*The Design, Testing and Implementation of Virginia's NOx Allowance Auction**

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I. Introduction

Among economists, at least, the use of tradable emission allowances under an aggregate emission cap is generally considered a mature policy technology. It has become the default policy option in controlling a variety of large scale air emissions, and is being increasingly considered for replacing inefficient source-specific regulation of water pollutants (Tietenberg, 2002). The same policy technology is also being used in fisheries regulation and elsewhere (National Academy of Sciences, 1999). In a competitive emissions market with low transaction costs, the initial allocation of rights will not affect the final use of the allowances. However, how the rights are allocated can have significant economic consequences through its effect on entry and exit decisions and on marginal tax rates (Goulder et al., 1999).

This paper concerns one of the first known cases where emission allowances were auctioned with the explicit intention of maximizing government revenues. On June 30th, 2004, the Commonwealth of Virginia's Department of Environmental Quality (DEQ) sold 3,710 allowances for emission of nitrogen oxides (NOx) in fiscal years 2004 and 2005 using a sequential English clock auction. The auction raised over $10.5 million; 19% above its target revenue of $8.8 million. Before settling on an auction format, Virginia engaged the services of experimental economists to assist in the auction design process. This paper examines the process by which the auction was designed, tested, and implemented.

In March of 2004, the DEQ contracted with the Interdisciplinary Center for Economic Science (ICES) at George Mason University to assist in designing an auction to sell 1,855, or approximately 8%, of its NOx allowances for each of the years 2004 and 2005. The DEQ's main goal for the auction was that it maximize revenue generated for the state. In addition, as a political consideration it was essential that the DEQ avoid negative political consequences from the auction. To this end, DEQ officials indicated that transparency of the auction mechanism was critical.

The law that enabled the auction of the allowances required that all allowances be sold by June 30th, 2004. The limited timeframe to employ such an auction required a mechanism that could be easily and quickly implemented, and that would execute all sales in a short period of time. The process for procuring a vendor and deploying the auction was likely to take no less than one month, so the DEQ insisted that final recommendations for an auction mechanism be presented by May 31st; leaving roughly eight weeks for the design, testing and analysis of alternative auctions.

In general, there are two potential pricing formats available to the auction designer: discriminatory (or "pay-as-bid") and uniform price rules. Auctions that use discriminatory pricing pose an ex-post problem to participants, particularly those who are bidding agents for firms. Specifically, nearly all participants who are included in the final allocation realize that they could have bid less and still obtained the same set of units. Furthermore, since discriminatory pricing encourages strategic bidding below value, there is often a set of bidders who could have made it into the final allocation by submitting a bid that more truthfully revealed their willingness to pay for the good, but failed to do so in their pursuit of extra profits. Thus, discriminatory auctions pose a sort of catch-22 to bidders: a bidder who wins has paid too much; a bidder who loses has bid too little.

Auctions that use a uniform pricing rule avoid this problem: all bidders pay one price, so no winning bidding agent appears to have secured a poorer contract for his principal than any other winning agent. Moreover, uniform pricing rules can encourage more revelation of bidders' willingness to pay.[1] However, uniform pricing creates a new problem on behalf of the government seller. The bidding information that is used to determine the price is available to the public, who may be disturbed by what they perceive as excessive surplus left in the bidders' pockets.[2] In the context of the Virginia NOx auction, the DEQ could potentially be second-guessed by the state legislature for not extracting "maximal" revenue from the buyers. Keeping the bidding information secret could resolve this problem, but because the auction was to be held on behalf of the state government, Virginia's Freedom of Information Act required eventual full disclosure of all bids.

[1] In the case of single-unit demand, a uniform price set equal to the highest rejected bid elicit full revelation. Ausubel & Crampton (1996) demonstrate that in multi-unit demand environments (as presented here) bidders have an incentive to demand reduce on all but their highest valued unit, as doing so may affect the price paid. However, Miller & Plott (1985) and Cox, Smith & Walker (1985) find higher levels of revelation among subjects under a uniform price rule as compared to discriminatory pricing.

[2] For example, in November of 2000 just prior to the demise of the California Power Exchange (CPX), CEO George Sladoje wrote an open letter announcing that, because of public pressure, a Blue Ribbon Panel had been formed to examine the CPX's policy of running a uniform-price rather than pay-as-offered auction for electricity. Apparently, during the ongoing investigations into the upheaval in California prices, several parties had suggested that switching the CPX to use of a ``pay-as-offered'' auction would go a long way toward curtailing inflated and volatile wholesale electricity prices.

Time constraints further complicated the selection of an appropriate mechanism. The two allowance vintages (2004 and 2005) were asymmetric substitutes and carried the risk of depreciation.[3] These characteristics meant that the revenue maximizing allocation would likely require the use of flexible combinatorial bids and linear optimization techniques. However, any such auction would be unfamiliar to potential participants and could require extensive training sessions for which there was little or no time given the proximity of the deadline for executing the auction. Complicated bidding and allocation rules could also deter potential buyers from participating, which would reduce the auction's ability to generate revenue. DEQ initially selected a combinatorial clock design, but the complexity of implementation proved prohibitive in the available timeframe, and ultimately a sequential clock was implemented instead.

Through laboratory experiments, we estimate that, under elastic demand conditions, a combinatorial pay-as-bid auction would have allowed the state to capture roughly 61% of the available surplus. Assuming unitary elasticity of demand, a sequential or combinatorial clock auction would generate the same level of revenue. However, in more elastic environments the both clock auctions outperform a pay-as-bid rule. For instance, with elasticity of demand equal to two using a sequential clock auction or combinatorial clock auction would increase the state's share to 71.4% or 74.1% respectively.[4] In our experiments, all three mechanisms yielded an allocative efficiency of 95% or better.

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[3] These characteristics of the commodities that were to be auctioned are discussed in section II

II. Background Information

NOx emissions from large emitters in Virginia and 18 other states in the eastern U.S. are governed by a cap-and-trade system of pollution allowances.[5] Total NOx emissions are capped at approximately 500,000 tons per year. Allowances are freely tradable throughout the 19-state region. There is an active private market for the trading of NOx allowances. In the month of May, 2004 3,000 allowances (0.6% of the total allowances available) were traded in the over-the-counter market. Brokers post a current bid/ask spread for 50 tons. According to www.natsource.com on June 23, the day prior to the auction, the spread for 2004 allowances was $2,200/$2,350 and for 2005 allowances $3,150/$3,200.

Each state has a NOx emissions budget, and has considerable flexibility in allocating its budgeted emission allowances to sources. In Virginia, allowances specific to their year of issuance are allocated to firms for whom NOx emissions are a byproduct of production.[6] Allowances are issued in one-ton face values, and are "bankable": allowances issued in year *y* may be saved for use in year *y* + 1 or later. However, emitters cannot borrow against future issuances of allowances for use in the current year. This asymmetric substitutability suggests that firms who needed the right to emit in 2005 would be willing to use allowances for 2004 instead, but the reverse does not hold.

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[4] In more inelastic demand environments the clock auctions become relatively less advantageous for revenue generation.

[5] For an excellent synopsis of this and related programs see Burtraw et al. (2005).

[6] Virginia Administrative Code, 2004.

However, the use of banked allowances is subject to a constraint designed to control the rate of their use in a given year.[7] By law, if the number of allowances carried over *region-wide* from year y to year $y+1$ exceeds 10% of the total regional budget for year $y+1$ (referred to in this paper as the "banking threshold"), then only a fraction of the source's banked allowances may be used to cover the emission of one ton of NOx in year $y+1$; the remaining banked allowances may only be used for 50% of their nominal value, or half of a ton. The proportion of the banked allowances that may be used to cover a ton of NOx is determined by the ratio of 10% of the regional budget divided by the regional total of banked allowances. If, for instance, a firm banked 99 tons of emission allowances of vintage 2004 for use in 2005, and regional banking amounted to 15% of the 2005 budget, only two thirds (10%/15%) of a firm's banked allowances would retain their face value of one ton of NOx emissions each. The remaining one third (33 out of 99) of the banked allowances could only be used to cover one half of a ton each of NOx emissions, leaving the firm with a total coverage of 82.5 tons.

This feature complicated the substitutability of 2004 allowances for 2005 allowances, as the likelihood that some 2004 allowances would lose half their face value would lead bidders to demand them at an appropriate discount. In early March, local NOx exchanges[8] were trading 2004 allowances for around $2,000 and 2005 allowances for $3,500, indicating that the banking threshold was very much believed to be a binding constraint.

[7] Virginia Administrative Code, 2004.

In Virginia, most emission allowances are given to firms in recognition of their historical rights to emit established by past fossil fuel inputs. Approximately 8% of 2004 and 2005 allowances were set aside for allocation among new sources of NOx emissions in each year.[9] The original intent of the legislature was to dispense the set aside allowances at no charge upon request from new firms.[10] However, because the state was facing budget difficulties (as was common among many states at the time), the legislature decided that these set aside allowances should be auctioned rather than freely granted to new sources.[11]

It is important to note that while a standard assumption of auction theory is that bidders draw their willingness-to-pay (i.e., value) for each unit from a known distribution, we had reason to believe that this would not be the case for the Virginia NOx auction. Bidders could come from a number of industries in eighteen states, so that for any one bidder there could be substantial uncertainty regarding the demand functions of his counterparts. Furthermore, new firms, whose value functions would be unknown, could also be potential competitors. Finally, although the spot markets for NOx are a ready source of previous contract *prices*, the range of these prices could not be considered the distribution of *values*, as each contract price need only fall somewhere between the buyer's and seller's use value for 50 tons of NOx. As a result, we expected considerable bidder uncertainty with regards to competitors' values.

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[8] Data on prices and trading volume may be found at www.natsource.com and www.evomarkets.com.
[9] Virginia Administrative Code, 2004.
[10] See § 10.1-1322.3 Code of Virginia.
[11] Subsection D of Item 383 of Chapter 899 of the 2002 Acts of Assembly, Commonwealth of Virginia.

III. Auction Design

The conventional wisdom in the design of auctions is that the details matter (Klemperer, 2002). Moreover, the price discovery process requires that substitute goods be offered simultaneously and that the auction is iterative so that prices move in response to excess demand (Milgrom 2000). However, as one provides for an open iterative auction, the ability of the bidders to tacitly collude is increased (Klemperer, 1999). These issues suggest that no matter what designs are selected, it is important to test their properties in controlled settings (Ledyard, 1993; and Smith, 1994). We begin by defining the goods being auctioned.

1. Allowance Characteristics

Recall that allowances are bankable: the 2004 allowance is a substitute for 2005 allowance, but the converse is not true. However, there is chance that if too many 2004 allowances are banked region-wide, they will be discounted in any future year that the banking threshold is exceeded. A standard price/quantity (PQ) auction would have each participant bid separately on each allowance type, where P is the price per unit of the bid and Q is the maximum number of allowances that the bidder would be willing to accept at or below the price P. Participants submitting such bids would be unable to indicate to the auctioneer whether they were willing to accept 2004 allowances in place of 2005 allowances, and if so, the exchange rate at which they would be willing to do so. This would force bidders to choose between bidding too conservatively or exposing themselves to financial loss. It would also deny the auctioneer flexibility in selecting an allocation to maximize revenue and efficiency.

2. Alternative Auction Mechanisms

The auction mechanisms we tested can be categorized into two generic formats: sealed bid without iteration and iterative English clock. The sealed-bid auction for allowances is an extension of the familiar first price auction that also allows bids for alternative vintages (2004 and 2005) to be linked. The iterative English clock is tested with simultaneous linked clocks and also with sequential auctions.

2.1 Sealed Bid Auction

The simplest and most transparent of all auction mechanisms is the simple sealed bid first price auction, in which participants submit bids by a given deadline and units are allocated to the high bidders on a pay-as-bid basis. In our tests this sealed bid auction framework was augmented by replacing the standard PQ bids with "Any/Or" (AO) bids. These bids take the format (p_{04},Q_{04} | p_{05},Q_{05}), where p_4 is the price per allowance that the bidder is willing to pay for a block of up to Q_{04} 2004 allowances, and p_5 is the price per allowance that the bidder is willing to pay for a block of up to Q_{05} 2005 allowances.[12] Bids with Q_{04}, $Q_{05} > 0$ indicate that the bidder is willing to purchase *either* up to Q_{04} 2004 allowances at p_{04} per allowance *or* up to Q_{05} 2005 allowances at p_{05} per allowance *or* any other proportionate combination. The quantities, q_{04} and q_{05}, allocated as a result of this bid are then subject to the following constraints: $q_{04} \leq \delta Q_{04}$; $q_{05} \leq (1\text{-}\delta)Q_{05}$; $0 \leq \delta \leq 1$. For example, a bid of the form (100, 10| 90, 20) could result in 4 allowances of 2004 vintage (δ =.4) and 12 allowances of 2005 vintage (1-δ =.6) being purchased. The AO bid

[12] Bids in which either Q_{04} or Q_{05} is set equal to zero is a standard PQ bid.

increases the message space for bidders to convey their preferences to the auctioneer, and provides the auctioneer considerable flexibility in allocating allowances.

Given each bid $j = 1,..., J_i$ submitted by each participant $i = 1,..., I$, the maximal level of revenue to be derived from selling 1,855 allowances of each vintage can be found by solving the following mixed integer programming problem for the optimal quantities q_{04ij} and q_{05ij} and the proportions δ_{ij}:

Maximize: $\sum_{i=1}^{I}\sum_{j=1}^{J_i}\left(p_{04ij} \cdot q_{04ij} + p_{05ij} \cdot q_{05ij}\right);$

subject to:

$$q_{04ij} \le \delta_{ij} Q_{04ij} \quad \forall \quad i, j$$

$$q_{05ij} \le \left(1 - \delta_{ij}\right) Q_{05ij} \quad \forall \quad i, j$$

$$0 \le \delta_{ij} \le 1 \quad \forall \quad i, j$$

$$\sum_{i=1}^{I}\sum_{j=1}^{J_i} q_{yij} \le 1{,}855 \quad \forall \quad y$$

$$q_{yij} \in \{1,2,3,...\} \quad \forall \quad y, i, j$$

where:

p_{yij} = the per unit bid price for year *y* allowances submitted in the j^{th} bid by bidder i;

Q_{yij} = the maximum quantity of year *y* allowances submitted in the j^{th} bid by bidder i;

q_{yij} = the quantity of year *y* allowances allocated to the j^{th} bid submitted by bidder i.

Although this combinatorial sealed bid (CSB) auction relies on discriminatory pricing and thus presents the aforementioned ex post bidding dilemma to bidders, it remained an attractive option for the DEQ. The sealed bid format was familiar to all parties involved, and this auction could be executed quickly and with a minimum of preparation.[13]

2.2 Clock Auctions

An alternative to sealed bid auctions is the iterative auction, which allows the bidding process to give feedback to bidders to guide their strategy in the auction. One iterative auction which has received much academic attention is the English clock auction. This auction eliminates the right of participants to specify bids. Instead, it uses a clock to quote successive prices, and each bidder is required only to indicate his quantity demanded at the standing price. (McCabe et al., 1988/1991; also see: McCabe et al., 1990; Cramton and Kerr, 2002; Porter et al., 2003; and Banks et al., 2003 who discuss the chaotic problems created in the absence of an English clock auction).

Formally, the English clock auction (ECA) is composed of an unspecified number of rounds, r. In each round, the price p_r is posted on an electronic "clock." In response to the clock price, each bidder $i = 1,...,I$ indicates the quantity for that round, q_{ir}, that he is willing to purchase. With a total supply of Q_s, if $\sum_{i=1}^{I} q_{ir} > Q_s$, the clock price increases

[13] Moreover, the pay-as-bid format rather than a uniform price would allow the DEQ to avoid explaining to legislators why some participants should receive allowances at prices well below their expressed willingness to pay.

by a predetermined increment, ε, to $p_{r+1} = p_r + \varepsilon$ and bidders submit a new set of $q_{i,r+1}$ at the updated price subject to the constraint that $q_{ir} \leq q_{i,r+1}$.

If in round k it is the case that $\sum_{i=1}^{I} q_{ik} = Q_s$, then the auction terminates and every bidder receives q_{ik} units at p_k per unit. If instead it is the case that $\sum_{i=1}^{I} q_{ik} < Q_s$, then every bidder with $q_{ik} > 0$ receives this quantity at p_k per unit. This leaves $Q_s - \sum_{i=1}^{I} q_{ik}$ units to be allocated. Among the remaining bidders for whom it was the case that $q_{i,k-1} < q_{ik}$, participants are selected at random to receive $q_{i,k-1} - q_{ik}$ units at p_{k-1} per unit until these leftover units have been allocated.[14]

For the purposes of the NOx auction, the ECA had two advantages over the CSB. First, previous experiments suggest that a uniform price rule encourages greater revelation of bidders' willingness to pay relative to a pay-as-bid rule, potentially resulting in a more efficient outcome (Miller & Plott, 1985; Cox, Smith & Walker, 1985). Second, it solves the *ex post* predicament of both the bidders and the auctioneer. As a uniform price auction, it ensures that no bidder appears to have paid too high a price, and tends to ensure that those left out of the allocation could not have profitably procured units. As an iterative auction, it stops revealing bidders' demand at the market clearing price, generating no information concerning how much more the buyers might have been willing to pay.

Despite these advantages, the case for an ECA mechanism was not clear-cut. Using one ECA to sell the 2004 allowances and another to sell the 2005 allowances would ignore their combinatorial nature, and might result in lower revenue and efficiency. On the other hand, a combinatorial auction design using simultaneous linked clocks for the ECA would present a more complicated bidding structure to be explained to participants, thus working against the auction's need for transparency and ready adoption by potential participants.

2.2.1 The Sequential English Clock Auction

A straightforward application of the ECA to the NOx auction would be sequential English clock (SEC) auctions. With an SEC, one year's allowances would be sold using the ECA mechanism described above, and the remaining vintage would be sold with a separate ECA at a time soon after. This would allocate the allowances in a straightforward manner, but it would also fall prey to the risk associated with simple PQ bidding in independent auctions.

2.2.2 The Combinatorial English Clock (CEC) Auction

The combinatorial version of the ECA takes into account the potential substitutability of the 2004 and 2005 allowances. Two clocks operate simultaneously, one for each vintage. Prices are posted for each clock. At the posted prices participants respond with quantities for 2004 and 2005. As long as the total quantity demanded of a given vintage is greater

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[14] It may be the case that one participant receives δq_{ik-1} units, where $0 < \delta < 1$.

than its supply, the clock price for that vintage increases. The clocks stop when total demand is less than or equal to the supply for both 2004 and 2005 allowances. If the supply exactly equals the registered demand for each vintage, the allocations are made based on the final clock prices. However, three modifications are necessary in order to allow the CEC to handle substitutions efficiently.

The first modification requires that any participant be allowed to submit multiple bids, each of which register a particular quantity of one particular vintage that he is willing to purchase at the current clock price. The second modification requires that during the auction, as the prices on the clocks increase, a particular bid for a quantity of one vintage can be switched to a quantity of the other. However, the quantity of demand that is switched to a given vintage is limited by any quantity attributable to that bid for that vintage earlier in the auction. For example, if a bidder had registered a bid consisting of demand for 10 of the 2004 allowances at a previous price and wished to switch that bid to the 2005 vintage given the current prices, the quantity of 2005 allowances demanded in this switched bid could not exceed 10 units.

A single exception exists to the above rule. On the first switch only (when no previous quantity of record exists) the following special rules apply: when switching from a lower to a higher priced vintage, the quantity of the higher priced vintage is limited to the quantity currently registered at the lower price; while when switching from a higher to a lower priced vintage, the quantity of the lower priced vintage is limited by the total budget committed to the current bid. The reason for the initial switch asymmetry is to accommodate two types of buyers: those who would seek a fixed quantity though the imperfect substitutes are worth more or less to them, or those who would seek proportionately more of the lesser valued vintage in order to compensate for its reduced quality.[15] For example, if the current clock prices are $1,000 for 2004 and $1,500 for 2005 a current bid of 20 units of 2005 allowances may be switched to 30 units of 2004 allowances if the bidder has not previously switched her bid. However, a current bid of 20 allowances of the 2004 vintage may be switched to a bid of no more than 20 allowances of the 2005 vintage.

The third modification requires that at the end of the auction, if the quantities demanded for at least one vintage are strictly less than the total available, then a revenue maximizing optimization is run (similar to the CSB auction) with the added constraints that bids from all rounds are considered, and any bids accepted from the previous rounds are purchased at the previous rounds' prices.

IV. Experimental Design

In this section we describe the demand parameters used in the experiment, the procedures for implementing the experiments and the treatment design of the experiments.

1. Demand Configuration

The demand conditions for 2004 and 2005 NOx allowances that were to be sold in the State of Virginia DEQ auction were not precisely known. Demand for a significant

[15] In our experiments this first switch rule simplified to the previous quantity in either direction because our subjects were allowed to redeem an equal number units of either 2004 or 2005 allowances, but at reduced

tonnage of emission rights could be similar across vintages or differ significantly.[16] Because of this uncertainty, it was important that the potential auction mechanisms be tested in a variety of demand environments. If one mechanism proved to be superior across environments, from a revenue/efficiency standpoint, a clear recommendation could be provided. If the mechanisms' performances were environment-specific, the DEQ would have to use the best available information on the real-world environment to inform their decision.

Because we were comparing a first-price mechanism with uniform price mechanisms, elasticity of demand was an important consideration. The first-price rule has the revenue reducing tendency to suppress demand revelation, but the revenue enhancing feature of allowing the auctioneer to reap the full benefit of high bids. Additionally, to the extent that demand reduction occurs under a uniform price rule, inelastic demand encourages such strategic behavior by increasing the potential price reduction that can be achieved by the bidders. The uniform price rule encourages fuller demand revelation, but awards units to the high bidders at a discount. In general, the elasticity of the demand function determines which of these opposing forces will dominate, and therefore determines the revenue-maximizing auction mechanism. In particular, inelastic demands have larger revenue gains when individuals pay as bid relative to a uniform price rule. However,

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values for the inferior quality (2004) good.

[16] Available data from brokerage firms was not sufficient to eliminate this uncertainty. In addition to the difficulty of inferring demand schedules from price data, the volume of a given contract executed by those firms did not exceed 50 tons. The state's auction, on the other hand, could theoretically allocate nearly *two thousand* tons of a given vintage to a single bidder.

when demand is elastic there is more room for revenue losses from systematic bid shading with the pay-as-bid incentive versus the uniform price rule. [17]

The magnitude of differences in the competitive equilibrium (CE) price[18] between allowance vintages also had the potential to affect the performance of a given mechanism. If the CE price was almost the same across vintages, there may have been no need to allocate 2004 allowances to participants seeking 2005 allowances. In such a case, sequential auctions could be just as effective at efficiently allocating allowances and maximizing revenue as simultaneous auctions. However, if the CE price for 2004 allowances were significantly lower than their 2005 counterparts, there would be those willing to purchase and bank 2004 allowances for later use even though they faced a probability of devaluation by the EPA. Similarly, speculators would always be willing to reinvest their budget in whichever year's allowances seemed most undervalued. In this case, carefully measured substitutions reflected by strategic bidding would likely become necessary, and the combinatorial auction designs should dominate.

In order to determine how different auction mechanisms fare under the demand conditions described above, each experimental session consisted of testing a single auction mechanism with at least three repetitions under each of the four value environments shown in Table 1. Subjects, unbeknownst to themselves, faced the value

[17] We refer the reader once again to Miller & Plott (1985) and Cox, Smith & Walker (1985), who find higher revenues in uniform price auctions under elastic demand conditions and discriminatory price auctions under inelastic demand conditions.

[18] The competitive equilibrium price is the price at which, if all units were sold at a uniform price, the quantity supplied would exactly equal the quantity demanded, and only the participants with the highest values for the good would be included in the allocation. Here, by CE price for a given allowance vintage

environments in rotation, so that every four auctions comprised a cycle. Values during each cycle were disguised from the previous cycle by shifting and rotating demand schedules so that subjects could not easily develop accurate forecasts concerning competitive prices on the basis of their assigned redemption values. In each session, then, subjects went through at least three complete value environment cycles.

Table 1: Value Environments

	Elastic Demand	Inelastic Demand
Same CE Price for both vintages	4	4
Different CE Prices for both vintages	4	4

In addition, for the CSB one feature of interest was the minimum accepted bid. Auction theory predicts that subjects' bids will be a function of their value, the distribution of values, and the number of competing bidders (Vickrey, 1961). Nevertheless, minimum accepted bids are a common safeguard against collusive activity among bidders. In most auctions we set the minimum accepted bids below the lowest assigned value, so that it was not a binding constraint. However, we also ran a number of auctions in which the minimum accepted bid was arbitrarily increased to make it a binding constraint. The effects of this high minimum bid in the laboratory would provide guidance to the DEQ as

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we mean the CE price if only units of that vintage were up for auction, or if they were each auctioned separately.

to whether the minimum accepted bid in the auction could be increased to improve revenue performance.

2. Experimental Procedures

A total of 25 experiment sessions were conducted, each using 11 to 12 volunteer human subjects selected at random from the George Mason University graduate and undergraduate population. Subjects were given oral instructions explaining the bidding and allocation processes of the mechanism under observation. No reference to NOx, emissions, pollution, or any other situation specific element was made in the instructions, to prevent subjects' behavior from being motivated by influences other than their potential payoffs.

All subjects' decisions were made through their private computer terminals, and communication between subjects was prohibited so as to prevent collusive behavior. Subjects received a small ($10) payment for attending the session, and the remainder of their earnings was based on their decisions during the experiment. Each experimental session lasted approximately 2 hours and the average earnings of a subject were $47.30.

Prior to each auction, each subject i was assigned $J_i \in \{3,4,6,7,9\}$ redemption values for one or both abstract goods representing 2004 and 2005 pollution allowances (denoted $v_{04,ij}$ and $v_{05,ij}$ respectively). Participants were motivated to buy units of the goods in the test auctions by being told at what precise cash value they could redeem each unit purchased in each auction. For convenience in exposition, we will refer to the abstract goods sold to the subjects in the test auctions as 2004 and 2005 allowances. Each value was for exactly one allowance of one vintage. In accordance with our beliefs regarding bidders' uncertainty with regard to the distribution of values, subjects were given no information on the values (or even the range of values) of their counterparts.

To model the imperfect substitutability of 2004 and 2005 allowances in the test auctions, some subjects were told that for a given allowance index j, they could purchase and redeem *either* one 2004 allowance at a value of $v_{04,ij}$ *or* one 2005 allowance at a value of $v_{05,ij}$, but not both.

Specifically, eight of twelve subjects received simultaneous substitutable values for both allowance vintages, with the value for each 2004 allowance given as some discounted value of the corresponding 2005 allowance. These subjects represented bidders who wish to emit in 2005 (or later) and have differing expectations of the probability that 2004 allowances will have their nominal tonnage value reduced, or bidders who intend to resell allowances purchased (speculate) and have differing expectations on future resale values. Subjects' discounted 2004 values ranged from 50% of the 2005 value (i.e., absolute certainty that 2004 allowances would be devalued) to 100% of the 2005 value (i.e., absolute certainty that there is future allowance equivalence).

Four of twelve subjects received values only for 2004 allowances. These subjects represented bidders who need to meet compliance standards in 2004, and for whom 2005 allowances would be of no use. For simplicity, no subjects were modeled as bidders who wished to procure emissions allowances for use in both 2004 and 2005. In cases where fewer than twelve subjects were available, the number of subjects valuing only 2004 allowances was reduced, and each such subject remaining was given an increased number of redemption values for those allowances, so that the total demand in the auction remained the same. No sessions were run with fewer than eleven subjects.

3. Treatment Design

As noted above, we tested three auction mechanisms with declared reserve prices. The initial treatment design was to conduct five experimental sessions on each mechanism. A good response from our subject pool, however, allowed us to run more.

In a given experimental session, each auction executed yielded one observation on the auction treatment being tested. Because of potential learning effects, observations from the first demand cycle (four auctions) during each session were excluded from the data analysis. Table 2 summarizes the number of sessions, subjects, and observations (after trimming the first four auctions per session) for each auction treatment.

Table 2: Treatment Design and Summary of Data Collected

Comment [AMW1]: I think we should combine the SEC 04-05 and SEC 05-04 data as mentioned above.

Treatment	Sessions	Subjects	Observations
CSB (Combinatorial Sealed Bid)	8	96	120
SEC (Sequential English Clock)	11	132	88
CEC (Combinatorial English Clock)	6	69	75
Total	**25**	**297**	**283**

Thus, we collected data for three auction treatments in each of the four environment treatments previously described in Table 1.

V. Results

The purpose of the experiments was to study revenues generated and allocation efficiency under various auction treatments. Because there are possible session and environment effects we use random effects models for the statistical analysis.[19]

Dependent Variables

The dependent variable for the revenue model is revenue in a given round normalized by the maximum possible surplus in that round. For the efficiency model the dependent variable is the sum of values satisfied by the final allocation normalized by the sum of values that would be satisfied by the optimal allocation. These variables allowed us to determine the percentage of the available surplus claimed by the auctioneer and the percentage of available social surplus realized by the auction.

1. Independent Variables

The primary independent variables are dummies indicating the auction mechanism used in a given observation (*SEC* and *CEC*).[20] To test the hypothesis that the auctions' revenue generation varied in more complex CE environments, we also include the dummy variable *Diff*, which took a value of 1 when the CE prices of the 2004 and 2005 vintages were different and 0 otherwise. *Diff* was interacted with the mechanism variables to allow for differences across auction types.

[19] Data used in our analysis and instructions for the experiments can be found at ices3.gmu.edu/VA_NoX

As noted above, the more inelastic the demand environment, the larger the discount uniform pricing confers on participants' bids. Moreover, demand elasticity in the neighborhood of the competitive equilibrium price is an important component of bidders' incentive to demand reduce in a uniform price auction and may therefore affect its ability to generate revenue. We define *AveElast* as the absolute value of the average elasticity of demand of both allowance vintages within two units on either side of their respective competitive equilibria. *AveElast* is bounded between 0 and ∞, with 0 indicating perfectly inelastic demand and ∞ indicating perfectly elastic demand.[21] The inclusion of this variable brings with it the implication that the treatment dummies measure revenue generation in a perfectly inelastic demand environment.

We statistically estimate the impact of the high minimum accepted bid rule with the dummy variable *HighMin*. As a binding constraint on bids the high minimum accepted bid rule sometimes resulted in a suboptimal quantity of units being awarded. The deviation from the optimal quantity allocated is captured in *DevUnits*.

All experiments were run with twelve subjects with the exception of three of the CEC sessions, in which the show-up rate would support only the eleven subject design. Because lower numbers of bidders tend to suppress competitive bidding, and because the eleven subject design was only used in the CEC treatment, we included the dummy

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[20] The CSB served as the baseline. Thus the constant term (α) represents the normalized revenue generated from a CSB.
[21] Observed values of *AveElast* ranged between 0.574 and 2.8.

variable *DevSubs,* which indicated sessions in which the number of subjects deviated from twelve.

Finally, four treatment-specific variables were included to account for learning effects. Each session consisted of a number of cycles through four value environments. Thus the variable *Cycle* was included which simply indicated the cycle in the session in which the observed auction took place. *Cycle* was also interacted with the treatment dummies to account for the possibility that learning occurred differently in the various auction mechanisms.

2. Revenue Results

Result 1: The CSB outperformed both English Clock designs in inelastic environments.

Support: The results of the revenue model are contained in Table 3. The estimated constant is 0.61 ($p < 0.001$), indicating that the CSB would generate 61% of the maximum revenue in a perfectly inelastic demand environment. The coefficients on *CEC* and *SEC* are both negative and significant ($p < 0.001$ in each case), and suggest that the two mechanisms would generate 47.12% and 48.19% respectively of the maximum revenue given perfectly inelastic demand.

Result 2: Elastic demand increased revenue in both English Clock mechanisms, but not in the CSB.

Support: The estimated coefficients on the *CEC*AveElast* and *SEC*AveElast* variables are both positive and significant ($p < 0.001$ in each case), while the estimated coefficient for *AveElast* is very small and falls just short of significance at conventional levels (p = 0.71). Elasticity so enhances the revenue generating properties of the English Clock mechanisms that unitary average elasticity of demand (i.e. *AveElast* = 1) is sufficient to equalize revenue across all mechanisms.[22] Holding the CE price constant across vintages, the CEC generates significantly more revenue that the CSB at an average elasticity of 1.5, while an average elasticity of 1.8 is necessary for the SEC to significantly outperform the CSB.[23] This suggests that the CEC is the preferred mechanism in a wider range of demand environments than the SEC. Combined with result 1, result 2 confirms our hypothesis that the English clock designs would generate more revenue than the CSB in elastic demand environments but less in inelastic environments.

Result 3: Differences in CE prices between allowance vintages negatively impact revenue generation in the CEC and SEC, but not the CSB.

Support: *Diff* does not have a statistically significant coefficient, indicating that different CE prices across vintages did not affect the performance of the CSB. However, the coefficients of both *CEC*Diff* and *SEC*Diff* are negative and significant ($p < 0.01$ in

[22] Wald tests on the hypotheses *CEC* + *CEC*AveElast* = 0 and *SEC* + *SEC*AveElast* = 0 return p-values of 0.904 and 0.761 respectively.
[23] Wald tests on the hypotheses *CEC* + 1.5(*CEC*AveElast*) = 0 and *SEC* + 1.8(*SEC*AveElast*) allow us to reject the nulls with $p = 0.046$ and $p = 0.043$ respectively.

both cases). The results indicate that both English Clock mechanisms generate roughly 5% less of the maximum revenue in complex combinatorial environments. When the total surplus is expected to be in the tens of millions of dollars, this effect is non-trivial. Notice, however, that the magnitude of the *AveElast* interaction variables are such that sufficiently elastic demand will more than offset this loss of revenue. An average elasticity of 1.9 is sufficient for the CEC to generate more revenue than the CSB when CE prices differ across vintages. The SEC requires an average elasticity of 2.2.[24]

[24] Wald tests of the hypotheses *CEC* + *CEC**Diff* + 1.9(*CEC**AveElast*) = 0 and *SEC* + *SEC**Diff* + 2.2(*SEC**AveElast*) = 0 allow us to reject the nulls with $p = 0.039$ and $p = 0.047$ respectively.

Table 3. Revenue Generation Results from Random Effects Regression

Variable	Coefficient	Standard Error	P-Statistic
α *(CSB)*	0.61**	0.0201	0.000
β_1*(AveElast)*	0.001	0.0055	0.071
β_2*(Diff)*	0.0034	0.013	0.791
β_3*(CEC)*	-0.1388**	0.0347	0.000
β_4*(CEC*AveElast)*	0.1349**	0.0086	0.000
β_5*(CEC*Diff)*	-0.0525**	0.0188	0.005
β_6*(SEC)*	-0.1281**	0.042	0.002
β_7*(SEC*AveElast)*	0.1159**	0.0082	0.000
β_8*(SEC*Diff)*	-0.0477**	0.0181	0.008
β_{12}*(HighMin)*	0.1834**	0.0138	0.000
β_{13}*(DevUnits)*	-0.0134**	0.0021	0.000
β_{14}*(DevSubs)*	-0.0601*	0.028	0.032
β_{15}*(Cycle)*	0.0015	0.0043	0.732
β_{16}*(CEC*Cycle)*	0.0045	0.0088	0.607
β_{17}*(SEC*Cycle)*	0.0143	0.0133	0.279
Observations	283	R^2	0.7635

* Indicates confidence at or 95% or higher.

** Indicates confidence at 99% or higher.

Result 4: High minimum bids increased revenues, but this was somewhat offset by unallocated units

Support: The *HighMin* coefficient is of substantial magnitude: 0. 1834 ($p < 0.001$). Auctions in which a bid-constraining minimum accepted bid was imposed generated over 18% more of the available revenues than auctions in which the minimum accepted bid was non-constraining. However, note the *DevUnits* coefficient of -0.0134 ($p = 0.000$). This implies that if the minimum accepted bid is raised beyond the CE price, 1.3% of the available revenue is lost for each unit that remains unallocated. In our experimental environment 13 units (about 36% of the total available) would have to remain unallocated to fully offset the revenue enhancement of the high minimum accepted bid rule. We should note, however, that the DEQ considered a failure to sell all available units a political liability, as it could raise questions about foregone revenue from the unsold allowances.

Result 5: There was no learning from cycle to cycle.

Support: Neither *Cycle* nor any of its interactions with the treatment dummies have statistically significant coefficients. We therefore cannot reject the hypothesis that participants' bidding behavior remains constant for all cycles after the first.

These results show that given sufficiently elastic demand, the CEC is the revenue maximizing mechanism, but the CSB raises more revenue in inelastic demand environments. Although a significantly large block of allowances was to be offered in the auction, we suspected that the revealed demand in the DEQ's auction would be quite elastic as participants were unlikely to pay prices significantly higher than those being charged elsewhere in existing over-the-counter markets for NOx allowances.

2. Efficiency Results

Result 6: Efficiency across mechanisms is comparable irrespective of the environment.

Support: Results from the regression on efficiency are contained in Table 4. The constant term indicates that the CSB is roughly 95.5% efficient in perfectly inelastic demand environments with identical CE prices across allowance vintages. Neither *CEC* nor *SEC* have significant coefficients, so we cannot reject the null that the English clock auctions are equally efficient in the same environment. Increasingly elastic demand does improve the performance of the CEC and SEC relative to the CSB, but the effect is very small (less than 1% per unit increase in average elasticity in each case). In complex demand environments, the CSB gained 1.45% of the maximum surplus ($p < 0.001$), while the CEC and SEC lost 1.55% ($p = 0.009$) and 2.35% ($p = 0.20$) respectively. Taken as a whole, these results suggest that efficiency would be roughly 95% regardless of the auction mechanism chosen.

Result 7: A high minimum bid rule slightly increases efficiency, but is quickly counteracted by unallocated units.

Support: The *HighMin* coefficient predicts 3.15% in additional social surplus when the high minimum accepted bid rule is in place ($p < 0.001$). However, *DevUnits* is estimated at -0.0238 ($p < 0.001$), indicating that when just two units (5.6% of available units) go unallocated the net effect of the rule is damaging to efficiency.

Table 4. Efficiency Results from Random Effects Regression

Variable	Coefficient	Standard Error	P-Statistic
α (CSB)	0.9546**	0.0058	0.000
β_1*(AveElast)*	-0.0008	0.0017	0.647
β_2*(DIFF)*	0.0145**	0.0041	0.000
β_3*(CEC)*	0.018	0.0098	0.068
β_4*(CEC*AveElast)*	0.007**	0.0027	0.010
β_5*(CEC*DIFF)*	-0.0155**	0.0059	0.009
β_6*(SEC)*	-0.0028	0.0128	0.826
β_7*(SEC*AveElast)*	0.006*	0.0026	0.020
β_8*(SEC*DIFF)*	-0.0235**	0.0057	0.000
β_{12}*(HighMin)*	0.0315**	0.0043	0.000
β_{13}*(DevUnits)*	-0.0238**	0.0007	0.000
β_{14}*(DevSubs)*	-0.0103	0.0068	0.127
β_{15}*(Cycle)*	0.0009	0.0013	0.498
β_{16}*(CEC*Cycle)*	0.0006	0.0028	0.817
β_{17}*(SEC*Cycle)*	0.0093*	0.0042	0.026
Observations	283	R^2	0.8863

* Indicates confidence at or 95% or higher.

** Indicates confidence at 99% or higher.

Result 8: Learning occurred only in the SEC treatment.

Support: Among the interaction variables including *Cycle*, only *SEC*Cycle* is significant (p = 0.026). It is, however, fairly small, indicating an improvement in efficiency of less than 1% per cycle.

V. Implementation Summary and Conclusions

Whatever their strengths and limitations, economic experiments in support of public policy decisions are only one step in the policy design and implementation process. The Virginia NOx allowance auction had to be implemented on an extremely tight time line in order to meet a statutory deadline. This tight timeline had three important effects: first, it forced state administrators to make very quick decisions; second, it forced selection of an easily implemented auction design that would be attractive to potential participants; and third, it limited the opportunities for involvement by outside parties in the decision process.

In late April of 2004, the staff responsible for the auction received reports of experimental results demonstrating a potentially significant revenue advantage of using a combinatorial English clock auction over a combinatorial sealed bid design.[25] The results of this research were not made public. Due to the short time line, those involved assumed that a sealed bid auction would be the only practicable option. A request for proposals (RFP) for brokerage services to implement an auction was published on May 17 for a 10-day period mandated by state procurement rules. Review of bids began on May 27. The

RFP had not specified an auction form and most proposals included either a sealed bid design or standard brokerage services or both. Astonishingly, the proposal from Amerex Energy of Houston recommended an English clock auction.[26] The proposal contained assurances that the auction could, in fact, be accomplished within the short remaining time period. This proposal was selected for its potential to achieve higher revenues as indicated by the experimental results. The contract for services was signed on June 8, just 22 days before the final deadline to hold the auction.

The extremely tight deadline for holding the auction drove a number of choices about the final auction design. A web-based auction design was chosen to maximize participation and to minimize the time needed for software development. To prevent bidders from using strategies based on default, all bidders had to demonstrate credit-worthiness with a credit instrument or an escrow account with their maximum possible bid.[27] A key compromise was the abandonment of the combinatorial auction design. Given the short time for training bidders, the hard choice was made to abandon combinatorial bidding in favor of two separate, sequential auctions of the 2004 and 2005 vintages.[28]

On June 24, the auction was held in two sessions. Vintage 2004 allowances were sold in the morning and 2005 allowances in the afternoon. Bidders included energy companies

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[25] Our expectation of this revenue advantage stemmed from our prediction that most bidders would not bid substantially more than the current spot market price for allowances. Regardless of underlying demand, revealed demand would therefore tend to be quite elastic.

[26] According to personal conversation with Amerex staff, the firm conducted research on the issue of emission auction design on the internet. An article by Cramton and Kerr (2002) convinced them that the English clock design should be used in their proposal.

[27] Some potential bidders refused to participate due to this requirement.

[28] The brokers received signals from several important potential bidders that they might refuse to participate under the novel, not-well-understood, combinatorial bidding format.

from across the 19-state region and a number of brokerage houses. In each case, the first two rounds were executed in 15 minutes each with all subsequent rounds executed in only 10 minutes each. Starting prices, at $1,900 and $2,900 for 2004 and 2005 respectively, were set, based on morning spot prices. In any round in which there was excess demand, the clock price ticked up by a predetermined increment in the next round: $50 for the first 2 rounds and $25 for any round after that.

Starting with 18 bidders, the 2004 auction went 15 rounds in 160 minutes. There were 10 winning bidders at the clearing price of $2,325, which was 3.3% higher than a morning transaction on the spot market. Sixteen bidders entered the 2005 auction, which went 19 rounds in 200 minutes. There were 5 winning bidders at the clearing price of $3,425, a 7% premium over the morning spot market trades. All of the winning bidders were energy firms. The $10.5 million in net revenues were deposited to the state's general fund. The Cantor Fitzgerald market index for 2004 NOx allowances rose 4.36% on the day, and 6.14% for 2005 allowances.[29]

Every application of an economic design problem in the field has its own unique features even though ex post it may be the case that some of the learning from past experience transfers to the new situation. The advantages of using the laboratory to test-bed a new application are that 1) it enables exploration of the parameter space where there are no empirical guidelines to identify the parameters, e. g., demand elasticity for allowances; 2) by comparing the revenue and efficiency of alternative auction designs it sets the stage for a more informed decision if compromises have to be made to satisfy time or other constraints on the final choice; 3) by reducing uncertainty and demonstrating feasibility—non-experts can actually execute the procedures—it enables all parties to feel more comfortable and confident of their ability to achieve a satisfactory outcome; 4) in this instance, it facilitated the final choice of a contractor to run the auction; and 5) the cost of achieving these benefits is small—in this case, less than 1% of the resulting revenue from the auction.

[29] See www.emissionstrading.com.

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