price. The highest 210 coupon bids will be accepted, and the price for all of these bought coupons will be set at the lowest accepted bid price. All bids higher than this uniform price will be successful and "filled" with coupon purchases.

For example, suppose that the lowest accepted bid price is 121, submitted by some other bidder (not the bids shown above). In the bid sheet shown above, the 6 coupons (bid at 195) and the 8 coupons (bid at 133) will result in $6+8 = 14$ purchased coupons at a price of 121 each. This is because the bid prices of 195 and 133 are greater than 121. The bid for 7 coupons at 60 each is not filled because the bid sheet indicated a willingness to pay only up to 60—while the uniform price is 121. More generally, if you submitted the example bid sheet above you would purchase 0 coupons if the bid price is above 195; you would purchase 6 coupons if the bid price is less than 195 but above 133; you would purchase $6 + 8 = 14$ coupons if the bid price is less than 133 but above 60; and you would purchase $6 + 8 + 7 = 21$ coupons if the bid price is less than 60.

Sometimes the uniform auction price may be equal to a bid price that you submitted on your bid sheet. For example, the lowest accepted bid could be 133 for the current example. In this case, the entire amount (8 coupons in the example) bid for at this price may not be available due to the overall limit of 210 sold coupons. In these cases, bids at the uniform price may only be "partially" filled; that is, some amount less than 8 coupons bid at that price would be purchased. (In this example, the 6 coupons bid for at the higher price of 195 would be purchased, since 195 is greater than the uniform price of 133.)

Only this paragraph varied across treatments, describing the various price controls. In the No Control baseline, the minimum price indicated is 0 and the maximum price indicated is 999. Note: One additional restriction on the possible bid prices is that they must be greater than or equal to 60 and less than or equal to 140. If more than 210 coupons are bid for at prices equal to the maximum price of 140, then all bid quantities submitted at this maximum price will be filled and all coupons will be sold at this maximum price. If fewer than 210 coupons are bid for at prices greater than or equal to the minimum price of 60, then all bid quantities at prices greater than or equal to this minimum price will be filled and all coupons will be sold at this minimum price.

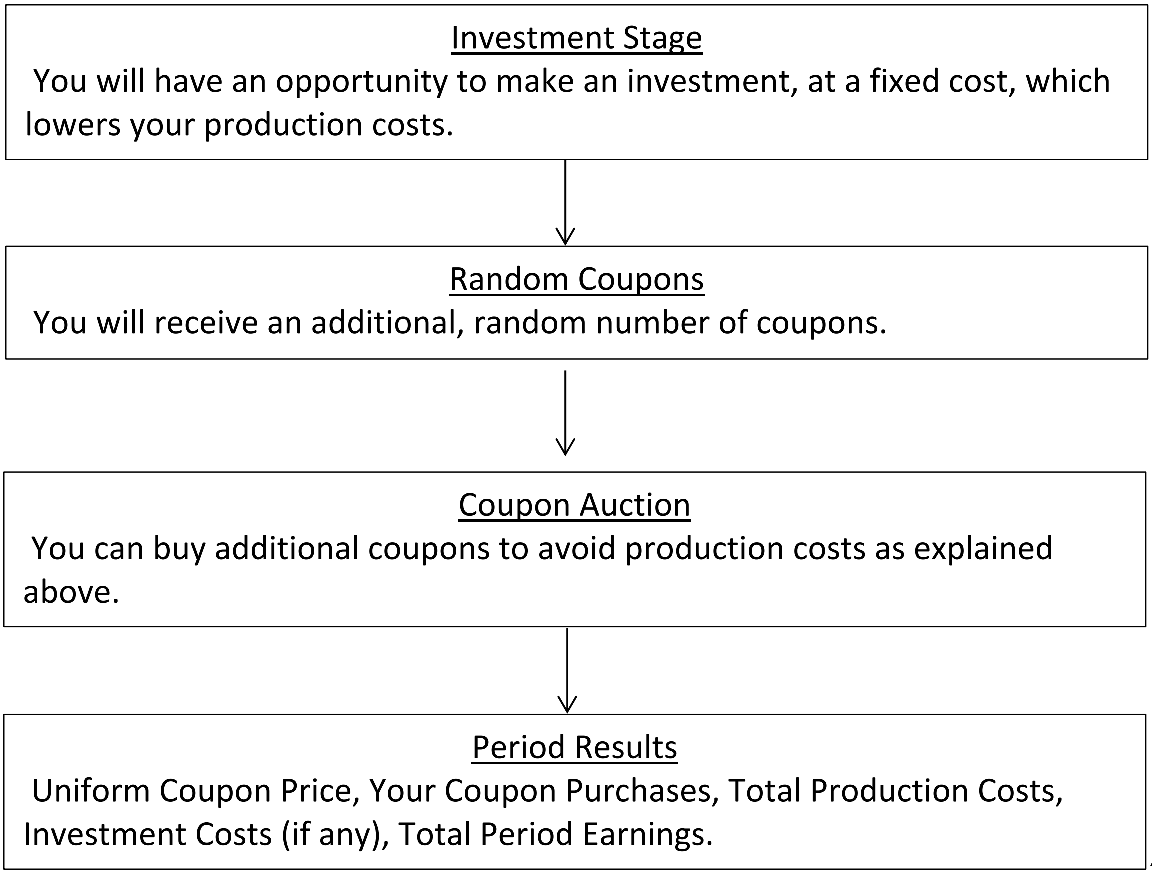
Period Structure

This part of the experiment will consist of 20 paid periods, following one unpaid practice period (labelled Period 0). Each period is identical and will include the following steps as shown in Figure 2.

Investment Stage

At the start of each period, you will indicate whether you want to make a costly investment at a **total fixed cost of 4300 points**. See Figure 3. If you make this investment, your production 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"). The actual costs differ from person to person, and are shown on your separate hardcopy record sheet.

Figure 8: (Labeled Figure 2 in Instructions)



Random Coupons

You and all the other traders today will also receive a random number of additional coupons after the investment stage but before the auction. 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 – 2 Coupons – OR – 4 Coupons – OR – 6 Coupons – OR – 8 Coupons

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, illustrated in Figure 4, is the same as the number received by each of the other people in your market.

Note: 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 4 additional coupons in the random allocation, this is equivalent to moving you down the list of costs to 4 purchased coupons. The extra costs avoided by purchasing more coupons will be adjusted accordingly. **Importantly, you should therefore consider the costs avoided ON YOUR COMPUTER SCREEN rather than on your hardcopy cost sheet while completing your bid sheet.**

Figure 9: (Labeled Figure 3 in Instructions. Additional caption:) Note: The numbers vary from person to person, and you must scroll down to see them all

Period 15 : Investment Stage

Do you wish to invest 4300 points to lower your costs from the left column to the right column?

No Yes

Coupons Purchased	Costs Avoided by Purchasing Coupons	
	Costs with No Investment	Costs if Investing
1	580 points	310 points
2	570 points	300 points
3	560 points	290 points
4	550 points	280 points
5	540 points	270 points
6	530 points	260 points
7	520 points	250 points
8	510 points	240 points
9	500 points	230 points
10	490 points	220 points
11	480 points	210 points
12	470 points	200 points
13	460 points	190 points
14	450 points	180 points

Auction Stage

After the investment stage and the random coupons are distributed in the steps described above, you may choose to buy additional coupons in the auction (Figure 1). Remember, you earn more from buying coupons if the price you pay is less than the production cost that you can avoid. These amounts are shown on your computer screen (and don't forget to scroll down the list). You may often find that your earnings increase when you buy many coupons in the auctions.

Period Results

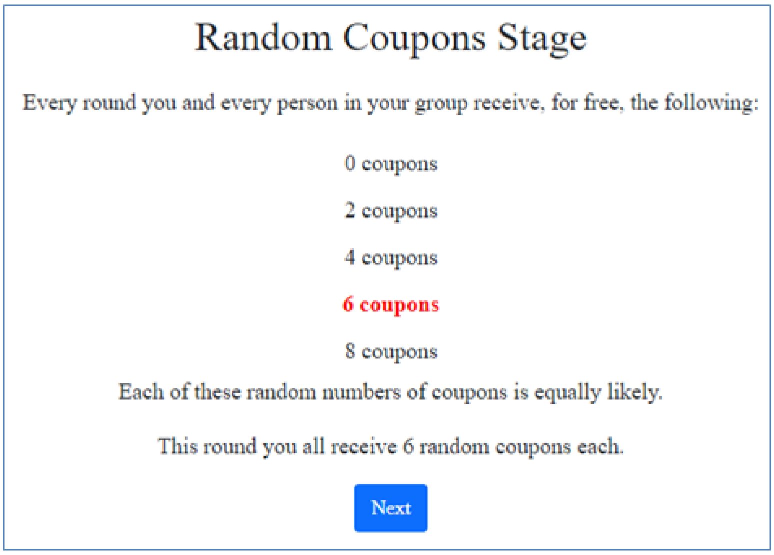
The results of the period will display on your screen after everyone submits their bid sheet, as illustrated in Figure 5. After reviewing this information, you should then click "Next" to begin the next period. Past periods are shown with additional columns. Each period will progress through the stages as indicated in the flow chart of Figure 2.

Summary

1. You can avoid paying production costs by buying coupons.

2. Your costs shown on your computer screen are the extra, additional costs avoided for each coupon that you buy.

Figure 10: (Labeled Figure 4 in Instructions)



3. At the start of each period you will decide whether to make a costly investment that lowers your production costs, and therefore reduces the extra costs avoided by purchasing more coupons.

4. 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.

5. You then submit a bid sheet, indicating the maximum amount you are willing to pay per coupon for different numbers of coupons.

6. The computer auctioneer selects a uniform price equal to the lowest price bid for 210 total coupons allocated to the 8 people in your group. At the end of this stage your coupons held will determine your production costs for the period.

7. Your coupon purchases, total production costs, and total period earnings 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.

If you have any questions during the experiment, please raise your hand and an experimenter will come to your seat. Before we begin we will now conduct a brief quiz on your computers.

Figure 11: (Labeled Figure 5 in Instructions)

Period 2 : Period Result

Period Number	0	1	2
Uniform Coupon Price (a)	1 point	98 points	106 points
Number of Coupons You Buy (b)	25	15	40
(Random Coupons for Free)	4	6	8
Did you Invest?	YES	YES	NO
Fixed Period Revenue (c)	9800 points	9800 points	9800 points
Total Production Costs (d)	60 points	660 points	780 points
Investment Cost (e)	4300 points	4300 points	0 points
Amount Spent on Coupons (a) * (b) = (f)	25 points	1470 points	4240 points
Total Earnings This Period (c) - (d) - (e) - (f)	5415 points	3370 points	4780 points

Next