Pollution Permit Consignment Auctions: Theory and Experiments[†]

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Abstract:

Unlike extant auction-based climate change markets, California's AB32 market utilizes a consignment auction design in which utilities are allocated a share of emissions permits that they must sell into the uniform-price auction. Auction revenue is returned to the consignee, which creates an incentive to increase the auction clearing price through strategic bidding. In a simple theoretical model, we show that consignees will accomplish this by overstating their quantity demanded in the auction, since this increases the probability that demand exceeds supply and the auction clears at a positive price. This results in inefficient allocations and inflated auction prices. We test this consignment mechanism through a series of lab experiments and confirm these predictions. We also find that overall firm profits are lower in a consignment auction, and that firms are more likely to incur penalties from program non-compliance due to allocative inefficiencies.

Keywords: Carbon Auction; Consignment Auction; Cap and Trade; Experimental Economics; Energy Policy; Environmental Policy; Auction Design

JEL Classifications: C90; C91; D44; D82; Q40; Q54

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1. Introduction

Throughout the past four decades, much scholarly work has been devoted to the study of market-based approaches to environmental policy, or 'emissions trading'. Much of the early work focused on tradeoffs between the various price-based approaches and standard regulatory approaches (Dales, 1968; Montgomery, 1972; Tietenberg, 2006). Since then, a number of inefficiencies associated with market-based approaches have been revealed. These include inefficiencies from political misallocation of emissions permits (Dewees, 2008; Ellerman et al., 2000), distortionary influences from regulatory governance (Arimura, 2002; Averch and Johnson, 1962), inefficiencies due to imperfect competition and market power (Hahn, 1984; Malik, 2002; Misiolek and Elder, 1989; Van Egteren and Weber, 1996), and distortionary interactions with deregulated electricity markets (Joskow and Kahn, 2002).

One difficult question is how permits in these markets should be initially allocated by the regulator. Early markets required the regulator to allocate the initial endowment of permits among existing firms ("grandfathering"), which created a complicated and contentious political process (Ellerman et al., 2000). More contemporary implementations auction off the initial allocations to the highest bidders. It is argued that auctions are more efficient, reduce tax distortions, provide more flexibility in the distribution of costs, provide greater incentives for abatement innovation, are fairer and, thus, reduce politically contentious arguments (Cramton and Kerr, 2002 and Burtraw and Sekar, 2014).

Here we caution that auctions can generate inefficiencies when designed poorly. If the regulator is willing to keep the revenues collected from the auction, then efficiency is not difficult to achieve: A sealed-bid auction with Vickerey pricing (or the ascending-clock variant of Ausubel 2004) gives full efficiency in equilibrium. A reasonable (though not fully efficient) alternative is to use uniform pricing, since it is transparent and sets a clear signal of the value of permits going forward.[1] But if the regulator is constrained to collect zero revenues (meaning revenues cannot be used to fund government activities or

[1] Studies of inefficiencies in emissions trading auctions have mainly been focused on strategic demand reduction under uniform pricing and imperfect competition (Ausubel and Cramton, 2002; Dormady, 2013; 2014; List and Lucking-Reilly, 1998; Weber, 1997).

reduce taxes), how should such an auction be modified? A naïve solution is to redistribute the collected revenue back to the bidders, as is done in the consignment process. But doing so distorts bidders' incentives and can generate serious inefficiencies. In general, any firm who will receive back more revenue than it will spend in the auction has an incentive to alter its bids so that total auction revenues are increased. In the case of consignment, these are exactly the net sellers who have more units to sell than they need to purchase.

Today's carbon markets in the U.S. utilize auctions for the initial allocation of tradeable permits, rather than grandfathering. Since 2008, nine East-coast states operate an auction-allocated carbon market known as the Regional Greenhouse Gas Initiative (RGGI) (see Dormady, 2013; RGGI, 2010). RGGI, which covers only the electricity sector, utilizes a non-consignment auction for the initial allocation of nearly 100 percent of its carbon permits. Revenues from the auction are used to either backfill state deficits or are invested in energy efficiency and renewable energy programs at the discretion of the state government. That revenue is not returned to the utilities or independent power producers (IPPs) that purchase the permits. Utilities pass through permit acquisition costs in their rate base, and IPPs pass through costs indirectly to utilities through wholesale markets.

Since 2012, California has been operating the Assembly Bill 32 (AB32) market in which consignment auctions are used quarterly to initially allocate permits to the electricity, natural gas and oil-refining sectors.[2] To prevent energy cost increases during a fragile recovery, California pre-allocates a fixed and significant quantity of permits to the main power distributors at zero cost. This is much like grandfathering, except these firms are then required to consign, or sell, all allocated permits into the quarterly permit auctions. The same firms also purchase from the auctions any permits they require for their own compliance. They receive the revenue from the sale of their consigned permits at the auction-clearing price and the revenues are required to benefit their respective ratepayers. This format of auction

[2] Through 2014, oil refiners have been extended waivers precluding their mandatory participation in the program due to fears that participation may cause gas price increases.

is a modified revenue neutral auction, similar to the Hahn and Noll (1983) auction, with the key difference being that only certain bidders (utilities) are allocated units to consign.

The divergence in auction design between the RGGI and AB32 markets has raised some new questions of efficiency in auction design more generally, and auctions as an allocative mechanism for emissions trading markets more specifically. Both markets utilize a second price uniform-price sealed bid auction format, but only the AB32 market uses consignment.

The efficiency implications of this consignment auction mechanism are presently unclear. Whereas in a typical uniform-price carbon auction, such as utilized in the RGGI market, it is clear that all firms have an incentive to bid strategically to acquire their emissions permits at the lowest possible cost, in a consignment auction it is not as clear cut. Those firms that consign a larger share of emissions permits than they need to purchase become net sellers of emissions permits in the market. Their incentives in the auction are distorted, so standard models of bidding behavior would not apply.

In June of 2014, the U.S. Environmental Protection Agency (EPA) released proposed rules to regulate greenhouse gases at the national level under the framework of the Clean Air Act. Under the Act, states are the compliance entities. The proposed rules currently allow significant flexibility, however they recommend carbon markets first above all other compliance approaches. These recommendations not only mention, but are based upon the existing structural designs of the RGGI and AB32 markets. There is significant national debate presently regarding which auction design is a model for the rest of the nation in compliance with the new rules. In addition, the European Union recently announced a directive to use auctions to allocate permits in all of its carbon markets. Thus, it is imperative that we understand what auction designs are truly efficient in this setting, and what pitfalls must be avoided.

In this paper we investigate the efficiency implications of this consignment auction design. We first study a simple theory of consignment auctions in which inefficiencies due to the consignment process are predicted. Then we test these predictions in controlled laboratory experiments on auction-based emissions trading markets. Our main treatment conditions compare the standard uniform-price auction to the uniform-price auction utilizing consignment. Our treatments also include differentiated production consisting of high and low emissions-intensity producers, allowing us to simulate alternative regulatory contexts to approximate East-coast and West-coast market conditions. We find that the consignment mechanism results in significantly higher auction-clearing prices across the board, as predicted by the theory. We also find that the consignment mechanism results in significantly lower efficiency, and that it is actually injurious to the profit of consigning firms.

Our findings are in partial contrast to existing empirical analyses of revenue neutral auctions. Prior work by Franciosi et al. (1993) and Ledyard and Szakaly-Moore (1994) reported on controlled laboratory experiments investigating the revenue neutral auction design. This work occurred during the design debates surrounding the use of auctions for small allocations of sulfur dioxide permits under the U.S. Acid Rain Program of the Clean Air Act.

Ledyard and Szakaly-Moore compare a revenue neutral auction to a double auction and find that the revenue neutral auction is less efficient than the double auction, and that it results in lower auction-clearing prices. When a monopolist is endowed with all available permits—and is therefore guaranteed to be a net seller—the revenue neutral auction continues to be less efficient than the double auction but now generates higher clearing prices. This finding is consistent with the intuition in our theoretical model, and broadly consistent with our experimental results.

Franciosi et al. compare the revenue neutral auction to a standard uniform-price auction and find that the revenue neutral auction results in higher auction-clearing prices; however their results do not hold at a high degree of statistical significance. And in stark contrast to the results presented here, they find the revenue neutral auction to be more efficient than the standard uniform-price auction. One possible reason for the difference in results between our paper and these is that our firms have a constant marginal value for permits (equal to the non-compliance penalty) and know with certainty whether they will be net buyers or net sellers. These differences stem from the fact that we take a short-run view in which firms cannot adjust pollution output in response to permit prices, while these other papers implicitly assume they can. How our theory would extend to the Franciosi et al. environment is not immediately obvious.

Our analysis does not consider the re-trading of permits, or the impact of permit prices on pollution abatement. Instead, we take a short-run view of a single quarterly auction. In this time frame we assume it is infeasible for firms to adjust their production levels or abatement technologies, so their value for a permit is simply the non-compliance penalty it avoids. A longer-run analysis would study whether or not re-trading solves initial auction inefficiencies, and how auction design might impact abatement innovation and pollution outputs, but is beyond the scope of our current work. Our goal is instead to highlight the short-run inefficiencies that can occur when auction revenues are refunded to bidders via the consignment process.

2. Experimental Design

The experiment is designed to test the efficiency of the consignment mechanism as utilized in a carbon auction, in comparison to a traditional non-consignment auction mechanism. We begin with a detailed description of the consignment mechanism.

2.1 The Consignment Mechanism

In a traditional Coasian market (see Fig. 1) the regulator sets a target annual emissions cap at the socially-efficient emissions level. That cap usually decreases annually at a fixed rate until the statutory target is achieved within a reasonable planning horizon. The regulator issues tradeable property rights (e.g., permits, credits, allowances) matching that annual cap, typically such that one emissions permit allows the holder to emit 1,000 tons of carbon dioxide equivalent (CO2e).

Auctions for the initial allocation of permits all utilize a non-discriminatory auction format: the uniform-price sealed bid auction, in which firms place a bid for both a price and a quantity of emissions permits. Bids are ranked by price from highest bid to lowest bid, and when the quantity of price-ranked bids meets the quantity of permits auctioned, permits are awarded to winning bidders at a uniform auction-clearing price. That uniform price is typically analogous to the second price auction rule (the highest losing bid). The revenue generated by the auction of these emissions permits is equivalent to the uniform auction-clearing price multiplied by the quantity of permits awarded. For a detailed description of the uniform price auction, see Milgrom (2004), Krishna (2009), and Dormady (2013).

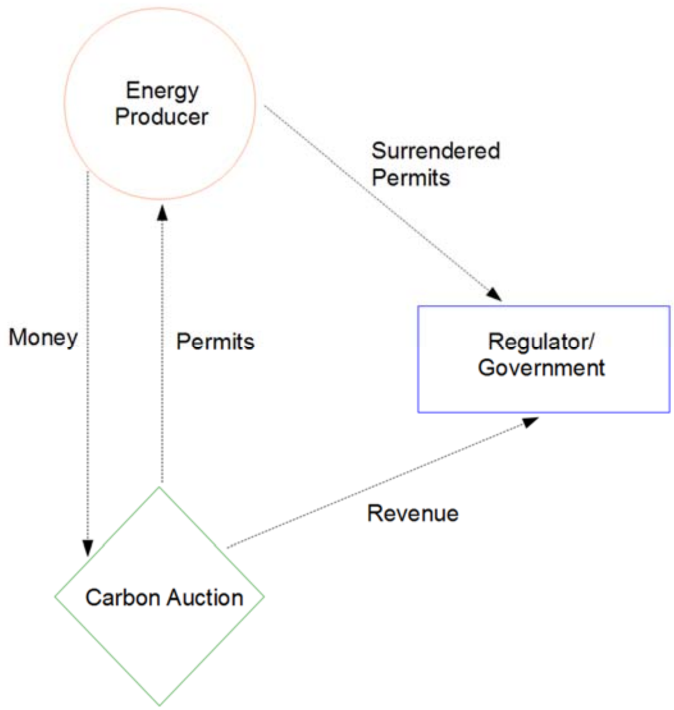

Figure 1. A Traditional Carbon Auction Design
(RGGI Inc., Waxman-Markey, Kerry-Boxer)

Under a consignment mechanism, the emissions permits are freely allocated to the utilities *before the auction* (see Fig. 2). The utilities are then required to consign, or sell, all of those allocated permits into the quarterly auction. The utilities then keep the revenue from the sale of those emissions permits. Firms purchasing emissions permits, including the consigning utilities, purchase emissions permits which they consigned, or which other utilities consigned. The revenue from consignment roughly offsets the cost of permit acquisition, so utility consumers see no cost pass-through. There are also typically other emissions permits sold in the auction by the regulator, from which the revenue goes to the state government. This is consistent with the accounting of emissions, as utility emissions are not the only emissions counted in the aggregate socially-efficient economy-wide cap.

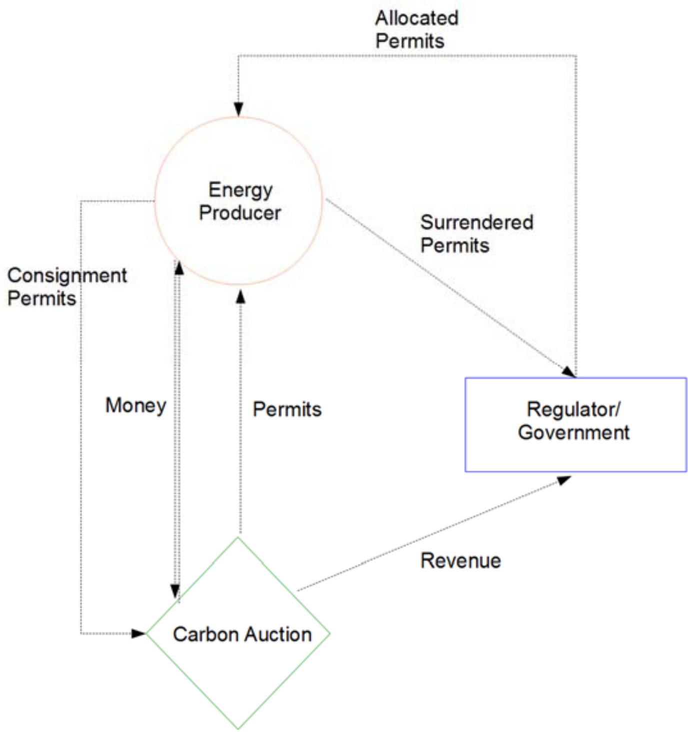

Figure 2. A Carbon Auction with Consignment
(California AB32)

2.2 Experiment Setup

The lab experiment simulates a Coasian permit auction under stochastic permit demand and a variety of treatment conditions. All treatments utilized the uniform-price sealed bid auction. In each session, 16 subjects participate for two practice periods and 51 actual periods, though they were not informed of the total number of periods.

At the start of the session, half of the subjects are randomly assigned to be a ‘High’ type, and the other half are assigned to be a ‘Low’ type. This type assignment remains fixed across all periods. In each period, the subjects are randomly matched into four groups of four, such that each group contains two High types and two Low types. Subjects are not aware of the identities of their competitors at any time; they only know that they are in a randomly-drawn group of four consisting of two High types and two Low types.

At the start of each period, each subject is randomly (and independently) assigned a production level of either 4, 5, or 6 units of energy, and are told that their firm must produce exactly this many units of energy. These values are broadly representative of low, intermediate and peak levels of energy production in the field.[3] Subjects receive revenue from their production: For every unit of energy they produce, they receive \$100 experimental. As such, in any period, subjects receive a fixed 'endowment' of production revenue that can be \$400, \$500, or \$600 experimental. Again, subjects have no choice in production; it is entirely determined by the random draw.

Production also creates pollution, and subjects need to purchase permits to cover the pollution they produce. The difference between High types and Low types is in the units of pollution emitted per unit of energy. High types emit two units of pollution for each unit of energy produced. Low types emit only one unit of pollution for each unit of energy produced. Thus, High types will demand twice as many permits as Low types for a given production level. These two types are broadly representative of coal and natural gas generation, respectively, which are the two main carbon-emitting sources of power generation today.[4] We refer to 'High' and 'Low' as the firm's *pollution type*, and 4, 5, or 6 as their *production type*. We view pollution types as publicly observable, while production types are private information. Note that pollution types are fixed throughout, that production types are redrawn each period, and that there is no correlation between pollution types and production types.

In each period, pollution permits are sold via the uniform price auction. Given the range of possible pollution types and production types, the aggregate permit demand in any period ranges from 24 to 36 permits. The aggregate supply of emissions permits sold at auction in any period is always 30 permits. Given the fixed supply of emissions permits, this design allows us to test our hypotheses for cases in which the permit demand exceeds and is exceeded by permit supply.

Subjects could bid for any quantity of emissions permits, irrespective of their individual pollution output. A subject holding a deficit of emissions permits at the end of the period incurs a non-compliance

[3] Peak production may also be broadly representative of low-hydro years in California, in which full generation output from fossil units is required to clear aggregate system-wide demand.
[4] Coal production is approximately twice (1.6 times) as carbon-intensive as natural gas production.

penalty of $50 experimental for each unit of pollution output greater than their number of permits on hand. Subjects face limited liability: if they lose money in a given period, their final profit for that period is adjusted to zero.

As stated above, we study here the short-run setting where firms are essentially locked in to their exogenously-given production and pollution levels. Abatement and production adjustments, if they were to occur, would be realized across periods and are therefore not included in our experimental design.

2.3 Treatments

The experiment includes four treatments (See Table 1). The control treatment is a baseline treatment in which no permit consignment is introduced. The remaining treatments include permit consignment that depends on firms' pollution types. Permit consignment consists of a pre-auction allocation of a fixed quantity of emissions permits to certain subjects, and entitles the allocated subject to the revenue from the sale of those permits at the auction's clearing price. In the main treatment of interest, all subjects are required to consign an allocated quantity of emissions permits. For robustness, we also study treatments in which only the High pollution types or only the Low pollution types consign permits.

In the main treatment group in which all subjects consign permits, High pollution types are allocated 10 permits and Low pollution types are allocated 5 permits. These represent the average permit needs for each pollution type. The firms are forced to sell their allocated permits in the auction (keeping the resulting revenue) and must purchase back any permits that they wish to use to cover their pollution output.

Table 1. Experiment Treatment Parameters

Treatment	Bidder (Type)	Energy Production	Permits Needed	Permits Allocated
Control - No Consignment	1 - Low 2 - Low 3 - High 4 - High	~U{4,5,6}	1 x Production 2 x Production	0
Treatment - All Consign	1 - Low 2 - Low 3 - High 4 - High	~U{4,5,6}	1 x Production 2 x Production	5 10
Treatment - Low Consign	1 - Low 2 - Low 3 - High 4 - High	~U{4,5,6}	1 x Production 2 x Production	5 0
Treatment - High Consign	1 - Low 2 - Low 3 - High 4 - High	~U{4,5,6}	1 x Production 2 x Production	0 10

With consignment, firms' incentives can vary widely depending on their production type. A firm with only 4 units of energy production receives more permits than they need, and therefore becomes a net seller of permits in the auction. They clearly prefer a higher auction price. A firm with 6 units of production does not have enough permits and becomes a net buyer, clearly preferring a lower auction price. A firm with 5 units is allocated exactly the number of permits that they need for their pollution output. By allowing production types to vary, we can study the impact these differential incentives have on bidding behavior.

In the treatment in which only Low pollution types consign permits, each Low type subject is allocated 5 permits. In the treatment in which only High pollution types consign permits, each High type subject is allocated 10 permits. Again, this creates net buyers and net sellers, depending on the realized energy production levels. Any bidder that is not consigning permits can also be thought of as a net buyer.

In each of the three consignment treatments, if the total quantity of permits sold at auction is less than the number consigned, then subjects receive the revenue from a quantity of permit sales equal to their proportional share of the total quantity consigned.

The High-only and Low-only treatments are broadly representative of markets with merchant coal and merchant gas production, respectively. These are also broadly representative of East Coast and West Coast markets, respectively. In very broad strokes, East Coast markets tend to consist of utilities generating native load mainly from coal power, with merchant gas supplying imbalance services and wholesale power acquisitions. The opposite is generally true in West Coast markets, in which utilities tend to generate more of their native load from gas and through tolling contracts or other agreements with merchant gas generation, for which they are responsible for pollution permits.

In actual permit markets the auction only determines an initial allocation of permits; firms are free to trade subsequently through bilateral exchange. Mutually beneficial trades may arise in practice as firms' production and pollution levels change over time. In our static setting, however, such trades would only be possible if the auction outcome is inefficient. Thus, we do not allow post-auction permit trading in our experimental design, and instead measure directly the frequency with which inefficient allocations obtain.[5]

2.4 Recruitment and Sampling

The experiments were conducted at the Ohio State University Experimental Economics Laboratory. Subjects were recruited by an email solicitation through the experimental economics subject pool at Ohio State. Subjects consisted entirely of undergraduate students in economics, as well as other majors across campus in the physical and natural sciences, and other social science disciplines. Subjects were matched to experimental sessions on the basis of their availability, and treatments were assigned randomly to scheduled sessions. Each subject participated in only one treatment.

[5] One potential weakness of our design is that, in practice, firms' expectations of re-trading may alter their bidding behavior. This depends on whether firms expect to make a profit in equilibrium through re-trades, which in turn is sensitive to things like bargaining power that are beyond the scope of our study. We therefore leave this as a topic for future work.

2.5 Experiment Operation

We conducted eight three-hour experimental sessions, excluding pilot sessions. Of these eight, we conducted two three-hour (approx.) experiment sessions for each of our four treatments. Each session began with a set of written subject instructions (see Appendix) and a walk-through of the user interface. Experimental software was programmed using the Zurich Toolbox for Readymade Economic Experiments (Z-TREE) and its companion client software application Z-leaf (Fischbacher, 2007). Subjects received two handouts consisting of the written instructions and a payment form, as well as consent forms.

3. Theoretical Demonstration and Hypotheses

3.1 Auctions with Consignment

To show how the consignment process causes inefficiencies in market outcomes, we solve for equilibrium of the permit auction with and without consignment in a setting that simplifies our experimental environment. We assume there are three firms in the market, and that all firms are of same type. When there is consignment, all firms are consigned ten permits, for a total of thirty permits available in the market. Firms need either eight permits or twelve permits to cover their pollution emissions. In our experimental context, this means we are restricting energy production levels to be either 4 or 6, and setting all three firms to be High types. Those that need eight permits are called 'net sellers' and those that need twelve are called 'net buyers'. Every firm is equally likely to be a net buyer or a net seller. Firms know which they are, but do not know whether their two competitors are net buyers or net sellers.

Any firm that does not acquire enough permits to cover their emissions must pay a non-compliance penalty of \$50 per unit of pollution not covered by a permit. Thus, all firms have a constant marginal value of \$50 per permit up their pollution output level, at which point their marginal value for permits drops to zero. This is common knowledge. Thus, firms are not uncertain about their competitors' value for permits; they are only uncertain about how many permits their competitors will demand.

Permits are sold via a uniform price auction, where each firm submits a quantity bid and a single price bid. (They cannot bid different prices for different units.) If the quantity bids of the three firms sum to less than 30 then there is excess supply. In this case, the clearing price is zero. Firms earn zero revenue from consigned units, and receive (for free) a number of permits equal to their quantity bid.

If the quantity bids of the three firms sum to 30 or greater then there is excess demand, and the clearing price equals the lowest winning price bid. All firms sell their ten consigned units at this clearing price and keep the resulting revenue. Firms whose price bid is above the clearing price purchase a number of permits equal to their quantity bid. Firms who bid exactly equal to the clearing price are then rationed: they are randomly ordered into a queue and sequentially purchase permits—up to their quantity bid—until 30 total units have been purchased. All remaining firms in the queue purchase zero units. Firms who bid below the clearing price also purchase no permits. All firms pay the clearing price on all permits purchased.

We solve for a quasi-symmetric Bayes-Nash equilibrium of this game.[6] Equilibrium bidding strategies for each type are summarized in Table 2. Both types of firms set price bids equal to their marginal value for permits ($50). Net buyers set quantity bids equal to their true permit demand (12). But net sellers bid for one more permit than they actually need (9).

Table 2. Equilibrium Bidding Strategies in the Three-firm Example

Firm Type	Permits Consigned	Permits Needed	Quantity Bid	Price Bid
Net Seller	10	8	9	$50
Net Buyer	10	12	12	$50

To understand this equilibrium—and why net sellers overbid in their quantity bid—consider a net seller facing two competitors whose types are unknown. There are two possible states of the world: no rationing (the sum of quantity bids is less than 30, so the clearing price is zero) and rationing (the sum of the quantity bids is at least 30, so the clearing price is $50). Net sellers clearly prefer a higher clearing

[6] Quasi-symmetric equilibria require that all firms of the same type choose the same strategy, though strategies may differ across types. We are confident that this is the only quasi-symmetric Bayes-Nash equilibrium, though asymmetric equilibria may also exist.

price, but in both states of the world they cannot increase the clearing price through their price bid. If they increase their price bid above $50, the competitors' bids will set the clearing price.[7] This is true whether that clearing price is $50 (under rationing) or $0 (no rationing). But by increasing its quantity bid, the net seller can increase the chance that rationing occurs, thus increasing the chance of the clearing price equaling $50 instead of $0.

To see how this works, first calculate the possible quantity bids that the two competitors might submit in this equilibrium. If they are both net buyers (which happens with 25% probability), their quantity bids will sum to 24. Our net seller would only need to bid for 6 units to trigger rationing and get a $50 clearing price. If one competitor is a net seller and one a net buyer (which happens with 50% probability), their quantity bids will sum to 21, and so our net seller would need to bid for 9 units to trigger rationing. Finally, if both competitors are net sellers then their quantity bids will sum to 18, and our net seller would need to bid for 12 units to trigger rationing. A 'truthful' quantity bid of 8 will only trigger rationing in the first case—25% of the time. A 25% chance of selling two units (net) at $50 apiece is worth $25 in expectation. An 'overstated' quantity bid will trigger rationing in two of the three cases—75% of the time. However, it also decreases the net number of units sold by our seller down to one. But the tradeoff is worth it: a 75% chance of selling one unit (net) at $50 is worth $37.50 in expectation, greater than the $25 expected profit from truthful bidding.

Net buyers could similarly underbid their quantity. This would decrease the chance of rationing, thus lowering the expected price on permits they must purchase. But it would also expose the firm to a non-compliance penalty. With our parameters, this penalty far outweighs any benefit of lowering the expected clearing price, so net buyers prefer to bid truthfully.

Finally, we must verify that net buyers would not want to lower their price bid. Doing so would drop the clearing price, but also make them the lowest price bidder, exposing them to rationing. If the other two competitors are net buyers, then they will purchase 24 units, leaving only 6 for the deviating net

[7] If the net seller also increased its quantity bid to at least 30 then it could affect the clearing price by changing its price bid. But in buying all 30 units, it would effectively become a net buyer and no longer prefer to raise the clearing price.

buyer. At that point our net buyer becomes a net seller, and no longer wants to have a lower price. If one competitor is a net buyer and one is a net seller, they purchase 21 units, leaving only 9 for the deviating net buyer. Again, our net buyer becomes a net seller and no longer prefers the lower price. Only if the two competitors are both net sellers does our deviator remain a net buyer, but this possibility is sufficiently rare (25% probability) that the deviation is not worthwhile.

Pareto efficiency in this market is violated if and only if one firm holds an unneeded permit while another pays a non-compliance penalty (NCP).[8] If all firms submit truthful quantity bids then the outcome would be Pareto efficient. In the equilibrium of this game, however, the overbidding by net sellers creates the potential for inefficiencies. If a net seller receives its quantity bid while a net buyer has its quantity rationed (by being last in the rationing queue), an inefficiency occurs. With our parameters, this occurs 25% of the time.[9] In dollar terms, the expected efficiency loss is 25% of $50, or $12.50.

The total number of non-compliance penalties realized is also slightly larger in this equilibrium than under truthful bidding. If bidders bid truthfully, we expect 1.5 non-compliance penalties on average (6 if there are three net buyers and 2 if there are two net buyers and one net seller). In equilibrium, it increases slightly to 1.75 penalties on average. Again, this is due to the inefficient rationing that can occur when net sellers overbid their quantity.

3.2 Auctions with No Consignment

When there is no consignment, all firms become net buyers. By the same arguments as above, these firms have no incentive to reduce their quantity bid because the non-compliance penalties are too prohibitive. But they do have an incentive to decrease their price bid. In the consignment case, decreasing the price bid turns net buyers into net sellers due to rationing. Without consignment this does not occur, so all firms have a strong incentive to underbid on price. Conditional on underbidding all competitors, the

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[8] In that case the firm with the unneeded permit could sell it to the firm paying the NCP at any price between $0 and $50, making both better off.

[9] Specifically, it happens if there are two net buyers and one net seller (which occurs with probability 3/8) and the net seller is not the one who gets rationed (which occurs with probability 2/3). The probability of both occurring is 3/8 x 2/3 = 1/4.

optimal price bid is zero. But underbidding its competitors exposes the firm to non-compliance penalties because they are more likely to be rationed, so the benefit of bidding zero is only worthwhile if the competitors' price bids are sufficiently high. For example, a firm needing 12 permits would prefer to bid zero if and only if bidding high would resulting clearing price would be $13.89.

Although we have been unable to solve for the equilibrium of this game (because it will involve complex mixed-strategy price bids), we know that equilibrium average clearing prices cannot be large when they occur, because the incentive to deviate to a zero bid would be too great. Thus, we have a definite prediction that price bids in the no consignment case will be significantly lower than with consignment. And, since the prediction involves mixing, we expect higher variability in clearing prices without consignment.

Since all firms bid truthful quantities, the auction outcomes will always be Pareto optimal.[10] No firm ever receives a permit that it does not need, and so no Pareto-improving trading of permits could occur after the auction clears. The total number of non-compliance penalties is 1.5 on average, the same as the consignment case with truthful quantity bidding.

3.3 Summary of Hypotheses

Given this theoretical demonstration, we provide the following hypotheses to be tested empirically in the laboratory. First, given the incentive to bid up the permit price, we expect higher permit prices under consignment than non-consignment.

H1: $Price_{consignment} > Price_{non\text{-}consignment}$

This stems from two sources: consignment should lead to rationing more often, meaning the clearing price is more likely to be positive. And, when the clearing price is positive, we expect it to be $50 under consignment but much less without consignment.

H1a: $Pr(Price>0)_{consignment} > Pr(Price>0)_{non\text{-}consignment}$

H1b: $Avg.\ Price_{consignment}\ if\ (Price > 0) > Avg.\ Price_{non\text{-}consignment}\ if\ (Price > 0)$

[10] For comparability with the consignment case, we include the auctioneer's revenue in our efficiency calculation.

Second, we expect this to hold regardless of firm type and consignment allocation. Recall that, in the experiment and in reality, not every firm consign permits. Firms without a compliance obligation, for example, may not receive an initial endowment of permits to consign into the market. Those firms consigning permits may be high efficiency firms, requiring fewer permits per unit of energy produced, or they may be low efficiency firms, requiring more permits per unit of energy relative to high efficiency firms. Given our theory, we expect higher prices whenever net sellers are present. Since high efficiency and low efficiency firms can both be net sellers in our design, we have the following predictions:

H2: *Price* $_{consignment}$ *(if only high efficiency producers consign) > Price* $_{non\text{-}consignment}$

H3: *Price* $_{consignment}$ *(if only low efficiency producers consign) > Price* $_{non\text{-}consignment}$

Third, we expect this price increase to be driven by the behavior of net sellers. That is, those firms that have an aggregate permit demand that is exceeded by their aggregate allocation of permits to consign, will bid strategically to inflate their individual demand for permits to drive up the price on the remaining permits they are consigning.

H4: *Net sellers inflate their quantity bids to increase the expected price.*

We expect that net buyers, those firms that have an aggregate permit demand that exceeds their allocation of permits to consign, will not bid strategically to reduce demand and reduce permit prices. Instead, we expect that these firms will submit truthful bids equivalent to the quantity of permits that they need for purposes of market compliance.

H5: *Net buyers submit truthful quantity bids.*

Finally, we predict that the inflated quantity bids by net sellers will cause increased inefficiencies due to increased non-compliance penalties. As such, we expect higher inefficiency in treatments with consignment, as well as higher expected non-compliance penalties.

H6a: *Inefficiency* $_{consignment}$ > *Inefficiency* $_{non\text{-}consignment}$

H6b: *E[non-compliance penalty]* $_{consignment}$ > *E[non-compliance penalty]* $_{non\text{-}consignment}$

4. Results

We report on the results of four experimental treatments and eight sessions in total. Each session ran for approximately 2.5 to 3 hours including subject instruction time, and all sessions ran for 51 bidding periods in total. Data in early periods are noisier due to subjects' learning, so we restrict all analyses to the final 25 periods, unless otherwise specified. In our appendix, we provide a replication of all results tables including all paid periods as a robustness check for interested readers.

4.1 Auction-clearing Prices

Our first hypothesis is that auctions with consignment will clear at significantly higher prices, with a lower frequency of zero-price periods, and higher prices when prices are positive. In Table 3 we show these averages by treatment. The average auction prices are substantially higher when all firms consign or when inefficient high-types consign permits. We will show that this is due in part to net sellers inflating the auction price to increase their revenue. Curiously, we find a slight decrease in average prices when only the efficient low types consign permits.

Table 3. Auction Clearing Price Summary Statistics

	Auction Clearing Price		
Treatment	Overall Average	% Periods With Price = 0	Avg. Price When Price > 0
Control (No Consign)	6.74	40.9%	11.39
Treatment (All Consign)	24.17	25.0%	32.23
Treatment (High Consign Only)	15.36	24.5%	20.35
Treatment (Low Consign Only)	5.86	35.1%	9.02

To test whether the differences in clearing prices are significantly different between treatments, we regress auction clearing price against dummy variables for each treatment (Table 4). We use a Tobit regression because auction prices are censored below zero, we control for aggregate permit demand, and cluster errors by session. The omitted category is the treatment without consignment. We find a significant increase in clearing price when all agents consign, and a marginally significant increase when only high types consign. The effect of the Low consignment treatment is insignificant, though positive once we control for aggregate permit demand. Similar results obtain when limiting to only periods with a positive price, though significance is reduced in all cases due to the smaller size of this subsample. A logistic regression (also clustered by session and controlling for aggregate demand) reveals that all three treatments have a significantly lower chance of generating a zero clearing price, with *p*-values all less than 0.01.

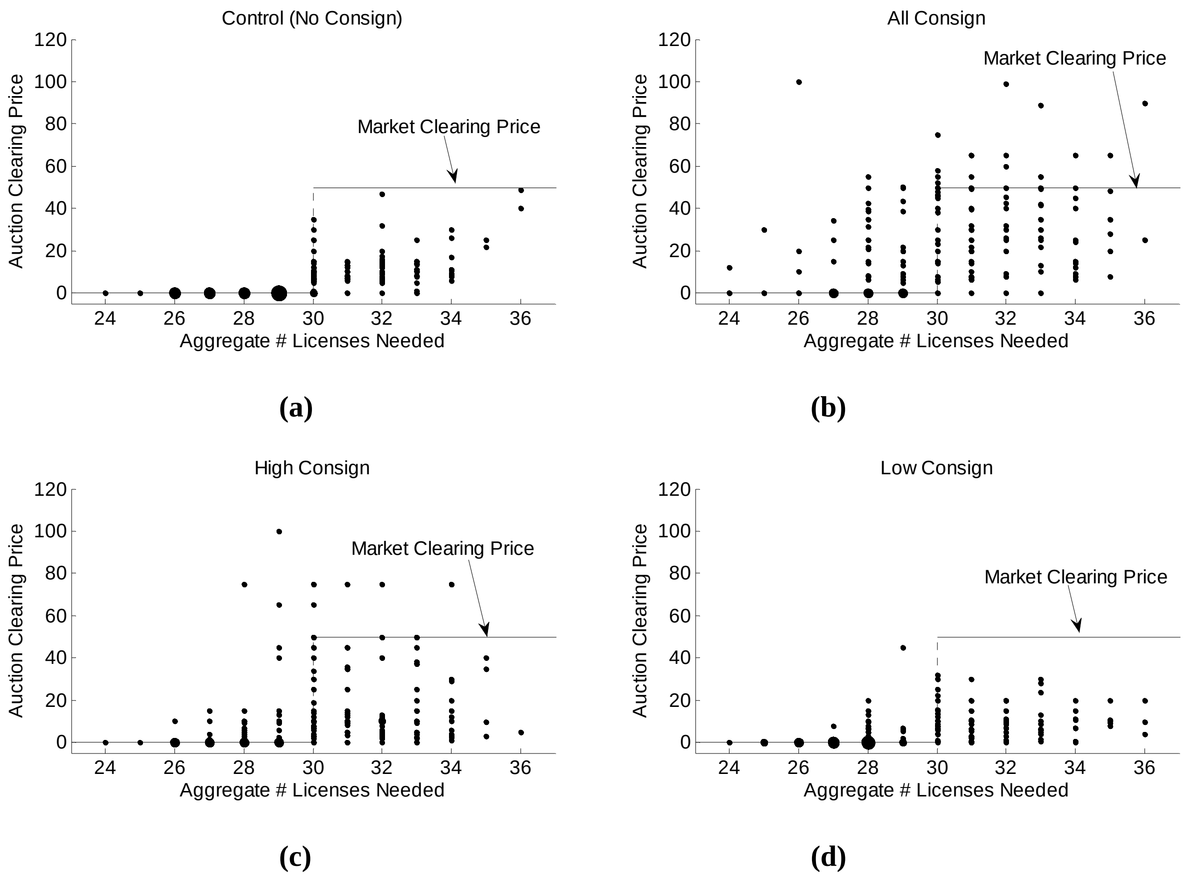
Table 4. Auction Clearing Price Regression

	Auction Clearing Price	
Independent Variable	Coefficient	Std. Err.
Treatment (All Consign)	22.73 **	7.63
Treatment (High Consign Only)	12.43 *	7.06
Treatment (Low Consign Only)	1.73	2.15
Aggregate Permit Demand	5.10 ***	1.13
Constant	-155.48 ***	36.02
N	832	
F-statistic	7.08 ***	
McFadden's Pseudo R^2	0.07	

**** p<0.001 ** p<0.01 * p<0.1, robust std. errors clustered by session*

Theses treatment differences are also visible in scatter plots of auction clearing prices versus aggregate demand (Figure 3). Recall that there is a fixed supply of 30 permits. Firms' marginal value for permits is $50 if they are facing non-compliance penalties and $0 if they have sufficient permits to avoid these penalties. Thus, the market clearing price is $0 when less than 30 permits are needed in the aggregate, and $50 when 30 or more permits are needed. With no consignment (panel a), auction prices are most often zero when demand is less than 30, and well below the market clearing price when demand is greater than 30. This is consistent with our theoretical prediction of a mixed-strategy equilibrium in price bids. With consignment by all firms (panel b) or high-type firms (panel c), auction prices frequently exceed the market clearing price, both when demand is low and high. When only energy-efficient low types consign (panel d), some increase in low-demand clearing prices is observed, though no clear difference is seen for high-demand periods.

Figure 3a-d: Auction Clearing Prices for Each Treatment



In summary, we broadly confirm the hypothesis that consignment leads to higher clearing prices and a greater frequency of positive prices, though these effects appear insignificant when only low types consign.

4.2 Price Bids

Table 5: Average Price Bids

Treatment	Type	Net Buyers	Zero Net Demand	Net Sellers
		Mean Bid Price		
Control (No Consign)	*Low*	60.08	-	-
	High	33.59	-	-
Treatment (All Consign)	*Low*	126.55	165.47	278.32
	High	72.14	82.21	94.67
Treatment (High Consign Only)	*Low*	107.57	-	-
	High	70.73	88.92	92.97
Treatment (Low Consign Only)	*Low*	59.83	66.29	84.29
	High	23.26	-	-

In theory, we expect all price bids to be $50 under consignment. Without consignment, bidders will play a mixed strategy, submitting bids substantially below $50. Table 5 provides the actual averages from the experiment. Although the point predictions of the theory are not borne out (due in part to several bidders submitting very high bids), we do see higher average price bids in the All Consign and High Consign treatments, but not in the Low Consign treatment. Low pollution types also submit substantially higher bids than the High pollution types. Finally, net sellers bid higher than net buyers or those with zero net demand.

To see whether these differences are significant, we regress the bid price on dummy variables for treatments (excluding no consignment), production type (net buyer or net seller), and pollution type.[11] The results are show in Table 6. The regression confirms that All Consign generates substantially higher bid prices, both in magnitude and significance. The effect of High Consign is also fairly large but significance is marginal. The Low Consign bid prices are indistinguishable from the No Consignment treatment. Net sellers clearly submit higher bids, and high pollution types submit significantly lower bids.

[11] The effect of aggregate permit demand is insignificant because it is not observable by subjects when placing bids. Thus, we do not include it in these bid regressions.

Table 6: Regression of Bid Prices

Independent Variable	Bid Price Coefficient		Std. Err.
Treatment (All Consign)	82.45	***	27.21
Treatment (High Consign Only)	45.59	*	24.46
Treatment (Low Consign Only)	-4.59		17.92
Treatment Net Buyer	-16.12		11.87
Treatment Net Seller	40.42	**	19.16
High Type	-50.39	***	17.77
Constant	72.03	***	16.72
N	3328		
F-statistic	5.80	***	
McFadden's Pseudo R^2	0.01		

***** *p<0.01 ** p<0.05 * p<0.1, robust std. errors clustered by subject*

4.3 Quantity Bids

Our theoretical prediction is that net sellers should submit quantity bids greater than their actual permit demand. We show the average amount by which quantity bids exceed permit requirements (*i.e.*, pollution output) in Table 7. In the control (No Consign) treatment, 97.2% of quantity bids are 'truthful', meaning they exactly equal the number of permits needed by the firm, so average overbidding levels are essentially zero for both pollution types. In the All Consign treatment only 78.4% of quantity bids are truthful (zero overbidding), while 18.0% of bids are for more units than needed. The percentage of quantity overbids in the High Consign and Low Consign treatments are similar at 16.3% and 16.7%, respectively. Though we see positive overbidding on average for all types, the net sellers and those with a zero net demand have higher average levels of overbidding.

Table 7: Average Quantity Overbidding

	Mean Quantity Overbid (Quantity Bid - Permits Needed)			
Treatment	Type	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	*Low*	0.02	-	-
	High	-0.01	-	-
Treatment (All Consign)	*Low*	0.11	0.54	0.27
	High	0.52	0.94	1.22
Treatment (High Consign Only)	*Low*	1.81	-	-
	High	0.24	0.27	0.63
Treatment (Low Consign Only)	*Low*	0.16	0.35	0.62
	High	0.44	-	-

We confirm these insights with a Tobit regression of bid quantities on permits needed, treatments, and bidder types. We use cluster-robust standard errors, clustering by subject. The results appear in Table 8. The coefficient on permits needed is slightly greater than one, but not significantly so (*p*-value 0.161). This enables us to view the remaining coefficients as a rough measure of the magnitude of quantity overbidding. Such overbidding is significant in all three treatments with consignment.

The theory predicts that overbidding should be related to the bidder's production type (net seller versus net buyer) but not their pollution type (High versus Low). The latter result obtains: High types are not more likely to overbid their quantities. The net buyers engage in significantly less overbidding than those with zero net demand, while net sellers behave the same as those with zero net demand. The difference between these coefficients is highly significant (*p*-value of 0.002), indicating that net sellers do engage in more overbidding than net buyers. Our theory did not include zero net demand agents, and so we had no prior hypothesis about whether these types should overbid or not. Intuitively, however, this appears to be a suboptimal strategy: overbidding turns the player into a net buyer who is now buying worthless units. However, these results on production type do not appear robust to the exclusion of outliers; if we exclude the 2.4% of bidders whose quantity bid was (weakly) more than twice the number of permits needed, then the regression coefficients for net buyers and net sellers become insignificant at the 10% level, while all other results remain unchanged. Thus, we view our results on overbidding by production types as fairly weak.

Table 8: Regression of Bid Quantities

	Bid Quantity	
Independent Variable	Coefficient	Std. Err.
Permits Needed	1.08 ***	0.06
Treatment (All Consign)	0.85 ***	0.33
Treatment (High Consign Only)	1.21 **	0.58
Treatment (Low Consign Only)	0.56 ***	0.17
Treatment Net Buyer	-0.72 **	0.34
Treatment Net Seller	-0.08	0.22
High Type	-0.60	0.54
Constant	-0.28	0.19
N	3328	
F-statistic	558.55 ***	
McFadden's Psuedo R^2	0.15	

**** p<0.01 ** p<0.05 * p<0.1, robust std. errors clustered by subject*

4.4 Inefficiencies and Non-Compliance Penalties

Quantity overbidding should lead to allocation inefficiencies. Bidders that inflate their bid quantity end up receiving more emissions permits than they need for program compliance, potentially taking permits away firms that need them for program compliance. We define an inefficiency as occurring if one emissions permit was sold to a bidder in excess of his permit demand and, at the same time, another bidder received a non-compliance penalty for being short by a single permit. We then count the number of such inefficiencies observed in each period. For example, if one firm has two extra permits while two firms each are paying one non-compliance penalty, we count that as two inefficiencies. On the other hand, if a bidder received a non-compliance penalty for being short a single permit, and all other bidders did not acquire permits in excess of their permit demand, then we identify that auction as having no inefficiencies.

Without consignment, inefficiencies are very rare, averaging 0.02 per period. In other words, we see roughly one inefficiency for every 50 periods of play. In no period were more than two inefficiencies observed, and this happened in only one period. The low rate of inefficiency follows because 97% of quantity bids are truthful. With consignment, however, inefficiencies are much more common. The average number per period in the All Consign, High Consign, and Low Consign treatments are 0.95, 0.53, and 0.65, respectively. Since each inefficiency represents a social loss of \$50, these correspond to per-period welfare losses of \$47.50, \$26.50, and \$32.50, respectively, compared to only \$1.00 without consignment. Using a dummy variable regression with cluster-robust standard errors (clustering by session), we find that each of these is significantly greater than the No Consign treatment, with *p*-values of 0.043, 0.001, and 0.002, respectively. Comparing among the three consignment treatments yields no significant differences, with Wald test *p*-values all greater than 0.31.

The increase in inefficiencies is not only due to them being more common; we also see greater numbers of inefficiencies when they occur. If we look only at periods with at least one inefficiency, the mean number of inefficiencies per period is 1.33 in the No Consign treatment, but jumps to 3.40, 2.68, and 2.65 in the All Consign, High Consign, and Low Consign treatments, respectively.

Non-compliance penalties (NCPs) can come from two sources: inefficient outcomes, and markets where permit demand is greater than supply. The latter occurs randomly in our experiment and is unaffected by subjects' decisions. Even if every period's outcome was efficient, each person would still pay an average of \$12.96 per period in NCPs. Thus, we calculate the actual average per period and subtract \$12.96 to give a measure of NCPs paid due to inefficiencies.

As expected, the results are perfectly in line with the inefficiency measure above. Without consignment subjects pay an average of \$0.32 per period in excessive NCPs. In the All Consign, High Consign, and Low Consign treatments, this increases to \$14.50, \$8.61, and \$7.47, respectively. These are all significantly different than without consignment.

Table 9. Average Non-Compliance Penalties in Periods with Inefficiencies

Treatment	Net Buyer NCPs	Zero Net Demand NCPs	Net Seller NCPs
Treatment (All Consign)	82.93	50.00	33.59
Treatment (High Consign)	76.92	46.98	15.91
Treatment (Low Consign)	33.33	63.26	3.03

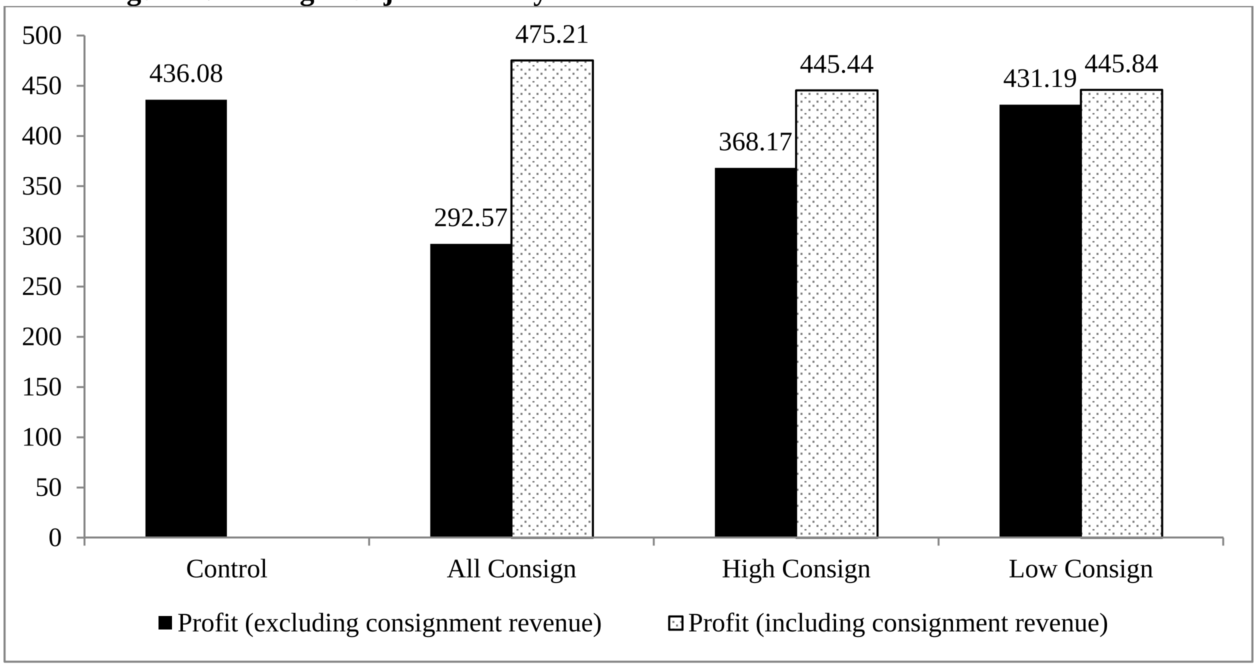
Our theory makes a specific prediction about how inefficiencies should arise: Net sellers buy too many units in equilibrium, making net buyers more likely to suffer NCPs. Thus, if we only look at periods with inefficiencies, we should see net buyers paying all the NCPs. The actual results (Table 9) are not quite that stark, but clearly show that net buyers in fact pay substantially more NCPs. To test significance, we regress NCPs on treatment and production type, clustering by individual. We find no treatment differences among the three treatments with consignment (all *p*-values greater than 0.45), and no difference between net buyers and those with zero net demand (*p*-value 0.407), but that net sellers do pay significantly fewer NCPs than those with zero net demand (*p*-value <0.001) and fewer than the net buyers (Wald test *p*-value 0.001).

4.5 Profit

The inefficiency from the overbidding distortion of consignment is also injurious to subject-level profit. In Figure 4 we provide the mean subject-level profit by treatment group. We define profit as the net of energy production revenue, non-compliance penalty and permit expenditures. Profit does not include revenue from consignment, as that would be incomparable across treatments. Figure 4, however, also provides profit including consignment revenue for treatment groups.

In the control group, the mean profit is approximately $436 experimental. It is $293 in the treatment in which all subjects consign. We conduct non-parametric hypothesis tests of mean subject profit and find that we can safely reject the null hypothesis of mean profit equality in the all consignment and high consignment treatments, at the $p<0.001$ levels. We cannot safely reject this for the low consignment case, as the mean subject profit is approximately that of the control group. Furthermore, roughly the same effects hold when these values are decomposed by permit demand level, not reported here for simplicity.

Figure 4. Average Subject Profit by Treatment



As mentioned previously, overbidding by net sellers creates inefficiencies on two fronts. First, it inflates the aggregate permit demand and as a result, over-bidders end up sitting on unused permits that they do not utilize. Second, the higher aggregate permit demand raises the likelihood that other bidders will receive non-compliance penalties from carrying an insufficient quantity of permits. In Table 10 we report mean profit by treatment group and by permit demand. And, we provide these same values including consignment revenue in Table 11. The results in Table 10 provide evidence that profit for net sellers is consistently lower than profit for net buyers, bidders with zero net demand, and also lower than all bidders in the control treatment without consignment.

Table 10. Average Profits

	Profit (excluding consignment revenue)		
	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	436.08	-	-
Treatment (All Consign)	305.05	297.03	274.79
Treatment (High Consign)	357.49	382.49	313.90
Treatment (Low Consign)	542.40	417.17	376.37

Table 11. Average Profits (Including Consignment Revenue)

	Profit (including consignment revenue)		
	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	436.08	-	-
Treatment (All Consign)	534.19	479.68	409.00
Treatment (High Consign)	540.23	429.08	414.12
Treatment (Low Consign)	579.77	422.98	400.17

It should be noted, however, that net sellers should ultimately receive a lower profit than net buyers by virtue of their lower production in the product market, all else being equal. That is, net buyers are producing more in the product market (energy) and receiving a larger quantity of production revenue. In this experiment, this was operationalized as a production of either 4, 5 or 6 units in the product market, with corresponding production revenues of $400, $500 and $600 experimental, respectively. Because permit allocations are fixed, all bidders with production of 4 units are net sellers, and all bidders with production of 6 units are net buyers. We would expect profit, therefore, to be approximately $200 larger for net buyers than net sellers. This is clearly mitigated by inefficiencies due to the distortion of consignment that results in higher permit prices, overspending on permits by net sellers, and more frequent non-compliance penalties.

We provide additional insight into these results with a Tobit regression of subject-level profit, provided in Table 12. We regress profit, excluding consignment revenue, on our treatment dummies, our dummies for net buyers and net sellers, and production type. The regression utilizes cluster robust standard errors, clustered by subject. The results provide robust evidence that subjects received significantly lower profits in treatments with consignment than in the control group without consignment, which is excluded from the model as the reference variable. Each treatment dummy is significant at the $p<0.01$ level, except the treatment in which only the low type subjects consign. The results also provide robust evidence that net sellers receive significantly lower profit than bidders with zero net permit demand. And, the results provide robust evidence that net buyers receive significantly larger profits than bidders with zero net permit demand. And finally, the results indicate that high types (who need twice as many permits) incur significantly less profit than low types.

Table 12. Regression of Profit

	Profit	
Independent Variable	Coefficient	Std. Err.
Treatment (All Consign)	-139.67 ***	16.19
Treatment (High Consign Only)	-66.52 ***	13.30
Treatment (Low Consign Only)	-1.97	7.61
Treatment Net Buyer	29.87 **	14.93
Treatment Net Seller	-43.10 ***	13.99
High Type	-78.97 ***	9.24
Constant	475.57 ***	7.05
N	3328	
F-statistic	67.04 ***	
McFadden's Psuedo R^2	0.02	

**** p<0.01 ** p<0.05 * p<0.1, robust std. errors clustered by subject*
D.V. excludes revenue from consigned permits

5. Conclusions

Our results provide an interesting complement to an existing problem among carbon markets in the U.S., and internationally. Because all of the firms purchasing emissions permits in carbon auctions have an incentive to lower compliance costs, the incentive to bid strategically to lower carbon auction clearing prices is ubiquitous. As a result, the problem of low price equilibria in auction-allocated carbon markets has taken center stage. The RGGI markets for example, saw carbon prices consistently at the price floor, or reserve price, for the past three years. In 2014, the member states cut the aggregate supply of emissions permits by 45 percent across the board, and prices have increased to approximately $5 per ton (from approx. $2 per ton) (RGGI, 2014). And every auction-based carbon market to date utilizes some form of reserve price (floor). Our finding that the consignment auction yields consistently higher auction clearing prices, except in contexts in which the energy demand is high and only high efficiency firms are consigning permits, provides some support for the assertion that consignment auctions can be utilized to mitigate the problem of low price equilibria.

The problem of low price equilibria may be more significant than misallocation alone. In auction-allocated carbon markets, the auction price plays a critical and systemic role of providing a price signal to producers, particularly long-term decision-makers. Given that energy firms, in particular, have a planning horizon that exceeds, in many cases, a decade, the current carbon auction price can send a long-term production and abatement signal with long-lasting macroeconomic implications. This has long since been understood in the environmental economics literature, as firms make long-term abatement spending and capital decisions on the basis of their discounted expected future permit price (Stevens and Rose, 2002). Should a consignment mechanism provide an effective tool for mitigating the problem of low price equilibria in the short term, it may have long-standing implications for the cost-effectiveness and macro impacts of the emissions trading program.

Furthermore, our findings have potentially significant implications for electric distribution firms (i.e., public utilities) that receive a pre-auction endowment of permits to consign. The argument among utilities, and the California regulator (CARB) is that the revenue from the sale of consigned emissions permits will offset any cost increases that pass through in the wholesale price of power. Our findings on the other hand, provide evidence that the overbidding incentive inherent to the consignment auction reduces the profits of consigning firms. In other words, we find that while utilities are making the argument that consignment will be more profitable, to the benefit of ratepayers, the bidding incentives of the consignment auction are deleterious to utilities' profit. This is a striking irony.

There are two factors that we do not model in our laboratory experiments or in our theoretical analysis that may serve to mitigate the inefficiencies of the consignment auction that we find. The first is that we do not model banking. Banking is the ability of firms to store un-surrendered emissions permits for future use, a program design that is allowed in a majority of the world's carbon markets and serves to enhance temporal flexibility. Our finding that the inefficiency of the consignment auction is driven by the overbidding incentive of net sellers, which is also consistent with Ledyard and Szakaly-Moore (1994), may be less of a public policy problem in the long run in light of banking. That is, firms may be bidding for an additional quantity of emissions permits to increase the auction-clearing price, however, that may not constitute a systemic inefficiency because firms can simply store those excess permits for future use. The second is *ex-post* trading—the 'trade' in cap-and-trade. While our analysis does not model post auction transfers, strategic overbidding, as well as underbidding for that matter, can be balanced in post auction transactions bilaterally among firms, with the inherent transactions costs involved in the trading process.

The debate surrounding the efficient design of carbon auctions has tremendous currency in both the U.S. and international policy context. In light of the European Union's directive for all member states to move toward auction-based allocation for their Europe-wide carbon market, and in light of the EPA's proposed rules to regulate greenhouse gases under the Clean Air Act, these results have broad policy implications. While it is the regulator's aim to effectively balance the social cost of emissions with the economic impacts to businesses and households of pricing those emissions, our findings would suggest that the regulator may not be able to balance the two with a simple revenue adjustment like a consignment mechanism. We find that the consignment mechanism results in a higher auction-clearing price, which sends a positive price signal to producers to internalize the negative externalities inherent to their production processes. However, the inherent tradeoff is the efficiency loss due to the perverse incentive inherent to the consignment mechanism to engage in overbidding.

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Appendix A. Results Including All Bidding Periods

In the preceding analysis, all results were provided with the first 25 bidding periods removed to allow for subject learning. Below, we provide all of the same results but include all bidding (except practice periods) periods as a robustness check.

Table A1. Auction Clearing Price Summary Stats (all periods)

	Auction Clearing Price		
Treatment	Overall Average	% Periods With Price = 0	Avg. Price When Price > 0
Control (No Consign)	7.69	39.2%	12.67
Treatment (All Consign)	21.08	22.8%	27.31
Treatment (High Consign Only)	15.51	21.6%	22.33
Treatment (Low Consign Only)	6.36	30.9%	9.19

Table A2. Auction Clearing Price Regression (all periods)

	Auction Clearing Price		
Independent Variable	Coefficient		Std. Err.
Treatment (All Consign)	17.95	**	6.51
Treatment (High Consign Only)	13.91	*	8.40
Treatment (Low Consign Only)	1.98		2.21
Aggregate Permit Demand	4.25	***	0.79
Constant	-127.83	***	-5.04
N	1632		
F-statistic	11.07	***	
McFadden's Pseudo R^2	0.05		

**** p<0.001 ** p<0.01 * p<0.1, robust std. errors clustered by session*

Table A3. Average Price Bids (all periods)

		Mean Bid Price		
Treatment	Type	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	*Low*	75.48	-	-
	High	40.88	-	-
Treatment (All Consign)	*Low*	100.22	135.6	228.39
	High	65.18	70.51	83.89
Treatment (High Consign Only)	*Low*	106.71	-	-
	High	75.21	83.66	89.82
Treatment (Low Consign Only)	*Low*	66.15	72.47	74.83
	High	24.39	-	-

Table A4. Regression of Bid Prices (all periods)

	Bid Price	
Independent Variable	Coefficient	Std. Err.
Treatment (All Consign)	48.78 **	24.86
Treatment (High Consign Only)	33.49	25.56
Treatment (Low Consign Only)	-14.31	19.89
Treatment Net Buyer	-10.71	11.63
Treatment Net Seller	31.99 *	16.38
High Type	-46.25 ***	16.92
Constant	81.17 ***	19.20
N	6528	
F-statistic	5.63 ***	
McFadden's Pseudo R^2	0.01	

**** p<0.01 ** p<0.05 * p<0.1, robust std. errors clustered by subject*

Table A5. Average Quantity Overbidding (all periods)

		Mean Quantity Overbid (Quantity Bid - Permits Needed)		
Treatment	Type	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	*Low*	0.13	-	-
	High	0.12	-	-
Treatment (All Consign)	*Low*	0.47	0.57	0.85
	High	0.69	1.45	1.2
Treatment (High Consign Only)	*Low*	1.98	-	-
	High	0.14	0.42	0.61
Treatment (Low Consign Only)	*Low*	0.37	0.58	0.63
	High	0.55	-	-

Table A6. Regression of Bid Quantities (all periods)

	Bid Quantity	
Independent Variable	Coefficient	Std. Err.
Permits Needed	1.02 ***	0.03
Treatment (All Consign)	1.07 ***	0.32
Treatment (High Consign Only)	1.22 **	0.58
Treatment (Low Consign Only)	0.58 ***	0.20
Treatment Net Buyer	-0.71 **	0.28
Treatment Net Seller	-0.25	0.25
High Type	-0.37	0.39
Constant	0.17	0.12
N	6528	
F-statistic	2025.77 ***	
McFadden's Psuedo R^2	0.12	

**** p<0.01 ** p<0.05 * p<0.1, robust std. errors clustered by subject*

Table A7. Average Non-Compliance Penalties in Periods with Inefficiencies (all periods)

Treatment	Net Buyer NCPs	Zero Net Demand NCPs	Net Seller NCPs
Treatment (All Consign)	96.68	58.77	48.46
Treatment (High Consign)	100.00	58.14	71.88
Treatment (Low Consign)	39.80	60.66	21.76

Table A8. Regression of Profit (all periods)

	Profit	
Independent Variable	Coefficient	Std. Err.
Treatment (All Consign)	-111.86 ***	14.23
Treatment (High Consign Only)	-83.90 ***	16.25
Treatment (Low Consign Only)	0.25	6.41
Treatment Net Buyer	33.71 *	13.41
Treatment Net Seller	-54.23 ***	12.82
High Type	-81.22 ***	10.02
Constant	467.23 ***	6.61
N	6528	
F-statistic	81.48 ***	
McFadden's Psuedo R^2	0.01	

***** p<0.01 ** p<0.05 * p<0.1, robust std. errors clustered by subject**

D.V. excludes revenue from consigned permits

Table A9. Average Profits (all periods)

	Profit (excluding consignment revenue)		
	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	426.68	-	-
Treatment (All Consign)	335.43	318.62	277.02
Treatment (High Consign)	324.69	366.83	280.22
Treatment (Low Consign)	536.70	407.71	369.91

Table A10. Average Profits (Including Consignment Revenue) (all periods)

	Profit (including consignment revenue)		
	Net Buyers	Zero Net Demand	Net Sellers
Control (No Consign)	426.68	-	-
Treatment (All Consign)	530.06	473.49	400.26
Treatment (High Consign)	531.64	417.62	401.03
Treatment (Low Consign)	574.53	415.02	396.20

Appendix B. Subject Instructions (Main Treatment)

SIMULATION INSTRUCTIONS

Welcome

Thank you for coming today and participating in this computer laboratory simulation! Your time and participation today is appreciated.

The simulation should last under 2 hours. We will begin with some instructions to help you through the simulation.

In addition to the money you have received for showing up today, you will get to keep a portion of the money you earn during the simulation. For every thousand dollars you make in the simulation, you will be paid one dollar. If you have any questions or the instructions are not clear in any way, please ask questions and do not be shy. The better you understand the rules of the simulation, the more money you will earn.

You are free to leave the room and excuse yourself from the simulation at any time. However, if you leave without completing the simulation, your only earnings will be your payment for showing up today. If you require any specific accommodation, please notify the instructor by raising your hand so that your need can be addressed appropriately.

If you have a cell phone or a beeper, please *turn it off and put it away* at this time. You are not permitted to communicate with other participants during this simulation at any time. Please do not look onto another participant's screen at any time.

The simulation will make use of the computers within this room. You are not permitted to use any application or program other than the program for the simulation. If you are found to be using any other software on the computer, you will be immediately excused from the simulation.

During the simulation, if you have any questions, please quietly raise your hand and ask the instructor to answer your question. Please do not ask another participant. Are there any questions at this time?

Notice Regarding Deception

You may or may not have participated in a prior experiment, simulation or survey that attempted to deceive or confuse you. Please note that there will be no deception whatsoever in this simulation.

Simulation Background

In this simulation you will be a producer. You will get paid for the products that you produce. For each product that you produce, you will need to get licenses. If you do not get enough licenses, you will be fined. You will be purchasing the licenses that you need for your products in an auction.

Periods

The simulation will consist of a number of periods, each of approximately two to three minutes. Each period will consist of a single auction, and each period a new auction will begin. Your earnings from any prior auction will not have any impact on any future auction, and your earnings from each auction will be recorded by the computer so that you can receive your payment at the end of the session.

Production

At the beginning of each period, you will be told how many products you have produced. You will be randomly assigned a production level of either 4 products, 5 products, or 6 products. The likelihood of being assigned to any of these three production levels is the same. For each product you produce, you will receive $100.00 in the simulation.

Licenses

There are two types of participants in the auction: Low type and High type participants. You will either be one or the other.

Low type participants will need to get *1* license for every product that they produce. *High* type participants will need to get *2* licenses for every product that they produce.

For example, if you have produced 5 products and you are a low type participant, you will need to get at least 5 licenses in the auction. On the other hand, if you have produced 5 products and you are a high type producer, you will need to get at least 10 (2 x 5 products) licenses in the auction.

Bank Account

At the beginning of each auction, you will be given money in a bank account to use to place your bids and buy the licenses that you need. That bank account will hold *$2,500.00* in the simulation.

The computer will show you this bank account at the start of each auction. And each auction, that account will be refreshed with a new *$2,500.00*.

Total Quantity

The total quantity of licenses that will be sold in any auction will be *30* licenses.

Other Participants

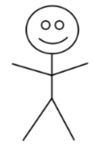
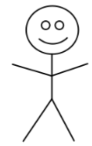
Table 1 below provides a graphic diagram of the participants within any given auction. In each auction, you will be competing against 3 other buyers who also need to purchase licenses. That means that in each auction for licenses, you will be 1 out of a total of 4 bidders.

You will not know who the other participants are. Each period, the participants in each auction will change, and you may or may not be competing against the same bidders during the next auction.

In each auction, two of the participants will be High type participants, and two will be Low type participants.

You will not know the production levels of the other three participants. You will only know your own production levels. This means that you will not know how many licenses are needed in total in any auction.

Table 1. Makeup of an Auction

 Participant Type: Low Production Level: 4, 5, or 6 Licenses Needed: 1 License per product	 Participant Type: Low Production Level: 4, 5, or 6 Licenses Needed: 1 License per product
 Participant Type: High Production Level: 4, 5, or 6 Licenses Needed: 2 Licenses per product	 Participant Type: High Production Level: 4, 5, or 6 Licenses Needed: 2 Licenses per product

Compliance

At the beginning of each auction, you will be told how many licenses you need to get, based upon both your type (High or Low) and your level of production (4, 5, or 6 products). You may choose to purchase the exact quantity of licenses you need. You may also choose to acquire more or fewer than the quantity of licenses you need.

Remember that your objective is to make money. You will get to make the decision of how many licenses to bid for in the auction. However, if you receive fewer licenses than you need, you will receive a penalty of $50.00 for every license that you are short.

For example, if you need to acquire 6 licenses, and you only receive 4 licenses, you will incur a penalty of *$100.00* (e.g., $50.00 x 2) in the simulation.

The Auction

In the auction, your bid for licenses will consist of a price and a quantity. That is, you will specify the quantity of licenses that you would like to buy and the price that you would like to pay for each license. Please note; your total bid cannot exceed your bank account of *$2,500.00*.

The auction will be a uniform-price auction. This means that your bid will be placed alongside the other participants' bids, and preference will be given to the highest priced bids. All bids will be ranked from highest bid price to lowest bid price. Licenses will be awarded to the bidders in order of price, from highest to lowest.

The lowest winning bid price will be the price that all winning bidders pay. This means that it is possible for you to acquire licenses at a lower price than your bid. In order to receive licenses, all you need to do is bid at or above the winning bid price.

Example

Consider the following example given in Table 2. Please note; this is just a hypothetical example with arbitrary numbers and provides no suggestions on how to bid in the actual simulation. In Table 2, you will see that four participants' bids are ranked by bid price. Participant #3 had the highest bid price of $7.50, for a quantity of 15 licenses. Participant #1 had the lowest bid price of $3.99, for 5 licenses.

Table 2. Example of Auction

Participant	Bid Price	Bid Quantity	Auction Price	Quantity Received	Price Paid for Licenses
Participant #3	$7.50	15	-	15	15 x $6.00 = $90.00
Participant #4	$6.25	12	-	12	12 x $6.00 = $72.00
Participant #2	$6.00	5	**$6.00**	3	3 x $6.00 = $18.00
Participant #1	$3.99	5	-	0	0 x $6.00 = $0.00

In this auction, 30 licenses are to be sold. The price that will be paid by winning bidders is $6.00. This price is determined by awarding the quantity of licenses to the participants in order of their bid price. After fulfilling participants' #3 and #4 bids, there are only 3 licenses left to award to Participant #2. Because Participant #2 is a winning bidder and acquires 3 licenses, his bid price becomes the uniform price that all winning bidders will pay. The column labeled "Quantity Received" indicates how many licenses each participant acquires.

The column labeled "Price Paid for Licenses" indicates the price that each participant pays for the quantity of licenses he/she will acquire. Participant #3 acquires all the licenses he bid for (15), at $6.00 per license, and pays a total of $90. Participant #4 acquires all the licenses he bid for (12), at $6.00 per license, and pays $72.00. Participant #2 acquires the remaining 3 licenses, at a price of $6.00 per license, which is his bid price, and pays $18.00 for those 3 licenses. And, participant #1 acquires zero licenses, and pays $0.00.

Please note that it is possible for the auction to clear at a price of *$0.00*. This can occur if all 4 bidders' bids are for a quantity that is less than the total of 30 licenses. If this occurs, you will receive the licenses you bid for, at a cost of $0.00 in the simulation.

<u>Ties</u>

If a tie between two or more bidders should occur, the computer will award the licenses randomly.

Are there any questions pertaining to the auction?

<u>Consignment</u>

At the beginning of each auction, you will be given a quantity of licenses to consign (sell) into the auction. These are licenses that you are given for free, but which you must sell into the auction. You will get to keep the money that is made from the sale of these licenses as your earnings. The computer will automatically place these licenses into the auction for you to sell. All of the total of 30 licenses for sale in each auction will be from consignment.

If you are a Low type participant, you will be given 5 licenses to consign into each auction.

If you are a High type participant, you will be given 10 licenses to consign into each auction.

When you sell licenses, you will be paid the auction price for each license that you sell.

Consider these hypothetical and arbitrary examples:

If you are given 5 licenses to consign and sell all 5, and the auction clears at a price of $20.00, you will receive $100.00 (or, $20.00 x 5).

If you are given 10 licenses to consign and sell all 10, and the auction clears at a price of $23.00, you will receive $230.00 (or, $23.00 x 10).

<u>Ties for Consignment</u>

Just because you are given a license to consign does not mean that the license will actually sell in the auction. It is possible for you to sell fewer licenses than you consigned. This can occur if fewer than the total of 30 licenses sells in the auction. If fewer than the total of 30 licenses sells in the auction, you will sell a *pro-rated* quantity of licenses that is proportional to the quantity of licenses you consigned. Because the quantity is pro-rated, you may sell a fraction of the licenses that you consigned.

Consider another hypothetical and arbitrary example as given in Table 3.

Table 3. Example of Pro-rated Consignment

Participant	Quantity Consigned	Total Quantity of Licenses Sold in the Auction	Pro-Rate	Quantity Sold	
Participant #1 (Low Type)	5	29	5/30	5/30 x 29 =	4.83
Participant #2 (Low Type)	5		5/30	5/30 x 29 =	4.83
Participant #3 (High Type)	10		10/30	10/30 x 29 =	9.67
Participant #4 (High Type)	10		10/30	10/30 x 29 =	9.67

In Table 3, you see that each of the 4 participants is given a quantity of licenses to consign. Remember that the low type participants will always be given 5 licenses to consign, and the high type participants will always be given 10 licenses to consign.

In this example, only 29 licenses are actually sold in the auction. Because the low type participants only consign a proportion of 5 out of the total of 30 licenses consigned, they will only sell 5/30 (or 1/6th) of the total quantity that is sold. And, because the high type participants only consign a proportion of 10 out of the total of 30 licenses consigned, they will only sell 10/30 (or 1/3rd) of the total quantity that is sold.

In this example, the two low type participants each sell 4.83 licenses, and the two high type participants each sell 9.67 licenses.

Please note, you will only sell a pro-rated quantity of licenses in the event that fewer than the total of 30 licenses sells. Remember however, that if fewer than 30 licenses sells, the auction will clear at a price of $0.00. This means that in the example just given, even though all of the participants sold licenses, they received $0.00 from consignment, because the auction cleared at a price of $0.00.

This means that the more licenses that sell in the auction, the higher the likelihood that you will be paid for selling licenses.

Are there any questions regarding consignment of licenses?

Profit

Your profit in each period of this simulation will include the following four factors:

1) It will include your revenue from producing products. Remember that you will earn *$100.00* in the simulation for each product that you produce, and you will produce 4, 5, or 6 products.
2) It will include your revenue from the sale of consigned licenses. Remember that you will earn the auction price for each of the licenses you consign.
3) It will include your cost of buying licenses. Remember that you will need to acquire licenses for the products that you produce. And, remember that if you are a high type you will need 2 licenses for every product, and if you are a low type you will need only 1 license for every product.
4) It will include any penalties that you incur from not receiving enough licenses for your products. Remember, you will incur a penalty of *$50.00* in the simulation for every license that you need but do not receive in the auction.

In summary:

PROFIT = *Earnings from producing products*

+

Earnings from consigning licenses

-

Cost of buying licenses

-

Non-compliance cost (acquiring too few licenses)

Questions

We will now proceed to the simulation. The first two auctions will be practice auctions. They will not have any impact on your earnings today. They will give you an opportunity to familiarize yourself with the auction environment. During the first practice period, you will be walked through the bidding environment.

Before we begin the walk through, are there any questions?

Walk Thru

Your instructor will now start the walk through simulation. Please do not place any bids at this time. *I repeat*, please do not place any bids until you are told to do so.

[Start Treatment]
[Stop Clock]

At the top left of the screen, you will see a number that indicates what auction number, or period, the simulation is currently in. Right now it should read "practice." During a paid auction, it will have an actual number there.

At the top left, you will see an item labeled "Time Remaining." You will have 90 seconds to place your bids during each auction. The red numbers will tell you how much time you have remaining to place your bids.

Under the words "The Market" in the top left, you will see how many licenses will be sold in the auction. That quantity will always be 30 licenses. Below that, you will see how much money you have in your bank account to buy licenses.

Below that, you will see how many licenses you are given to consign, or sell into the auction. Remember that if you are a Low type participant you will always be given 5 licenses to consign, and if you are a High type participant you will always be given 10 licenses to consign.

Under the words "Your Status" on the top right, you will see what your type is (either High or Low). You will see how many products you have produced. Remember that that number will always be 4, 5 or 6 products.

And below that, you will see how many licenses you need to acquire for your products.

In the center of the screen, under the words "Place Your Bids", you will see two boxes in which you will place your bid price and your bid quantity for licenses.

Below that, you will see a red button labeled "Submit Bids." You will use your mouse to click that button once you have decided on the bid price and bid quantity that you wish to bid in the auction, and wish to submit that bid as final.

You will see a button on the far right hand side of the screen, adjacent to the submit bids button. If you click on that button, it will open up a Windows calculator. Feel free to use the calculator at any time during the simulation to help you make decisions.

At the very bottom of the screen, you will see a box labeled “Your History.” You can always refer to your prior bids to help inform your bidding in the current auction, or to track your performance across time.

Let me walk you through each of those items:
The first item in that box tells you how many products you have produced. The second item tells you what your bid price was. The third item tells you what your bid quantity was, in other words, how many license you bid for. The fourth item tells you how many licenses you needed, based upon your type and your production of products. The fifth box tells you how many licenses you received in that auction. The sixth box tells you how many licenses you sold from consigning your licenses. The seventh box tells you what the auction price was. And the last box tells you what your profit was.

Are there any questions at this time?

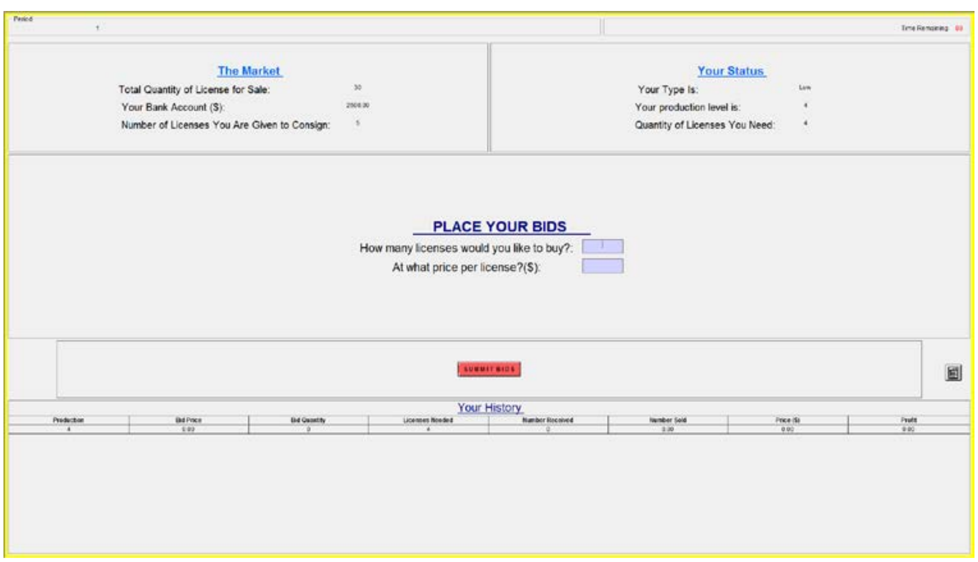
[Pause]

Please go ahead and place a bid price and a bid quantity at this time, and click submit when you are ready to proceed.

After you have clicked the submit button, please do not touch the computers until you have heard further instructions.

[Pause]

After you have clicked the submit button, do not make any further entries until you are instructed.



There will be two screens at all times in any auction. The first screen is the one you just saw, where you place your bids. The second screen is the screen that you are now looking at. This screen will inform you of how you performed in the auction, and how much money you earned.

Under the words “License Auction” at the top of the screen, you will see the price at which the auction cleared. Below that, you will see the quantity of licenses that you received in the auction.

On the left you will see your revenue, and on the right you will see your costs.

Under revenue, you will see what your revenue from production of products was. That will always be $100.00 times the quantity of products you produced.

Below that you will see your revenue from selling licenses that you consigned. It will tell you how many licenses you sold. Remember that you will earn the auction price for each license you sell.

Under the box labeled costs on the right, you will see both your costs from buying licenses, and any non-compliance costs from not receiving enough licenses.

Under the costs of purchasing licenses, you will see the quantity of licenses you received in the auction and the costs of buying licenses. The cost of buying licenses will always be the quantity of licenses you purchased multiplied by the auction price.

Under the item labeled “Non-compliance cost” you will see the quantity of licenses you needed, and the quantity you received. You will also see what your non-compliance penalty is. Remember, you will receive a penalty of $50.00 for every license you needed and did not receive.

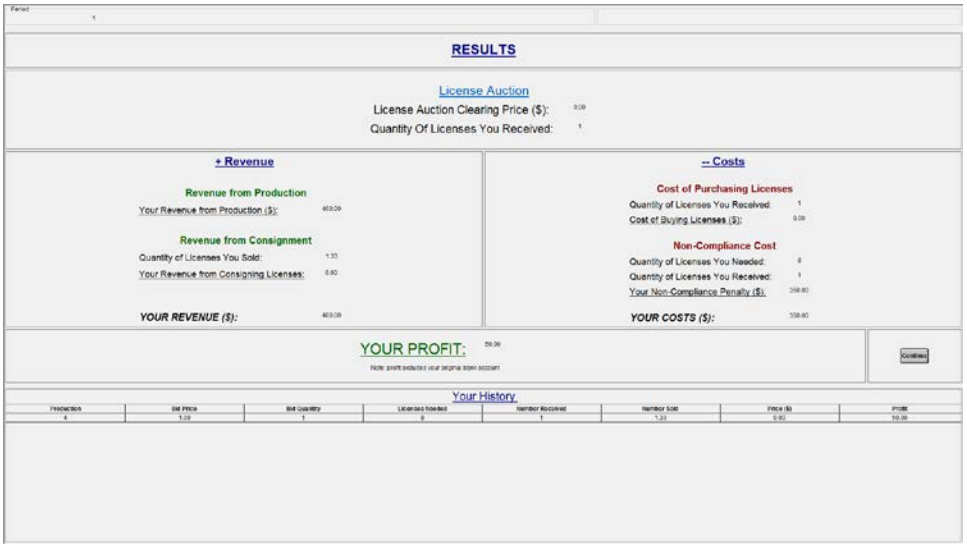
At the bottom of that box, you will see your total costs.

In the bottom center of the screen, next to the green label “Your Profit,” you will see your total profit, which is the difference between your revenues and your costs. Please note, that your bank account is not included in this total. Please also note, if you should ever go negative in profit, or lose money, the computer will record your profit as zero.

Are there any questions at this time?

[Pause]

Unless there are any other questions, please proceed to the next practice auction by clicking the continue button. You will only have one more practice auction. After this, the paid sessions will begin.



RESULTS
License Auction
License Auction Clearing Price ($):
Quantity Of Licenses You Received:
+ Revenue
Revenue from Production
Your Revenue from Production ($):
Revenue from Consignment
Quantity of Licenses You Sold:
Your Revenue from Consigning Licenses:
YOUR REVENUE ($):
-- Costs
Cost of Purchasing Licenses
Quantity of Licenses You Received:
Cost of Buying Licenses ($):
Non-Compliance Cost
Quantity of Licenses You Needed:
Quantity of Licenses You Received:
Your Non-Compliance Penalty ($):
YOUR COSTS ($):
YOUR PROFIT:
Your History