An Experimental Investigation of Hard and Soft Price Ceilings in Emissions Permit Markets

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Abstract

Tradable emissions permits have been implemented to control pollution levels in various markets and represent a major component of legislative efforts to control greenhouse gas (GHG) emissions. Because permits are supplied for a fixed level of pollution, allowing the market for permits to determine the price, price control mechanisms may be needed to protect firms from price spikes caused by fluctuations in the demand for permits. We test permit markets in an experimental laboratory setting to determine the effectiveness of several price control mechanisms, with special attention on the soft price ceiling. We focus on a static setting similar to some of the earliest experimental work focused on price ceilings. Results indicate that both permit supply adjustments and price ceilings (hard ceilings) effectively limit elevated prices in this setting. By contrast, reserve auctions to implement soft ceilings do not consistently control prices, especially when a minimum reserve permit price is applied. Furthermore, the grandfathering of permits allows permit sellers to realize significant welfare gains at the expense of buyers under a soft ceiling policy. Our results thus highlight several advantages of hard ceilings for controlling short term price increases.

Keywords : greenhouse gases ; hard price ceiling ; laboratory economic experiments; pollution controls ; price controls ; reserve auction ; soft price ceiling ; tradable emissions permit market

(1) Introduction

Emissions permit markets have been established for many pollutants to control environmental degradation. In such markets, a government supplies a fixed level of permits and firms must obtain and report permits equaling their pollution level at the time of demonstrating compliance each period. To minimize costs in a competitive emissions market, firms purchase permits at a price equal to their marginal cost of abatement, so that all firms have the same marginal cost of the last unit abated. In theory, this minimizes the total cost of achieving the target level of emissions abatement.

Price controls have been considered in many pollution markets to manage the price fluctuations of permits. Policies which introduce permits into the market at a fixed quantity corresponding to the level of pollution allowed in the market can contribute to large price volatility (Fankhauser and Hepburn, 2010). This is due to the inelastic supply of government policies that fix the permit level. Any shocks to the marginal cost of abatement will cause fluctuations in the demand for permits. Given a controlled quantity of permits, and therefore perfectly inelastic supply, any fluctuations in demand for pollution abatement are realized through adjustments to the market price and not quantity.

The purpose of price controls is to introduce elasticity in the supply curve over the range of non-zero prices, mitigating the effects of shocks or unexpected shifts in the cost of pollution abatement on permit prices. Typical controls involve the use of a price collar, which combines a ceiling and a floor. Price ceilings help firms to avoid exorbitant costs associated with price spikes due to volatility or aggressive abatement targets. Price floors stimulate investment in emissions abatement technologies in an environment where low prices provide an insufficient incentive, thus encouraging lower emissions levels in the future (Burtraw, et al., 2010). Based on simulations with stochastic emissions, Fell and Morgenstern (2010) demonstrate under various banking and borrowing rules that a price collar is consistently more cost-effective than a price ceiling alone.[1]

In the context of greenhouse gas (GHG) legislation in the United States, various price collars have been proposed that are only differentiated by their ceilings. Each policy has a hard price floor, not allowing purchases of permits below a minimum price. The various ceilings, however, fall into one of two policy definitions: hard ceilings which set an absolute maximum on permit prices and soft ceilings which introduce a minimally priced reserve of permits into the market beyond the original target quantity. The former provides absolute price control with some emissions flexibility while the latter provides absolute emissions control while allowing prices to fluctuate beyond the soft ceiling level.

Laboratory experiments have been used to investigate a broad range of cost and price control mechanisms to manage price volatility in permit markets.[2] For example, Cason and Gangadharan (2006) find that banking diminishes price volatility in the presence of emissions shocks. However, emissions are greater when banking is allowed due to lower permit compliance rates. Stranlund et al. (2010) extend this analysis by explicitly separating compliance and reporting violations as two separate events. They find that enforcement efforts should focus on untruthful reporting since large fines applied directly to non-compliance of

[1] This conclusion assumes that policies are compared for equal expected accumulative emissions. Because the price floor decreases the number of permits utilized with the price collar, simulations testing only the price ceiling were provided with a more limited number of permits to equalize expected emissions. In this context, the higher cost induced by the price floor was outweighed by the higher cost of a more restrictive permit allotment when testing the price ceiling alone.

[2] Cason (2010) provides a comprehensive outline of various experimental evaluations of emissions permit market structures.

emissions have little effect. In either case, banking of permits allows subjects to allocate permits reasonably well over time, even in the presence of noncompliance. Stranlund et al. (2011) consider the ability of banking and hard ceilings to dampen volatility, finding that both tools are capable of individually controlling price volatility, even though the hard ceiling contributes most of the dampening effect when the two are implemented in tandem.

A broad and comprehensive set of experiments would test both hard and soft ceilings in a dynamic setting, with various combinations of banking and enforcement mechanisms, in order to compare the degree of price control in the presence of permit supply or demand shocks. However, given the limited study of the soft ceiling proposal, and the lack of any experimental research on this policy, this study begins with a more modest goal of first understanding how the soft ceiling behaves in a repeated static environment.

Earlier research on hard price ceilings does focus on isolating within-period price effects to determine if there are any behaviors which would cause deviations from theory. For instance, a non-binding hard ceiling placed at the equilibrium price should mathematically produce the same equilibrium outcome as if there were no ceiling policy. However, researchers have found that a non-binding hard ceiling at the equilibrium price decreases transaction prices in an experimental double auction when compared to markets with no price ceiling (Isaac and Plott, 1981, Smith and Williams, 2008, Smith and Williams, 1981). This effect is strongest in the initial periods and for subjects with less trading experience, with outcomes featuring welfare shifts from sellers to buyers of permits. Coursey and Smith (1983) also confirm the presence of price depression in a posted offer market.

The soft ceiling policy is more complex than a hard ceiling, and yet there are no analogous experimental studies to determine how subjects will trade within this new environment, or how trading behavior may deviate from theoretical predictions. The purpose of this research is to begin to lay the experimental foundation for the soft ceiling. Specifically, similar to earlier research on the hard ceiling, we focus on the within-period price and welfare effects of this new policy. We find that under certain conditions, not only does the soft ceiling lack absolute price control, but prices are elevated and welfare gains from trade are transferred from buyers to sellers compared to theoretical predictions. There are also indications that splitting available permits between an initial and a reserve auction, an essential aspect of the soft ceiling policy, creates a coordination problem. Subjects do not fully account for the eventual permit allotment over both auctions, but are instead influenced by the short-term allocation before both auctions have been conducted.

The remainder of this paper is organized as follows: Section 2 provides detailed descriptions of both hard and soft ceilings, while section 3 describes how agents may trade when subjected to the soft ceiling policy. Section 4 provides the methodology for the study, and explains the identical theoretical outcomes between policy scenarios and the baseline treatment. Section 5 presents the results, with section 6 providing a discussion of the implications and policy recommendations.

(2) Structure of Ceiling Mechanisms

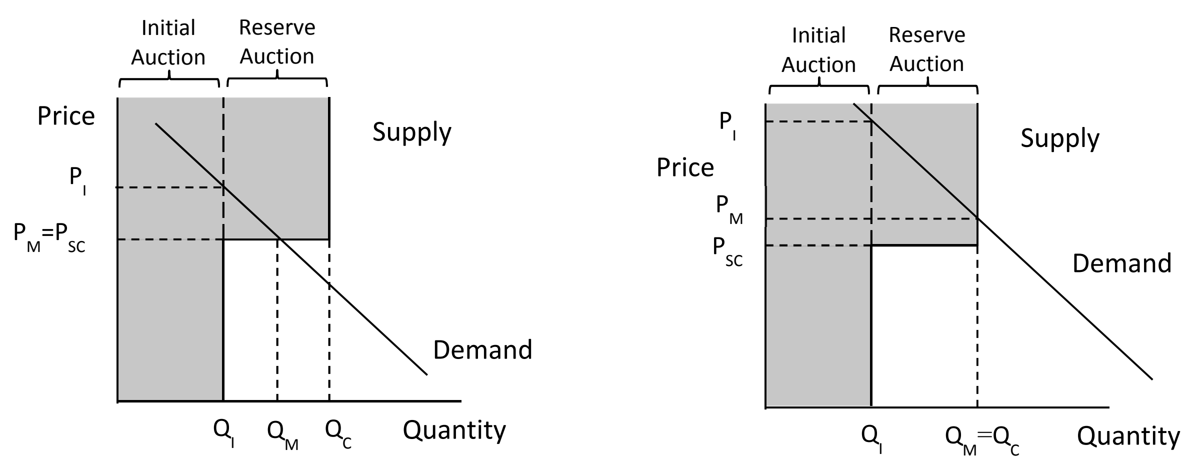
A hard price ceiling is simply a price control which sets an absolute maximum value on permit prices. Assume an initial permit allotment (Q_I) with an equilibrium price (P_I). When trying to avoid prices higher than a desired maximum (P_C), a ceiling caps prices at Pc and buyers can purchase as many permits as desired at this price from an unlimited government reserve. When demand is sufficiently high such that $P_I > P_C$, the market price (P_M) will rise no higher than P_C and the market quantity (Q_M) is elevated relative to the initial permit allotment (Q_I). In such a situation, the price ceiling is binding, working effectively as an emissions tax (t) with $t = P_C$. By implementing perfectly elastic supply, a hard ceiling places utmost importance on controlling prices at the expense of releasing as many permits as required into the market to keep prices below the ceiling. A notable example of such a price ceiling in Federal GHG legislation was proposed by Senators Cantwell and Collins (Cantwell, 2009) as part of the Carbon Limits and Energy for America's Renewal (CLEAR) Act. This act proposed a hard price ceiling with scheduled annual increases set automatically as a function of the real discount rate.

By contrast, the soft price ceiling does not set an absolute upper limit on the price of permits. In fact, the term "soft price ceiling" is not a ceiling by definition, but the terminology we utilize for a reserve auction of permits with a minimum reserve price as desribed by Murray, et al. (2009). Fell et al. (2010) have employed the term "soft collar" when analyzing the effectiveness of a reserve auction in comparison to a hard collar with an absolute maximum price. Such a reserve auction was passed in the House of Representatives as part of the permit trading market proposed in H.R. 2454 by Congressmen Waxman and Markey (Waxman and Markey, 2009). Slightly different structures have been proposed in other policy initiatives, including a contingency reserve of unsold allowances which could be a triggered by a soft ceiling as part of the Regional Greenhouse Gas Initiative (Burtraw et al., 2007) and a more complicated variant with three price tiers established in the California GHG permit trading scheme (Pavley and Nunez, 2006).

In a permit market with a soft ceiling (Figure 1), an initial quantity of permits (Q_I) is introduced to the market equal to desired emissions levels. In the absence of additional permits or controls, the equilibrium price for this initial allotment would occur at P_I. At the time when permit holders are expected to demonstrate compliance, an additional quantity of permits called the allowance reserve is offered at auction with a minimum reserve price (P_{SC}), potentially allowing those with insufficient permits to make up for their shortage. The aggregate of the initial and reserve auction permits represents a quantity control on the total market (Q_C). The introduction of reserve permits as described by Murray et al., as well as Waxman and Markey's legislation, is not induced by a price trigger but is provided automatically every period. Firms are not bound by the soft price ceiling in the initial auction and will have reserve permits available regardless of trading prices earlier in the period.

Figure 1: Controlling high prices with a soft ceiling
(Shaded regions represent allowable trades.)

(a) Demand intersects supply at soft ceiling (b) Demand intersects supply above soft ceiling



The soft ceiling (P_{SC}) receives its name from the intended impact of the minimum reserve price on the market price for permits (P_M) by introducing supply elasticity as represented by the horizontal section of the supply curves in Figure 1. If demand were to intersect supply such that $P_I < P_{SC}$, the market price would be equal to P_I and none of the reserve would be purchased. As demand increases, P_M increases until $P_M = P_{SC}$ (Figure 1a). Under such conditions, firms perfectly coordinating prices across auctions would purchase permits at the minimum reserve price. In this way, while there is no absolute maximum, the horizontal portion of supply acts as a kind of soft ceiling over a range of demands. As demand continues to increase, however, the market price would eventually rise above the soft ceiling when the reserve allotment is exhausted (Figure 1b). Nonetheless, prices would still be lower than if there were no reserve at all. This design is appealing to policy-makers primarily concerned with climate change because unlike hard ceilings it allows for an absolute cap on emissions (Q_C), while still providing some, although not absolute, control of prices.

(3) Expectations in a Repeated Static Environment

Non-experimental studies comparing the effects of hard and soft ceilings on prices and total emissions are limited. A macroeconomic analysis of proposed legislation predicts that permits in the initial market would be purchased at the ceiling price for many years in order to bank permits in expectation of higher future prices (Williams, 2010). Fell et al. (2010) perform a dynamic numerical analysis, comparing the two mechanisms with banking of permits available. When targeting identical cumulative emissions goals in the presence of shocks to baseline emissions levels, they find the intuitive result that the hard ceiling decreases price volatility more than a soft ceiling, and the hard ceiling level required for emissions parity with the soft ceiling is higher.[3] While such findings are helpful for policy-makers in determining the optimal level and pathway for price ceilings, they do not address the behavior of individual agents who may deviate from theoretical assumptions of how optimization occurs within a single period of the price discovery process. There are many types of behavior which could cause markets to deviate from the competitive equilibria described in Figure 1, in which costs are minimized by balancing marginal costs with the price of permits across both the initial and reserve auctions. Large deviations could introduce potentially significant consequences with respect to controlling prices.

For instance, if agents in the initial auction were to ignore reserve auction permits altogether, and thus price permits based on the initial auction only, one would expect initial auction prices to equilibrate close to P_I. One of the earliest emissions permit auctions, which regulated SO_2 levels under the Clean Air Act, demonstrated that the spot market was more heavily influenced by current market conditions and not the anticipated future auction of additional permits (Burtraw, et al., 2011). While this factor may play a role in elevating prices during the earlier periods, the repeated static nature of the experiment should allow agents to gain experience and more successfully equilibrate across auctions in later periods as compared to a dynamic setting.

Another factor which could cause prices to deviate from the competitive equilibrium is market power. Buyers with market power wanting to avoid prices above the floor of the reserve auction could withhold demand to depress prices in the initial auction while sellers with market

[3] Fell et al. (2010) study a price collar, which provides a hard price floor in the initial auction in conjunction with either a hard or soft ceiling.

power wishing to hold out for the reserve would tend to increase prices. In this set of experiments, as well as for the beginning years proposed in the Waxman-Markey legislation, sellers could maintain market power due to extensive grandfathering of permits. Goeree, et al. (2010) study the impacts of grandfathering vs. auctioning initial permit allotments before a single-round, limit-order call market. Agents with large grandfathered permit allocations strategically withheld permits from the market, generating elevated prices in comparison to both the theoretical equilibrium and the allotment by auction. Sellers could exercise similar market power in our experiment, exacerbating the resulting price elevation above the price floor in the reserve market.

Finally, we expect price increases from the floor of the reserve auction to be further augmented based on past experimental studies of bidding behavior in the presence of price floors and ceilings. In the context of a double auction, Smith and Williams (1981) found that a hard price floor elevated bids of both buyers and sellers in comparison to non-bound theoretical equilibria at or in close proximity to the price floor. Sellers with market power able to observe this behavior could construct higher price expectations for the reserve and revise their bids in the main auction upwards as a result. For these reasons, we would expect prices to be elevated, and therefore not controlled, compared to the theoretical equilibrium.

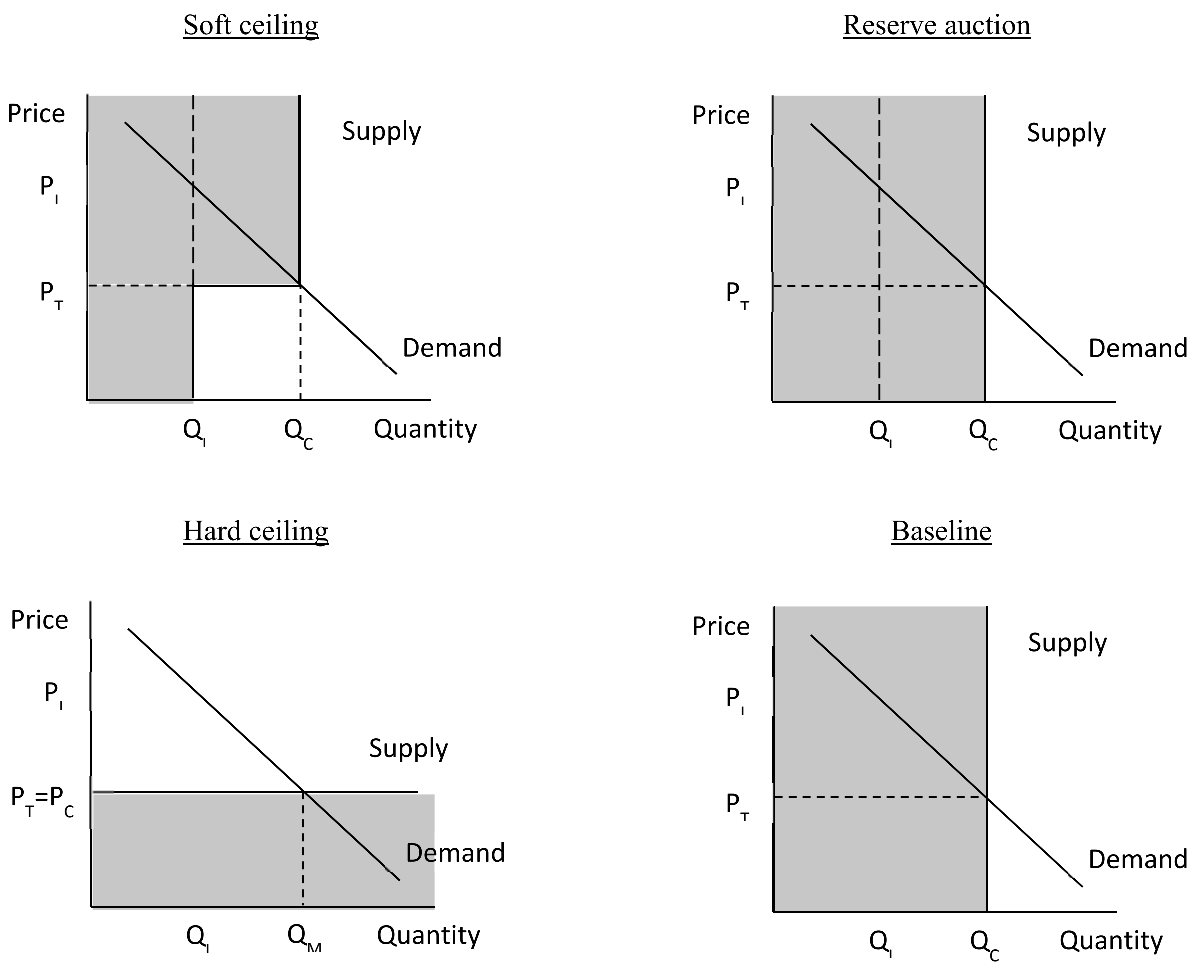
(4) Methodology

We use an experimental laboratory setting to compare the ability of soft and hard price ceilings to control prices. To isolate the impact of the soft ceiling, we consider stationary repetition of identical single period environments (i.e., no banking or borrowing of permits) and adjust only the price control mechanism across treatments.

We conduct 16 experimental sessions across four treatments consisting of a soft ceiling, a reserve auction with no soft ceiling reserve price, a hard ceiling, and a baseline with no price controls or reserve allocation for comparison. Figure 2 depicts the four policy choices tested. In each case, an initial auction of Q_I permits yields an equilibrium price of P_I, with $P_I > P_T$ and P_T denoting the target maximum price in the auction for permits. Each policy targets the same price, quantity combination such that any differences in actual price outcomes are caused by subject behavior and not policy targets. Starting in the upper left-hand corner of Figure 2, we test the soft ceiling, defined as a reserve auction with the key structural components outlined in Waxman and Markey, a reserve floor price and substantial grandfathering of permits (Soft ceiling). Moving clockwise, we test the same structure, but relax the minimum price floor in the reserve auction, thus eliminating the soft ceiling. We then test increasing the quantity to the same total cap (Q_C) as the first two policies, but in a single auction without the use of a reserve auction (Baseline), providing a control for the other treatments. Finally we test a hard price ceiling (P_C) where the ceiling price equals the target price of the other three policies (Hard Ceiling). Due to its straightforward nature, the hard ceiling treatment was conducted in only 1 of the 16 sessions, which allowed us to confirm that prices readily converged to the ceiling price and to dedicate experimental earnings more heavily towards the other treatments.

We employed 8 subjects per session for a total of 128 subjects recruited from the population of undergraduate students at Purdue University with no prior experience in experiments related to emissions permit markets. In addition to a $5.00 show-up fee, subjects earned experimental dollars which were converted immediately to U.S. Dollars at the conclusion of their experimental session. Average total earnings were \$26.69, with a standard deviation of \$6.37.

Figure 2: Four policy treatments tested as price controls in an experimental market.
(Shaded regions represent allowable trades.)

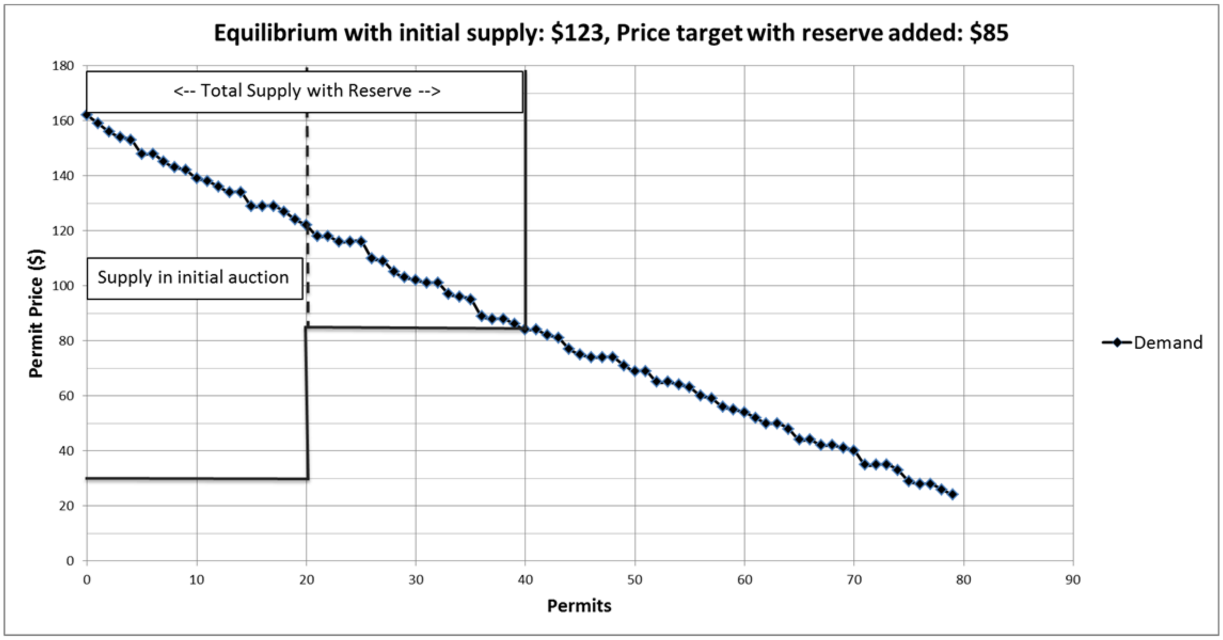


Subjects were provided the opportunity to manage a firm with an existing level of pollution and a fixed revenue stream. They were incentivized, through monetary payments, to minimize costs while accounting for all pollution through some combination of abatement and permit purchases. While this research focuses on pollution abatement, subjects did not view any environmental terminology. For example, the level of abatement of pollution was written as "units of an experimental good produced" and emissions permits were called "coupons." All experiments were conducted over a computerized network, with subjects interacting in markets through a client interface programmed in Z-tree (Fischbacher, 2007).

For each session, 8 subjects participated in 14 identical and separate periods, the first 2 of which were practice with no payment. Within each period, all subjects were required to abate up to 10 units of pollution with increasing marginal costs of abatement or obtain permits to substitute for pollution not abated. At the end of each period, the sum of permits held and pollution abated were required to equal 10 under a rule of automatic compliance. Each subject had a unique set of marginal costs, which when aggregated together determined the market demand for permits as illustrated in Figure 3.

For all treatments, 40 permits were distributed to the market in each period, with half being distributed before the initial auction and half before the reserve auction. (The one exception occurred in the Baseline treatment in which all permits were distributed before a single auction.) While a typical soft ceiling design would likely distribute a smaller proportion of the permit allotment in the reserve, we distributed 50% in order to increase the disparity between equilibrium prices with and without the reserve, and thus magnify behavioral effects on prices in our experimental market setting. The predicted equilibrium price in the initial auction is $123. A successful price control would decrease the price in the initial auction down to a new equilibrium of $85 as shown in Figure 3.

Figure 3: Demand and supply for permits in emissions market (Soft ceiling).



After initial permits were allocated, subjects were free to purchase and sell permits with each other in a double auction. We used this method to simulate the heavy grandfathering of permits built into the early years of the Waxman and Markey legislation. We utilized a continuous double auction trading institution similar to Cason and Gangadharan (2006) in which any subject could continuously make or accept single permit price bids for both selling and purchasing of permits. Experimental instructions for the soft ceiling treatment are provided in the Appendix. Instructions for other treatments are available from the authors upon request. We posted all price ceilings and floors at the top of the screen during trading, both for the initial auction and the future reserve auction when applicable.

After completing the initial auction, reserve permits were distributed (except for the baseline treatment which ended at this point in each period). Subjects then traded permits again using a double auction similar to the first phase of the period. We used the same trading procedures after grandfathering reserve permits for two reasons: (1) the auction format already placed a high level of cognitive demand on subjects, and learning two completely different auction formats would have added unnecessary complexity; and (2) substantial grandfathering of permits is common during initial years of many permit trading schemes in the field. For both the initial and reserve allocations, permits were heavily distributed towards the 4 lowest cost abaters to induce a high volume of trading and create active markets.

(5) Results

We have implemented four treatments designed to achieve equal emissions levels and target the same equilibrium price in order to determine the effectiveness of a soft and hard ceiling in maintaining a maximum price. We test a hard ceiling treatment, a soft ceiling treatment, as well as a reserve auction only treatment against our control, the baseline treatment in which the reserve amount is added to the initial auction, and the target equilibrium price.

(a) Prices in the main (initial) auction

Result 1: The hard ceiling controls prices, with market prices converging closely to the target equilibrium price.

Support: Figure 4 displays the mean trading prices, indicating that the hard ceiling price quickly approaches the maximum target of $85 by the eighth period and averages $84.6 over the final five periods. Since the hard ceiling effectively achieves the objectives of controlling the price at the target, this treatment serves as a useful benchmark against which to evaluate other treatments.

Figure 4: Mean of last 8 trades in initial auction for each period (all sessions)

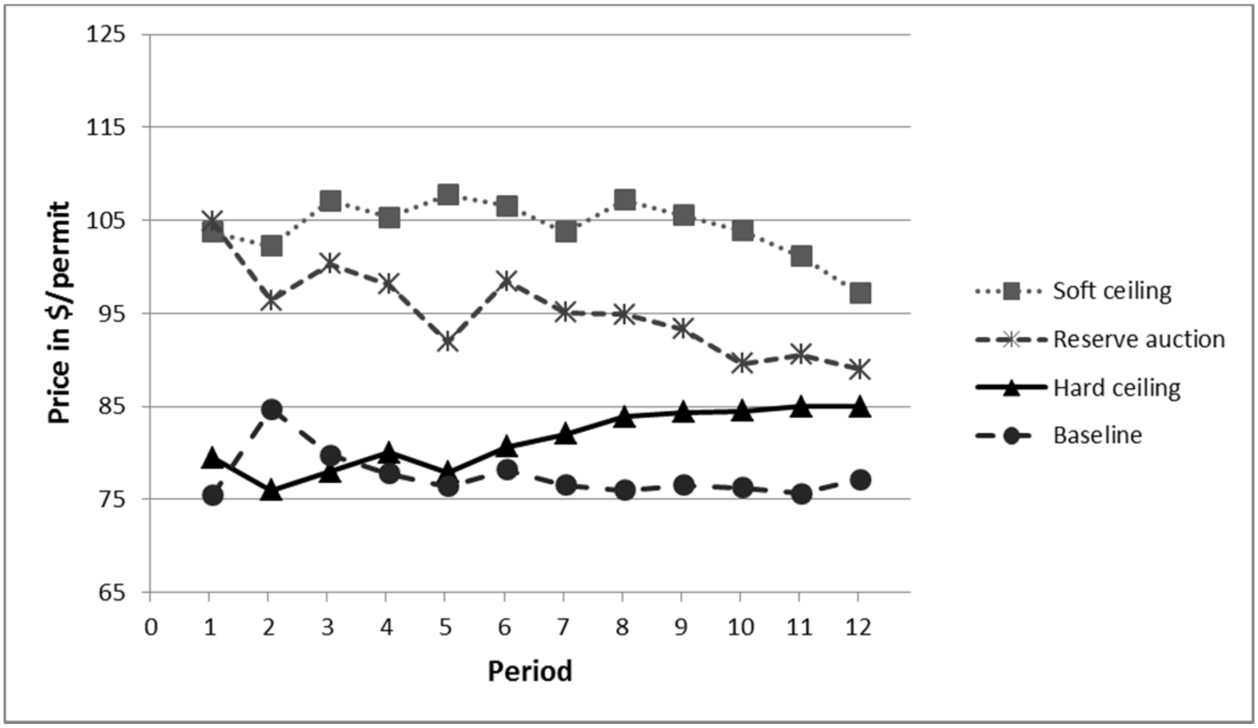
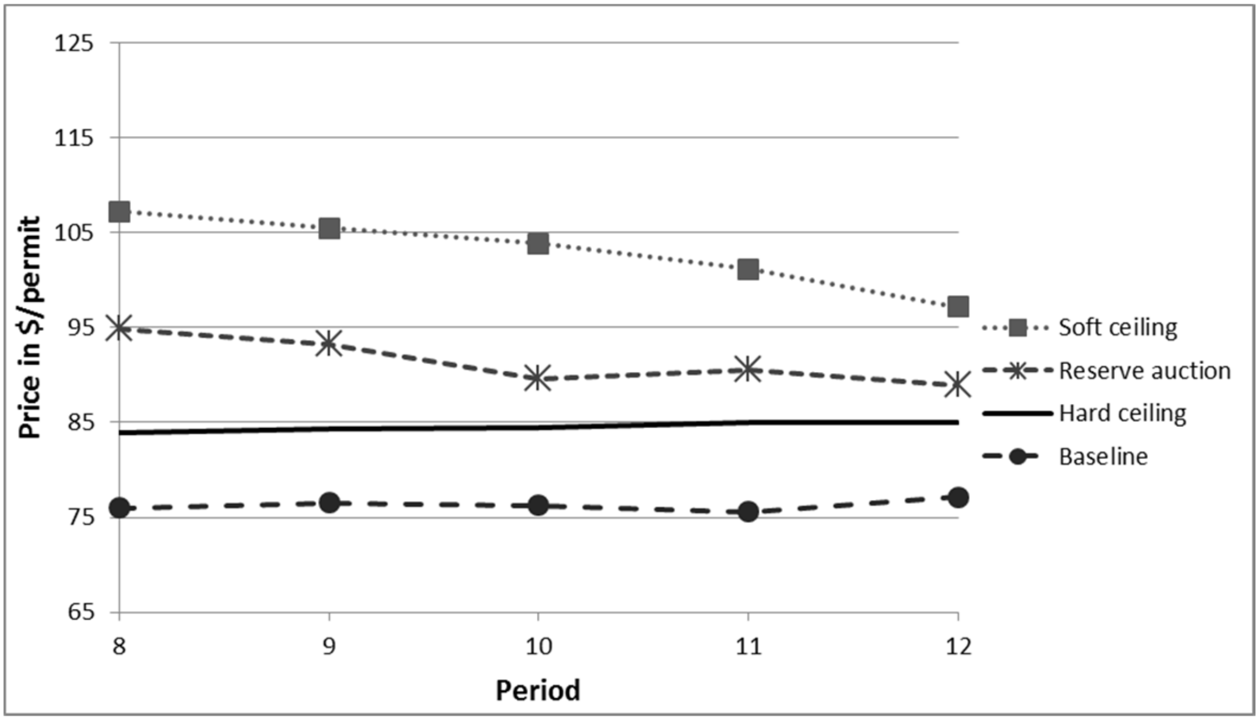


Figure 5 demonstrates that the hard ceiling treatment price converges on the target of $85.0, with the average market price in the final two periods equaling the ceiling price exactly. Past research assessing price ceilings in experimental markets has demonstrated eventual convergence of price with the ceiling under certain conditions, with more experienced subjects converging more quickly (Isaac and Plott, 1981). Our subject pool was drawn from students with no experience in emissions permit markets, and showed convergence speed commensurate with inexperienced subjects in other studies.

<ins>Result 2</ins>: In the baseline treatment with no price controls, prices attain the equilibrium price when the entire permit supply is provided in a single auction.

Figure 5: Mean of last 8 trades in initial auction for last 5 periods (all sessions)



Support: Table 1 reports Wilcoxon Signed Rank tests, a non-parametric test which compares the average initial auction price over the last 5 periods for each session to the target equilibrium price (85). For the baseline treatment this test does not reject the null hypothesis that mean prices equal the equilibrium level.

Table 1: p-values for main auction treatment comparison[a]
(non-parametric Mann-Whitney Test and Wilcoxon Signed Rank Test[b])

Treatment	**Soft Ceiling**	**Reserve Auction**	**Baseline**
Mean price, $/permit (std err)	103.0 (2.9)	91.5 (8.8)	76.3 (4.5)
vs. Reserve Auction	0.548		
vs. Baseline	0.008**	0.310	
vs. Equilibrium (85)	0.062#	0.438	0.188

a Session means based on final 8 trades of initial auction over each of the last 5 periods.
b The Wilcoxon Signed Rank Test is only used for comparisons to equilibrium.
significant at 10%
**significant at 1%

While non-parametric tests utilize data from the last 5 periods of each session, such tests do not differentiate data between periods. Therefore, any information regarding experience gained and its impact on mean and error correlations across periods is lost. Additionally, information from the first 7 periods is excluded. Given the visual evidence in Figures 4 and 5, which indicates that prices may still be decreasing slightly over time for the reserve auction and soft ceiling treatments, it is desirable to adopt a model which can differentiate estimates of prices in the initial auction for each period. Specifically, we adopt a model introduced by Noussair et al. (1995) and utilized in several applications to test for convergence of adjusting prices in experimental markets (Cason and Noussair, 2007). For each treatment i, Table 2 provides estimates for the mean price in the main auction for the first period with no experience (β_{i1}), for the end of session period based upon the price to which the model converges with maximum experience (β_{i2}), and for the change in price over the course of the experiment. The model is specified as follows:

$$\text{Price}_{jt} = \left(\sum_{i=1}^{n} \left(\beta_{i1} D_i (1/t) + \beta_{i2} D_i (1 - 1/t) \right) \right) + \varepsilon_{jt},$$

where i indexes the treatment, j indexes the session, t indexes the period,

$\text{Price}_{jt} \equiv$ mean of the last 8 prices of the initial auction in period t, session j,
$\beta_{i1} \equiv$ the parameter for the starting price in treatment i,
$\beta_{i2} \equiv$ the parameter for the asymptotic price outcome in treatment i,
$D_i \equiv$ the dummy variable for treatment i, and
$\varepsilon_{jt} \equiv$ the error term for session j in period t.

This model accounts for the time pattern of prices using the terms (1/t) and (1 – 1/t). In the first period when t = 1, (1 – 1/t) = 0 and 1/t = 1 so β_{i1} provides an estimate for the price at the start of the markets for treatment i. As t grows larger, (1/t) → 0 so β_{i2} provides an estimate for the price outcome approached in the limit for treatment i as t →∞.

Table 2: Estimates of the mean price in the main auction for
the first period (β_{i1}, t = 1), the end period (β_{i2}, t → ∞), and the change across periods[a,b]

$$\text{Price}_{jt} = \beta_{11}D_1(1/t) + \beta_{12}D_1(1-1/t) + \beta_{21}D_2(1/t) + \beta_{22}D_2(1-1/t) + \beta_{31}D_3(1/t) + \beta_{32}D_3(1-1/t) + \varepsilon_{jt}$$

Treatment Parameter	β_{i1}, t = 1	β_{i2}, t → ∞	β_{i2} - β_{i1}
	Mean Price ($/permit) test vs. equilibrium[c]	Mean Price ($/permit) test vs. equilibrium	Price Change ($/permit) test vs. 0
Soft ceiling ($\beta_{1.}$)	103.1 (2.1)	102.1 (2.4)	-1.0 (2.9)
	< 0.001**	< 0.001**	0.733
Reserve auction ($\beta_{2.}$)	104.4 (6.9)	90.6 (8.4)	-13.8 (5.4)
	0.005**	0.506	0.010**
Baseline ($\beta_{3.}$)	70.7 (3.0)	81.4 (4.4)	10.7 (5.9)
	< 0.001**	0.414	0.069#

a Mean prices and price changes are provided with standard errors in parentheses and p-values below.
b Robust standard errors are assumed based on session level clusters with an autoregressive correlation structure.
c p-values for estimates of the mean price are for tests against an equilibrium price of 85.
significant at 10%
**significant at 1%

Accounting for interdependencies between periods within each session requires the use of panel data regression methods. We define each of the 15 experimental sessions (excluding the single session testing the hard price ceiling) as a data cluster. A generalized linear model procedure is employed which provides robust standard errors based on an autoregressive structure to account for correlated errors within each session.

Table 2 shows that the baseline treatment β_{i2} estimate for asymptotic prices (t →∞) is 81.4, which is not significantly different from the equilibrium prediction of 85 (p-value=0.414). With experience, we cannot reject that subjects achieve the competitive equilibrium.

Result 3: The reserve auction alone appears to control prices to equilibrium after subjects have had time for price discovery. However, prices are elevated above equilibrium at the beginning of the price discovery process.

Support: For the Reserve Auction treatment, Table 1 shows a comparison of mean prices averaged over the last 5 periods for each session to the equilibrium prediction of 85 using the Wilcoxon Signed Rank test and to the baseline treatment using the non-parametric Mann-Whitney Test. No significant difference in the main auction prices is detected when compared to the equilibrium or the baseline treatment. The asymptotic price estimate of 90.6 (Table 2) can also not be rejected as being equivalent to the equilibrium price (p-value=0.506) or the baseline treatment (p-value=0.333, Table 3).

Table 3: Comparing estimates of the main auction mean price across treatments (β_{i2}, $t \rightarrow \infty$)[a]

Treatment	Soft ceiling	Reserve auction	Baseline
Mean price, $/permit (std err)	102.1 (2.4)	90.6 (8.4)	81.4 (4.4)
vs. Reserve auction	11.6 (8.7)		
	0.186		
vs. Baseline	20.7 (5.0)	9.2 (9.5)	
	< 0.001**	0.333	

a Differences between means are provided with standard errors in parentheses and p-values below.
**significant at 1%

In the early periods of the reserve auction treatment, prices are elevated (104.4) compared to the equilibrium (Table 2), rejecting the null hypothesis that first period prices equal the target price of 85 (p-value=0.005). As subjects gain experience, the prices decrease significantly (p-value=0.010) to 90.6. Thus, while the reserve auction alone does not provide absolute control of prices over all periods, it yields prices that are not significantly different from the competitive equilibrium once subjects have gained experience across trading periods.

The reserve auction treatment increases the complexity of the baseline in that cost minimization efforts must be balanced across two separate auctions. These results indicate that for experienced subjects, we cannot reject the hypothesis that the reserve auction can effectively control prices in the main auction.

Result 4: The soft price ceiling does not control prices as intended in the main auction. Prices are above equilibrium for both early and late periods.

Support: Non-parametric tests reject the null hypotheses that the soft ceiling price is equivalent to either the equilibrium price or the baseline treatment price (Table 1). Price estimates of the soft ceiling design are significantly elevated above the equilibrium price both for early and late periods (Table 2). The null hypothesis that prices are equal to the baseline treatment (Table 3, p-value < 0.001) is clearly rejected. Price estimates also do not change significantly over time (Table 2, p-value $= 0.733$).

(b) Session price trends and reserve auction prices

The data indicate that the hard ceiling controls prices in the main auction to the competitive equilibrium while the soft ceiling does not. However, there is still some uncertainty regarding how well the reserve auction alone actually controls prices, even though we cannot reject price control for this treatment. Recall from Table 2 that no statistically significant difference exists between prices in the main auction and the equilibrium price in either the baseline or the reserve auction only treatments. When analyzing transaction prices in individual sessions for each of these two treatments, some have prices predominantly below equilibrium while some have prices predominantly above. Only in the soft ceiling treatment do we observe average period prices consistently above the equilibrium price for all sessions. Therefore, the ability of sellers to consistently trade permits above equilibrium in the main auction must be attributable to the reserve auction having a price floor as in the soft ceiling design.

Result 5: The minimum reserve price of the soft ceiling increases trading prices in the reserve auction.

Support: Table 4 reports price estimates generated for the reserve auction using the same regression techniques as in the main auction. Reserve prices with a floor in the soft ceiling design are 96.0, significantly higher than equilibrium (p-value < 0.001). Reserve prices without a floor were not significantly different than equilibrium (p-value = 0.818).

Table 4: Estimates of the mean price in the reserve auction ($\beta_{i2,}$ t $\rightarrow \infty$)
and comparison to equilibrium[a]

Treatment	**Soft ceiling**	**Reserve auction only**
Mean price, $/permit (std err)	96.0 (2.1)	86.7 (7.3)
vs. Equilibrium (85)	11.0 (2.1)	1.7 (7.3)
	< 0.001**	0.818

a Differences are provided with standard errors in parentheses and p-values below.
**significant at 1%

Given that sellers receive better prices in the reserve auction and consistently better prices in the main auction with the soft ceiling design, it is useful to determine whether higher prices translate to improved welfare outcomes for sellers.

(c) Welfare gains from trade

Recall that permits were more heavily allocated to the 4 traders with low marginal costs of abatement in order to create a thicker market. Such traders became net sellers of permits while the other 4 traders with small initial permit allotments became net buyers. For each period, a subject's welfare gains are calculated as:

Revenue from permits sold – Marginal abatement costs realized from selling permits
– Cost of permits purchased + Marginal abatement costs avoided from buying permits

Welfare gains differ from total profits in that they do not include fixed period revenues or initial abatement costs before trading. Thus, welfare gains are completely determined by the trading decisions of subjects.

In an efficient market for this experimental environment, net buyers would purchase enough permits at the equilibrium price (85) to avoid any marginal abatement costs above this price. Similarly, net sellers would sell enough permits at the equilibrium price to incur any marginal costs below this price. The theoretical welfare gains for such an efficient market can be calculated for the aggregate of net sellers and net buyers separately. The proportion of efficient welfare gains realized is determined by calculating the ratio of actual realized welfare gains to theoretical efficient welfare gains. Note that this proportion can be greater than 1. For instance, if net buyers are able to consistently purchase permits below the equilibrium price, they could realize welfare gains greater than the efficient level at the expense of net sellers.

Result 6: The soft ceiling policy allows net sellers of permits to realize greater welfare gains than efficient levels at the expense of net buyers.

Support: The same regression model and panel data methods used to analyze prices are also used for welfare analysis, with the proportion of efficient welfare gains replacing average price as the dependent variable. We are interested in late period welfare gains after subjects have gained experience. Table 5 shows that under the soft ceiling, net sellers realize welfare gains 1.31 times the efficient level based on the asymptotic estimate for this model. This is consistent with the high prices observed for this treatment and significantly different at the 5% level and 1% level than the proportions for the reserve auction (0.87) and baseline (0.82) treatments respectively. As deadweight losses for the soft ceiling are not statistically different than the other two treatments (ranging from 0.14 to 0.20), this large welfare gain occurs at the expense of net buyers, who realize a gain of only 0.5 times their efficient level.[4] This low realized gain for net buyers in the soft ceiling treatment is significantly different at the 1% level from the proportions for the baseline (0.91) treatment.

[4] Deadweight losses are a proportion of efficient welfare gains from trade that go unrealized, and are considerably smaller when reported as a proportion of efficient total profits.

Table 5: Comparison of welfare gains from trade for end of session ($\beta_{i2,}$ t → ∞)[a]

Treatment	Soft ceiling	Reserve auction	Baseline
Proportion efficient gain realized (std err) Sellers	1.31 (0.05)	0.87 (0.21)	0.82 (0.12)
Difference vs. soft ceiling Sellers		-0.44 (0.22) 0.044*	-0.49 (0.13) < 0.001**
Proportion efficient gain realized (std err) Buyers	0.50 (0.07)	0.74 (0.14)	0.91 (0.05)
Difference vs. soft ceiling Buyers		0.24 (0.16) 0.139	0.41 (0.09) < 0.001**

a Differences between means are provided with standard errors in parentheses and one sided p-values below.
* significant at 5%
**significant at 1%

(6) Discussion

A hard ceiling provides an absolute maximum for prices, allowing the number of permits, and therefore the amount of emissions, to increase as much as needed when prices hit the ceiling. Some scientists, economists, and policy-makers have advocated for reserve auctions and soft ceiling designs, which have the desirable property of placing an absolute cap on emissions levels, while still providing some level of price control. A hard price ceiling could increase emissions considerably if the market price consistently hits the ceiling.

We have demonstrated that while a hard price ceiling can act as an effective price control, the soft ceiling fails to control prices to theoretical predictions under the conditions of our experiment. The evidence points to the presence of the minimum reserve price as the culprit for elevated prices in the main auction. The grandfathering of permits, in conjunction with the guaranteed minimum price in the reserve auction, allows net sellers to strengthen negotiating power in this multilateral trading institution, which translates to higher trading prices and greater welfare gains to sellers.

Previous research has also shown that the grandfathering of permits elevates prices compared to the direct auctioning of permits by the government (Goeree et al., 2010). In the reserve auction without a price floor, traders eventually converged on the equilibrium price. When the price floor was introduced, prices remained significantly higher than equilibrium. This is partly due to the nature of the soft ceiling, which does not allow for price deviations below the equilibrium in the reserve auction. Interestingly, the elevated prices carried over into the main (or initial) auction even though it places no restrictions on prices. By contrast, when the reserve had no minimum price, we observed some sessions in which sellers traded below equilibrium in the main auction and some in which they traded above. Sellers were not able to consistently elevate prices without the guarantee of the minimum reserve price. As a result, only in the soft ceiling treatment did sellers achieve significant welfare gains at the expense of buyers.

Another concern relates to elevated prices in the main auction for inexperienced subjects. We observed such price increases for both reserve auction treatments, regardless of the presence of a minimum reserve price. From the data, it cannot be determined whether high prices are due to inexperience with the trading mechanism or inexperience with the static demand and supply conditions in the market. If the latter contributes in any way, this would further hinder the ability of the soft ceiling to control prices in a dynamic setting.

Our results raise serious concerns regarding legislation that combines a soft ceiling design with the grandfathering of permits. This design is not an absolute price control in theory, and our results indicate that it actually elevates prices compared to theoretical predictions. If absolute price control is the primary goal, a hard ceiling would be preferred. Alternatively, if the reserve auction is desired to control the absolute level of admissions, eliminating the minimum reserve price or the grandfathering of permits would be beneficial to controlling prices, although more study is required for verification.

An alternative policy not studied here could provide the best of both worlds. Such a hybrid policy would utilize a hard price ceiling for short term price stability, and the ceiling level could be adjusted periodically to achieve cumulative emissions targets. Unlike other pollutants which may be toxic based on flow levels to the environment within each period, the deleterious nature of greenhouse gases is determined by stock amounts within an ecological system. This affords regulators utilizing a hard ceiling system the flexibility to manage greenhouse gas levels across periods without extreme concern for emissions spikes within a given period. In such a system, quantity control adjustments of the hard price ceiling could replace the discount rate adjustments currently proposed in most legislation. The rule for making adjustments should be well-defined and clearly communicated so as not to introduce additional uncertainty to permit markets.

A similar approach has been recommended by Metcalf (2009) for emissions taxes, with the tax adjusted yearly to a greater or lesser extent as a function of proximity to cumulative emissions benchmarks. Adjusting a hard price ceiling yearly using similar criteria would avoid the artificially inflated prices of the soft ceiling while providing for control of cumulative emissions over time. Furthermore, allowing the market to set prices within a controlled price range would provide more information regarding price discovery than Metcalf's variable tax.

Acknowledgments

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Appendix: Experimental Instructions

Attached are the instructions for the soft ceiling treatment as presented to subjects at the beginning of an experimental session. A sample record sheet is also included.

Instructions

General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of _200__ Experimental Dollars = 1 real Dollar. Notice that the more Experimental Dollars that you earn, the more cash that you receive at the end of the experiment.

We are going to conduct a number of periods. Attached to these instructions you will find a sheet labeled Personal Record Sheet, which will help you keep track of how your decisions impact your earnings. You are not to reveal this information to anyone. It is your own private information.

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

At the beginning of each period you will receive cash in the form of a Fixed Period Revenue. There will then be two coupon trading stages during which time you may purchase or sell coupons with other participants. (Each of you will receive coupons before one or both trading stages so that you have something to trade.) At the end of each period you will pay your production costs. Your earnings each period are determined as follows:

Earnings = Fixed Period Revenue – Total Production Costs
+ Sale Proceeds from Selling Coupons – Amount Spent when Buying Coupons.

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

Production Costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs may or may not be different from the costs of other participants. Your production costs are always shown on the left side of your computer screen, as illustrated in Figure 1 (the numbers on this example screen are different from the actual numbers used in the experiment, and you won't actually learn your values until the experiment begins). Everyone can produce up to 10 units, and the cost of each unit is written separately.

For example, based on the numbers shown in the *example* in Figure 1, your first unit produced would cost 100, your second unit produced would cost 200, etc. If, for example, these were your production costs and you produced 3 units, your **total** costs would be 100+200+300=600. So you must recognize that the costs shown on your screen are the **extra** costs associated with each **additional** unit produced.

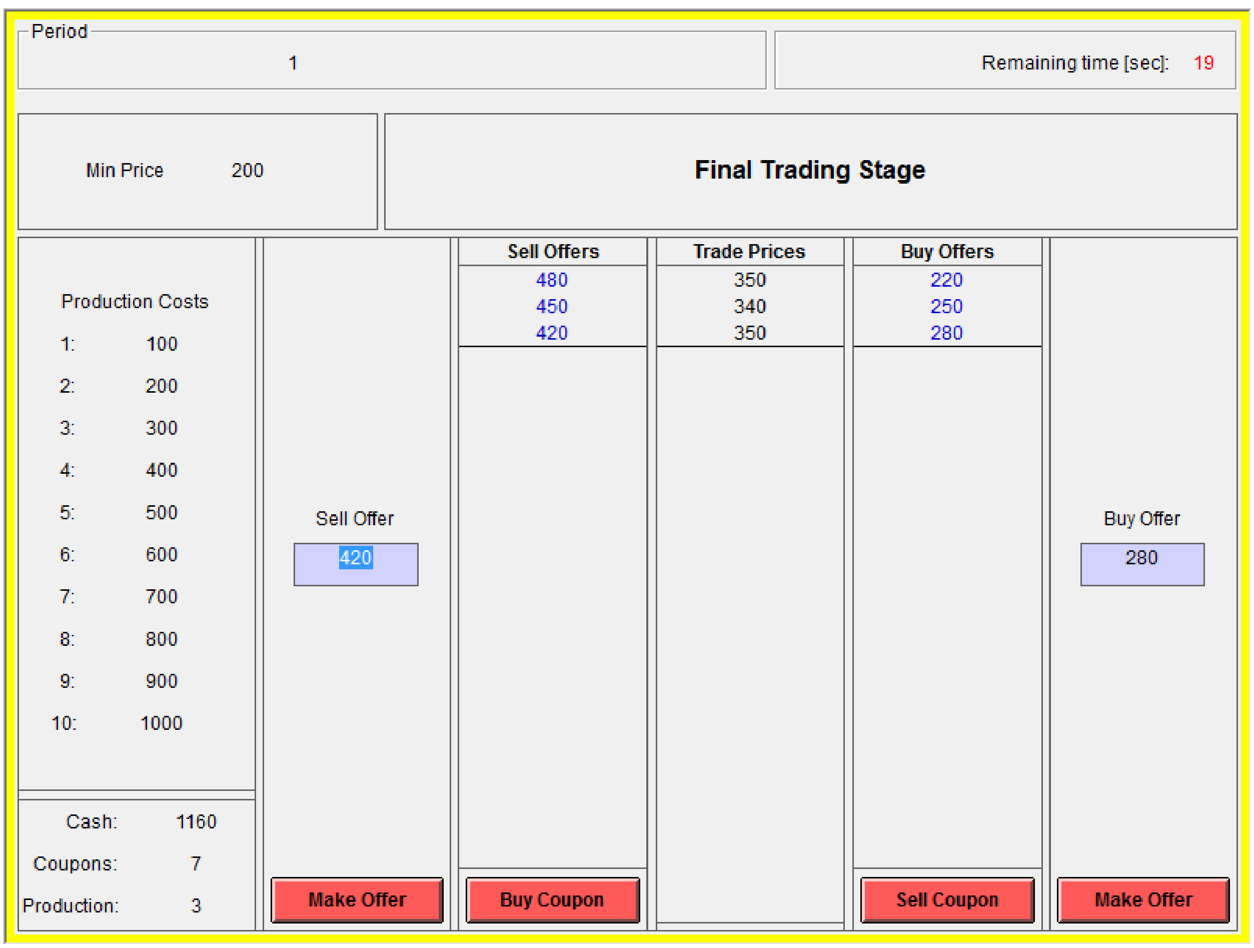

Figure 1

Coupons

We've already explained that your Fixed Period Revenue never changes, but your costs increase when you increase production. So why should you ever produce any units? The reason comes from today's compliance rule:

Compliance Rule: The sum of your production amount + coupons must equal 10

This rule means that you can avoid production (and save on your production costs) by holding coupons. Anyone can adjust their own holding of coupons by buying and selling them in a market that will operate over the computer network. If you sell coupons your cash increases by the sale amount, and if you buy coupons your cash decreases by the sale amount. Later in these instructions we explain the rules for buying and selling coupons.

Why might you want to buy a coupon? <u>Remember that coupons allow you to avoid production, and they are always applied to the most expensive production first</u>. If you currently hold 7 coupons, for example, and if you had the example production costs shown in Figure 1, then the last unit that you are supposed to produce is the 3rd unit (so that your production of 3 + coupons of 7 = 10). The production cost of this 3rd unit is 300. So if you can buy a coupon for less than 300, this might be a good idea since it allows you to save the production cost of 300. For example, if you bought one additional coupon for 280, you save the production cost of 300 and therefore make a profit (because of the lower costs that you need to incur) of 300-280=20.

Why might you want to sell a coupon? Continuing the illustration based on the example production costs shown in Figure 1, suppose that you currently still hold 7 coupons and the cost of the last unit produced is still 300. If you had 1 less coupon, the cost of the next unit produced (the 4th unit) would be 400. If you can sell a coupon for more than 400, this might be a good idea since these sales revenues exceed the production costs of this 4th unit. For example, if you sell a coupon for 420, even if you incur the additional (4th unit) production cost of 400 you would still make a profit on this sale of 420-400=20.

Coupon Trading Stage: How to Buy and Sell Coupons

During the trading stage, coupons can be purchased from and sold to other participants. At any time during the trading stage, everyone is free to make an offer to buy a coupon at a price they choose; likewise, everyone is free to make an offer to sell a coupon at a price they choose. Also at any time during the period, everyone is free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best offer price specified by someone wishing to buy. (Of course, there are some limits: to sell a unit or make a sales offer, you need to have a coupon to sell. And to buy a unit or make a buy offer, you need to have enough cash to pay.)

You will enter offer prices and accept prices to execute transactions using your computer. Figure 1 (displayed again on a separate sheet for your convenience) shows the market trading screen for one of the coupon trading stages. The time left in the period is shown on the upper right of the trading screen. You will have 2 minutes to buy and/or sell coupons in each trading stage.

Buying coupons

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

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

Another way to buy coupons is with the "Buy Coupon" button. Anyone wishing to buy can accept the best (that is, lowest) sell offer price by simply clicking the "Buy Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you buy coupons, your coupon and cash totals will be updated at the time of purchase. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Selling Coupons

Participants interested in selling can submit offer prices using the “Sell Offer” box on the left side of the screen, and then clicking on the “Make Offer” button below this box. This offer price is immediately displayed on all traders’ computers on the left part of the screen, labelled “Sell Offers.” Once this offer price has been submitted, it is binding in the sense that anyone wishing to buy can accept this price offer. Such an acceptance results in an immediate trade at that price.

If there are already Sell Offers displayed in the current period, then new sell offers submitted by anyone wishing to sell must provide better trading terms to the buyers. Buyers prefer lower prices, so any new sell offers must be lower than the current lowest sell offer. Your computer will give you an error message if you try to offer a higher price than the best price currently available.

Another way to sell coupons is with the “Sell Coupon” button. Anyone wishing to sell can accept the best (that is, highest offer price) by simply clicking the “Sell Coupon” button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you sell coupons, your coupon and cash totals will be updated at the time of sale. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Period Structure

This experiment will consist of 2 practice periods followed by 12 paid periods. Each period is identical and will include the following steps in Figure 2:

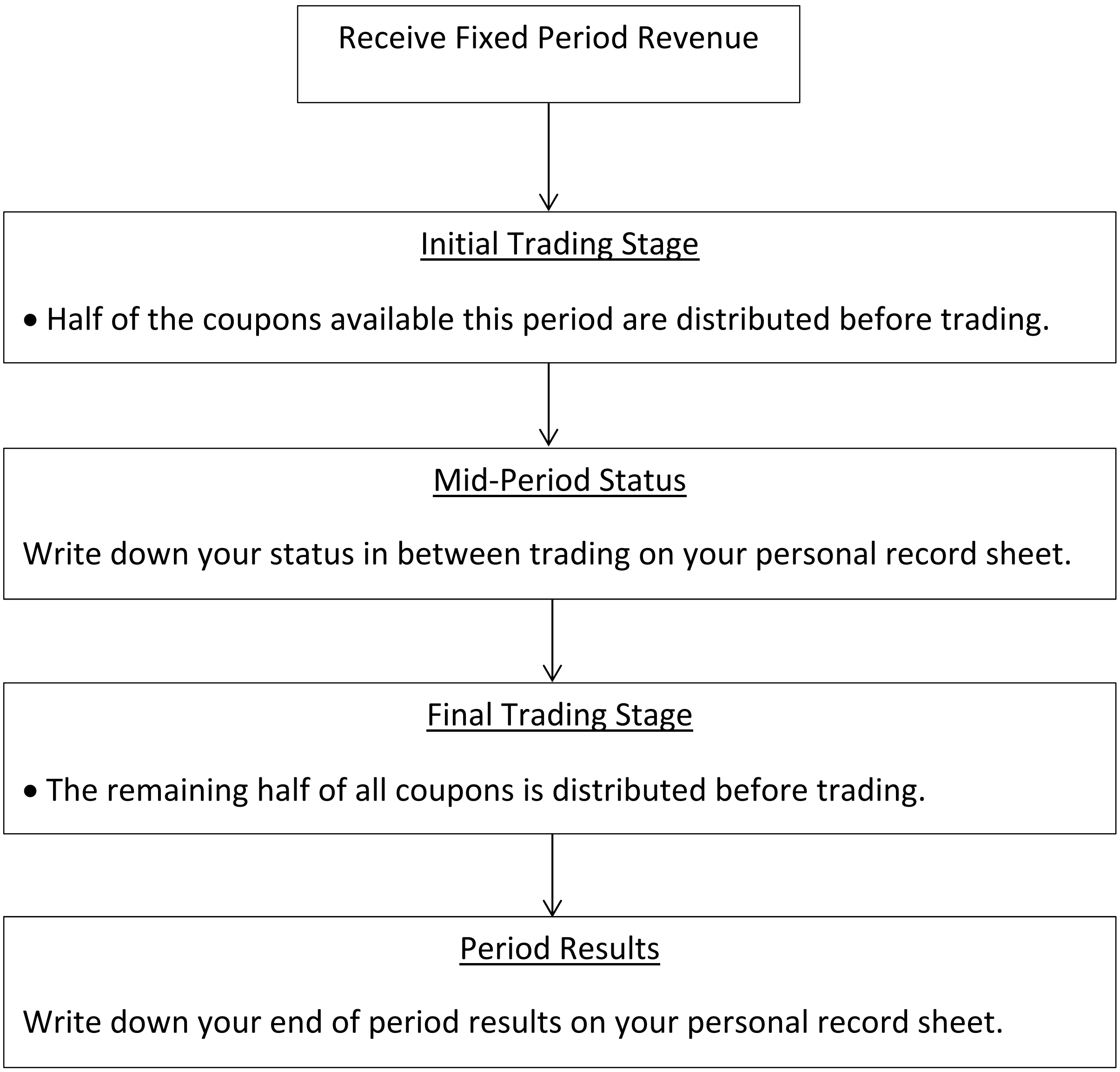

Figure 2

Initial Trading Stage and Minimum Prices

During each period, you will have two separate trading stages during which you may choose to buy and/or sell coupons, an "Initial Trading Stage" and a "Final Trading Stage," each lasting 2 minutes. Each trading stage will also have a "Min Price," which is the minimum or lowest price at which a coupon can be purchased or sold. During the Initial Trading Stage, the Min Price and the Min Price Next Stage are listed in the top left corner of the screen (Figure 3).

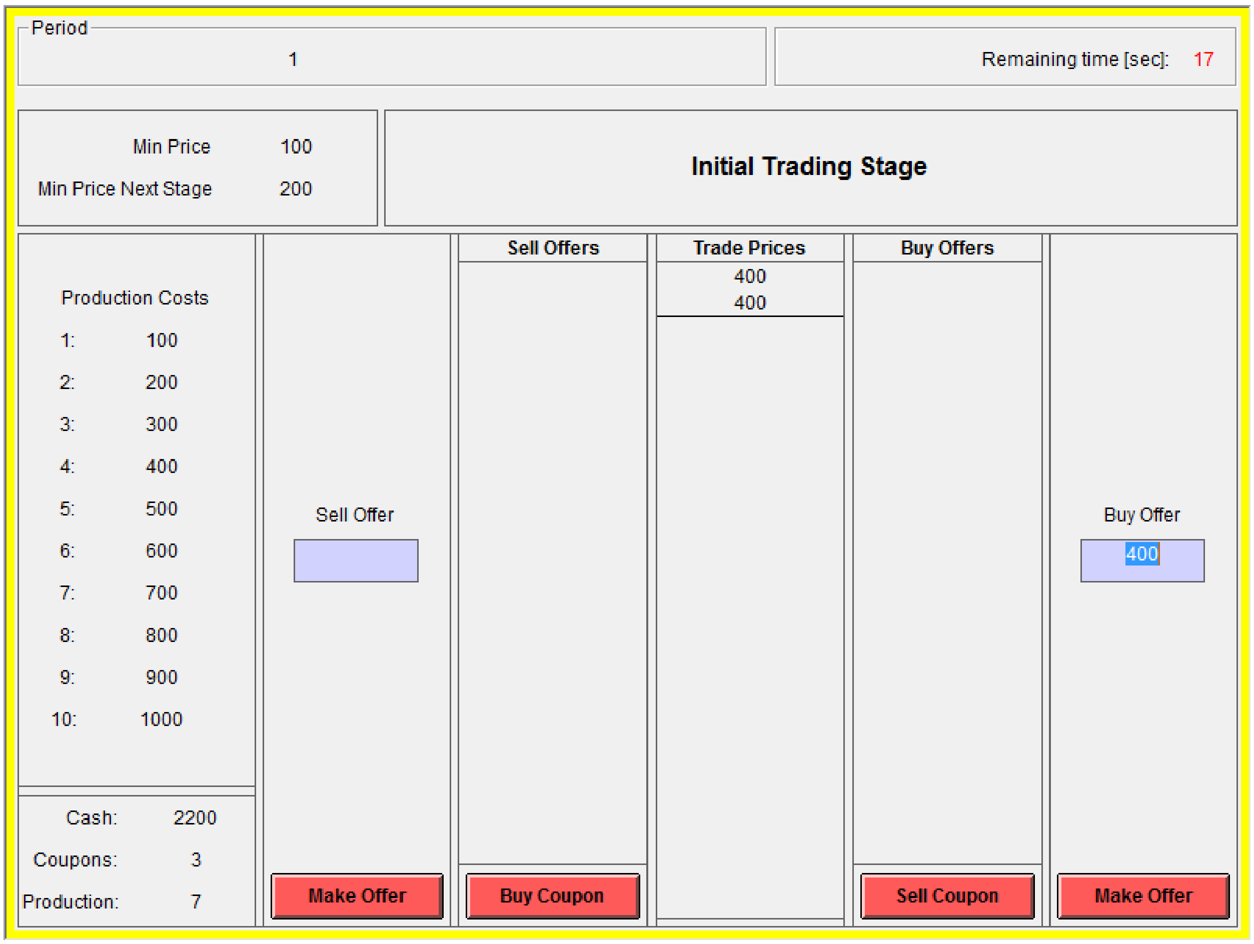

Figure 3

In the example in Figure 3, you would be trading in the Initial Trading Stage with a minimum price of 100, knowing that the minimum price in the Final Trading Stage will be 200. Suppose you wished to purchase a coupon for 150. You would only be able to make this trade in the Initial Trading Stage since the minimum price during final trading would be higher than 150.

Mid-Period Status and Coupon Distribution

Each period, coupons will be distributed to participants at the beginning of both trading stages. Half of all coupons will be distributed amongst participants before the Initial Trading Stage, with the remaining half distributed before the Final Trading Stage. (Your personal coupon amounts are already on your record sheet.) The Mid-Period Status screen (Figure 4) will provide you with a summary of your coupon levels. You will enter this on your record sheet.

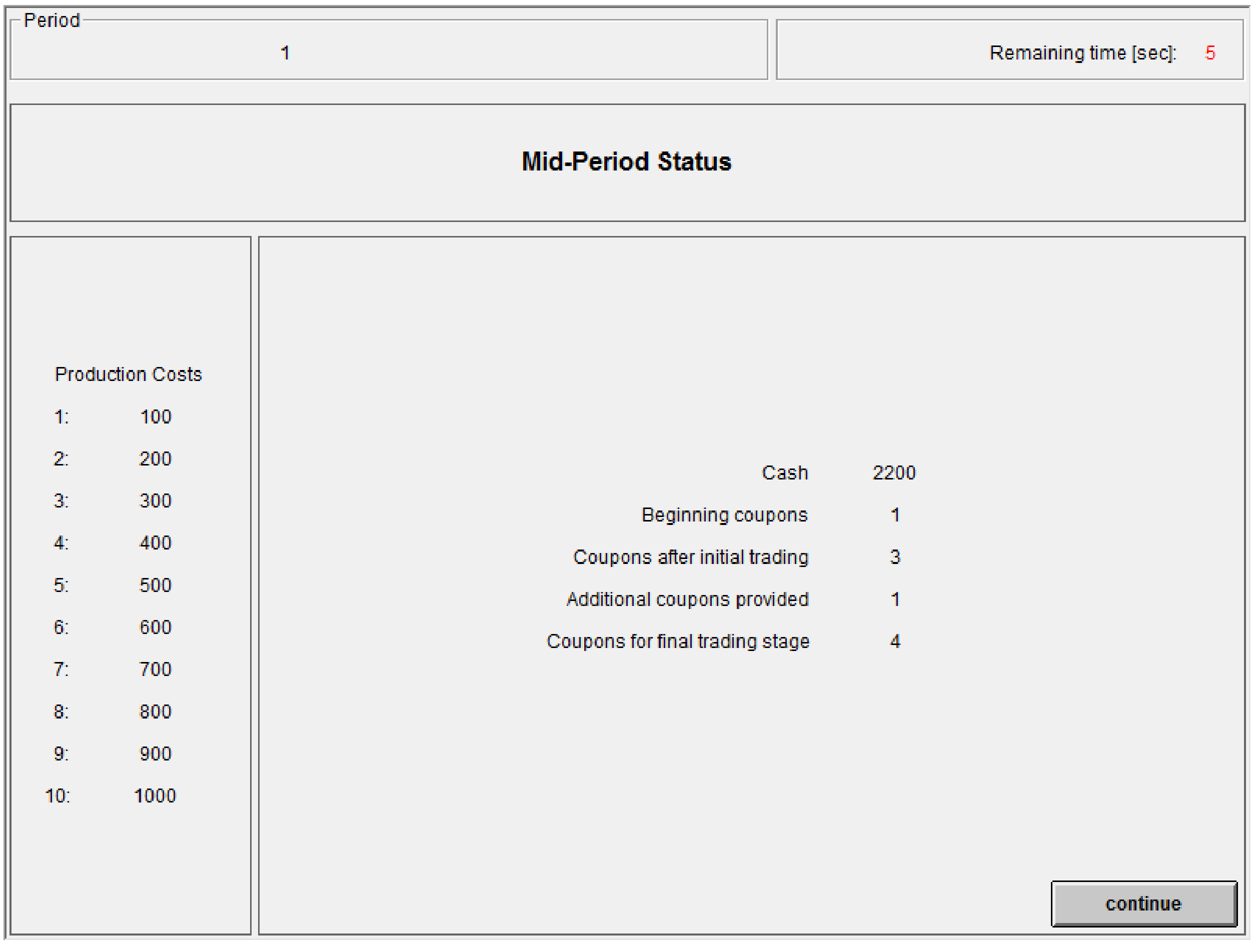

Figure 4

In this example, you started the Initial Trading Stage with 1 coupon and held 3 coupons after initial trading was complete. You receive 1 additional coupon, bringing your total coupons to 4 for the start of the Final Trading Stage.

Once you have recorded the Mid-Period Status information, you can hit the continue button.

Final Trading Stage

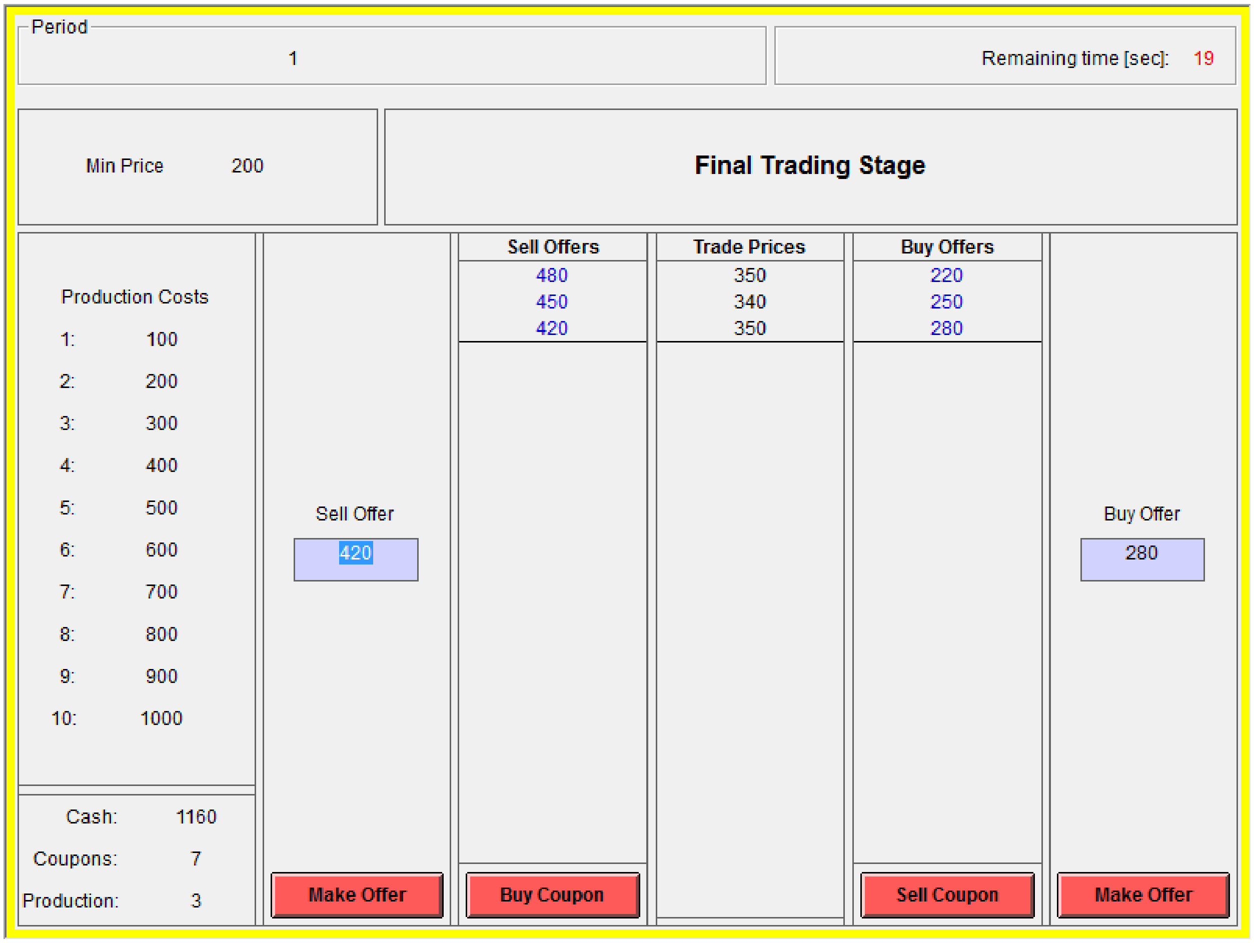

Figure 1 (repeat)

The Final Trading Stage screen is similar to the other trading screen. Note that the Min Price in this example is 200, as you were told it would be from the previous trading stage. This confirms that the lowest price at which a trade can now be made is 200. Any offers made below 200 would be rejected.

Period Results

Once trading has been completed, the results of the period will display on the screen. You should copy this information onto your Personal Record Sheet at the end of each period, and then click "continue" to begin the next period.

Figure 2 provides an example of the information provided in the period results. In this example, you have accumulated 7 coupons and are therefore required to produce 3 units of the good based on the compliance rule (7 coupons + 3 units produced = 10). Your actual production level is determined automatically by the computer using this compliance rule.

Since you produced 3 units of the good, your total production costs are the sum of the costs for each of the first three units (100 + 200 + 300 = 600). Note that your production costs are still listed on this page in order to help you assess your strategies for buying and selling coupons during the trading stages. Lastly, your period and total profits are provided.

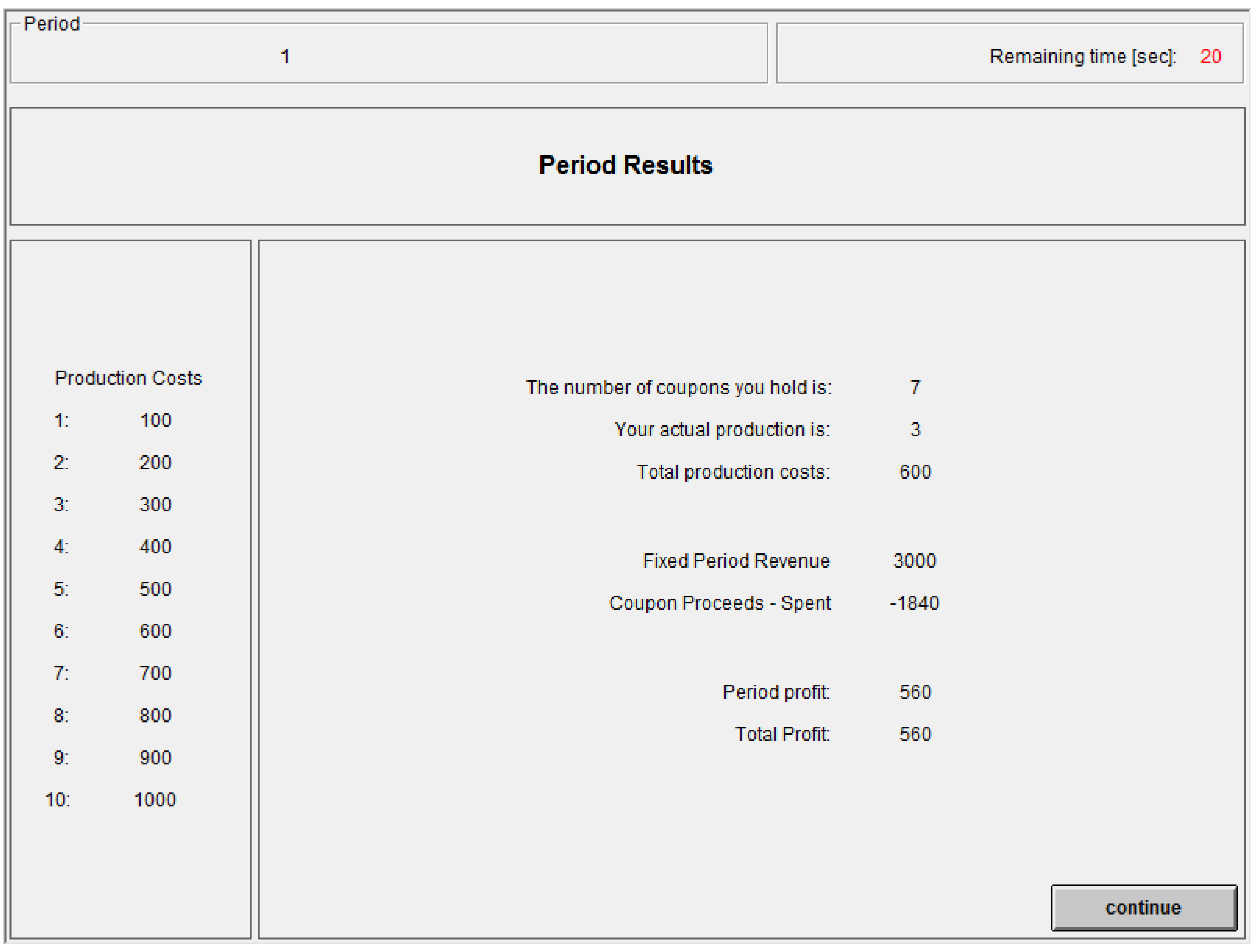

Figure 5

Summary

- Your production costs shown on the left of your computer screen are the extra, additional costs incurred for each unit that you produce.
- To be in compliance, your coupons + units produced = 10.
- There will be 2 trading stages. During either trading stage, coupons can be purchased or sold by anyone at any price above the Min Price listed on the screen. The Min Price will be higher for the Final Trading Stage.
- Half of all coupons will be distributed before initial trading with the remaining half distributed before final trading. You might be provided with coupons at the beginning of either trading stage during each period.
- Your current cash and coupon holdings, as well as the corresponding production level, are always provided during trading on the bottom left of your computer screen.
- Your coupon receipts and changes in coupon levels will be provided during the Mid-Period Results stage in between the 2 trading stages.
- Your coupon holdings, actual production level, and period profits will be provided during the Period Results stage at the end of each period. No coupons or cash will be carried over into the next period for use in trading.

Please note that while you cannot purchase coupons if you do not hold enough cash, you can have a negative profit for a period if your production costs are greater than your available cash after trading. Once we begin the experiment you should be careful to maintain positive cash holdings, since anyone whose period profit is below zero for 3 consecutive periods will be considered bankrupt and will no longer be allowed to participate in the experiment.

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

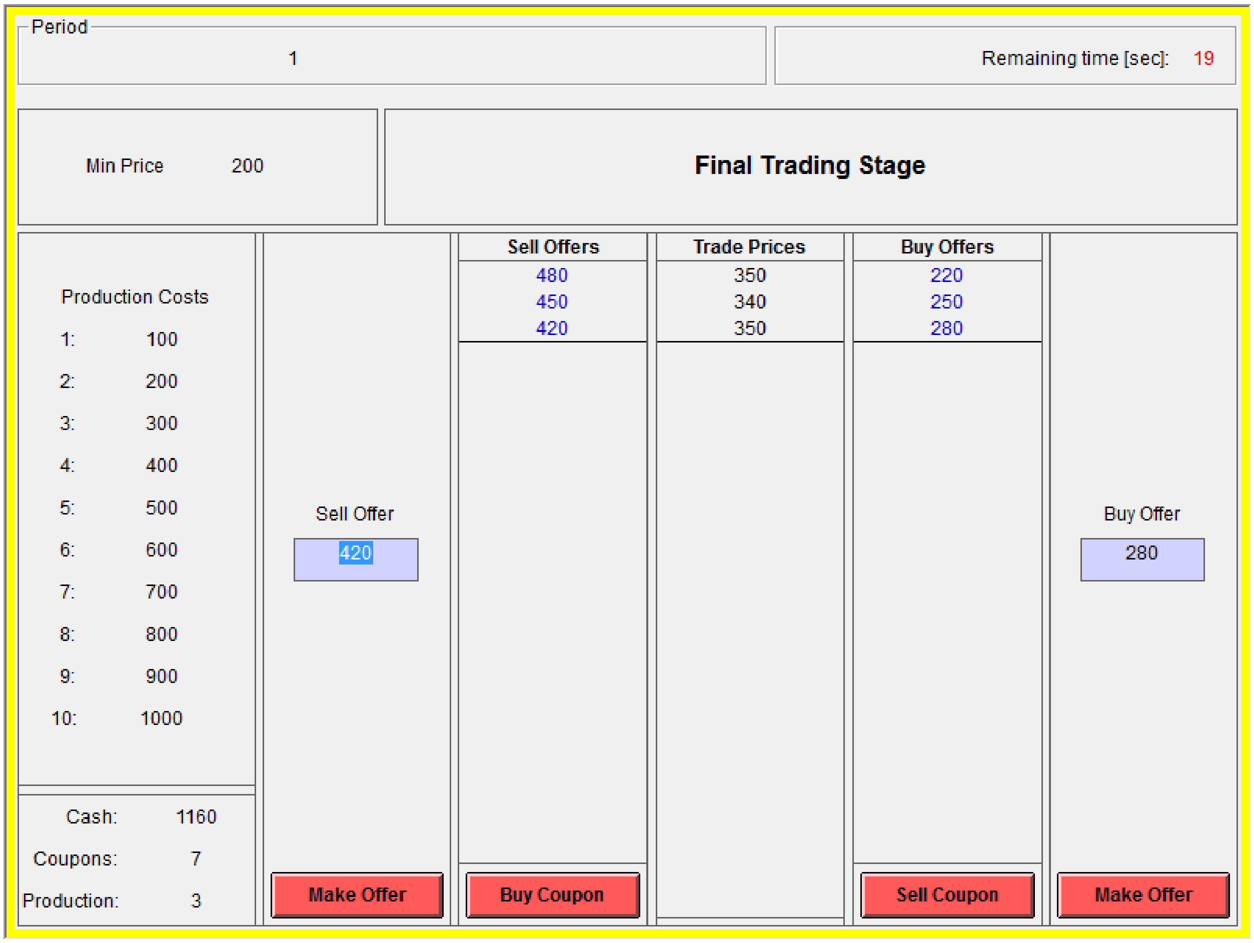
Period
1
Remaining time [sec]: 19
Min Price 200
Final Trading Stage
Production Costs
1: 100
2: 200
3: 300
4: 400
5: 500
6: 600
7: 700
8: 800
9: 900
10: 1000
Cash: 1160
Coupons: 7
Production: 3
Sell Offer
420
Make Offer
Sell Offers
480
450
420
Buy Coupon
Trade Prices
350
340
350
Buy Offers
220
250
280
Sell Coupon
Buy Offer
280
Make Offer

Figure 1

Personal Record Sheet for Subject ID _________

	Mid-Period Status					**Period Results**						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1220			Practice
2		1		0					1220			Practice
1		1		0					1220			
2		1		0					1220			
3		1		0					1220			
4		1		0					1220			
5		1		0					1220			
6		1		0					1220			
7		1		0					1220			
8		1		0					1220			
9		1		0					1220			
10		1		0					1220			
11		1		0					1220			
12		1		0					1220			
									Conversion Rate →	Total Profits / 200	Converted Total →	

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