Mechanism Choice in Emission Allowance Auctions: An Empirical Analysis of the Sulfur Dioxide Allowance Auction

Rong Zhou

Department of Economics, University of Connecticut

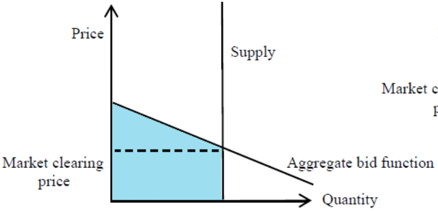
August 2015

Introduction

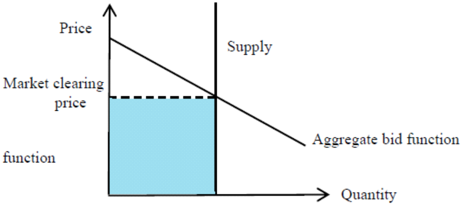
- There is increasing interest in permits in environmental policies.
  - e.g., air and water pollution rights, fishing rights
- Permits are allocated either for free (grandfathering) or through auctions.
- Two most widely used auction mechanisms:
  - Discriminatory price auction ("pay-as-bid" auction): the SO_2 permit auction in the US.
  - Uniform price auction: the GHG permit auctions under the EU ETS and the RGGI in the US.

Introduction (cont.)

- Two mechanisms differ in the way bidders are charged & the incentives to underbid, which lead to different outcomes, e.g.,
  - Allocations
  - Market-clearing prices
  - Revenues



(a) Discriminatory auction



(b) Uniform auction

Motivation

- In the auction literature:
  - There is not a consensus on which mechanism performs better (e.g., Ausubel and Cramton, 2002; Engelbrecht-Wiggans and Kahn, 1998a, 1998b; Hortaçsu and McAdams, 2010).
  - It depends on bidders' actual valuations (Ausubel and Cramton, 2002).
- In the emission permit auction literature:
  - Theoretical studies (e.g., Cason, 1993; Dijkstra and Haan, 2001)
  - Descriptive analyses (e.g., Joskow et al., 1998; Lopomo et al., 2011)
  - Experimental studies
    - They assume parametric distributions of bidders' valuations.
    - Some find that a uniform price auction performs better than a discriminatory one, in terms of efficiency and revenue (e.g., Cason and Plott, 1996).

The main purpose and the method

- Purpose: evaluate the performance of a permit auction, based on a framework from the auction literature, using (recovered) actual valuations instead of hypothetical ones. (The application is the discriminatory SO_2 allowance auction.)
- Method:
  1. Recover bidders' true valuations (i.e., max WTP) from the observed individual-level bid data, based on a structural model from the auction literature.
  2. Evaluate the performance of the discriminatory SO_2 auction and conduct counterfactual comparisons based on the recovered valuations.

Two main contributions

First, I apply a structural model from the empirical auction literature to the study of permit auctions.

- It allows me to recover bidders' valuations from the observed individual-level bid data.
- It provides some new insights into mechanism choice in an emission permit auction.

Second, I propose an alternative way to construct the bounds on the marginal valuation functions (i.e., WTP).

- The literature typically assumes discrete marginal valuation functions (Chapman et al., 2007; Hortaçsu and McAdams, 2010; McAdams, 2008).
- This paper considers a more general case, assuming continuous marginal valuation functions.

Outline of the discussion

- Background on the SO_2 permit auction
- Data
- Model of a discriminatory emission permit auction
- Empirical strategy
- Results: estimated marginal valuations & evaluation of the auction
- Robustness check
- Conclusion

Background on the SO2 permit auction

- The SO_2 allowance trading program
  - Created by Title IV of the Clean Air Act Amendments of 1990.
  - Implemented in two phases:
    - Phase I (from 1995 to 1999): an annual 5.7 million permits (tons) were allocated to the 263 dirtiest large generation units.
    - Phase II (since 2000): nearly all fossil-fueled electric generation units over 25MW are subject to an aggregate cap of 8.95 million tons annually.
- The EPA withdraws 250,000 permits (2.8% of total) to auction off.
  - discriminatory mechanism

Data

- EPA's SO_2 Permit Auction website: names of bidders, individual-level bid price-quantity pairs, revenues, etc.
- Period: 2003 to 2010
- Three categories of bidders:
  - environmentalists
  - emitters (e.g., American Electric Power, Granite Ridge Energy LLC)
  - brokers (e.g., Morgan Stanley, Element Markets LLC)

Summary statistics

Table Summary statistics

Variables	Mean	Std. Dev.	Min	Max
Number of bidders in an auction	22.63	8.21	14	38
Number of emitters in an auction	8.625	5.40	4	21
Number of brokers in an auction	5.875	3.36	2	11
Number of successful bidders in an auction	12.13	5.87	3	20
Number of bidpoints in an auction	80.25	18.13	58	115
Number of successful bidpoints in an auction	28.38	12.52	14	52
Market clearing price (dollar)	361.67	293.69	36.20	860.07
Auction revenue (thousand dollars)	46437.71	37471.50	4713.84	110388
Quantity demanded (thousand)	506.13	199.50	288.54	892.34
Demand from environmentalists (%)	0.006	0.004	0.002	0.013
Demand from emitters (%)	56.86	25.77	24.26	79.66
Demand from brokers (%)	43.13	25.77	20.33	75.73
Cover ratio	28.08	10.44	14.01	43.32

Notes:

1. * refers to the number of bidders that won at least one unit.
2. † refers to the number of total bidpoints submitted by all bidders, not the total bidpoints submitted by individual bidder.
3. †† Cover ratio is defined as total supply divided by amount demanded.

Model: Basic setup

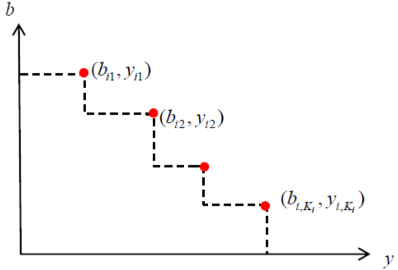
- The structural model builds on Hortaçsu (2002), which analyzes the Turkish Treasury Bill auction.
- I extend his basic framework to allow for asymmetric bidders.
- I assume $N(\geq 2)$ risk-neutral bidders, N_E emitters and N_B brokers. The number of bidders is common knowledge (relaxed later).
- Total supply, Q, is constant and commonly known to all bidders, normalized to one unit.

Model: Basic setup (cont.)

- I assume independent private value framework.
- Bidder i's private information about its valuations is given by the private signal S_i, $i$ndependent across bidders and auctions. The distributions are common knowledge to all bidders.
- $v_i(y, S_i) =$ Bidder i's marginal valuation for winning a share y. It is strictly increasing in S_i, and weakly decreasing and continuous in y.

Model: Basic setup (cont.)

- Assume discrete step bid function
- Denote i's bid vector as
$\overrightarrow{Y_i} = \left(\overrightarrow{b_i}, \overrightarrow{y_i}, K_i\right) = \{(b_{i1}, y_{i1}), (b_{i2}, y_{i2}), ..., (b_{iK_i}, y_{iK_i})\}$.



Model: Bidding strategy and equilibrium

- The objective of bidder i

$$\max_{\left(\overrightarrow{b_i},\overrightarrow{y_i},K_i\right)} ES(S_i) = \sum_{k=1}^{K_i} \left\{ \begin{array}{c} \Pr\left(b_{i,k+1} < p^c(S, Y(\cdot, S)) \le b_{ik}\right) \\ \times \sum_{j=1}^{k} \left[\int_{y_{i,j-1}}^{y_{ij}} v(q, S_i) dq - b_{ij}(y_{ij} - y_{i,j-1}) \right] \end{array} \right\}$$

for $i = 1, ..., N$, where $S = \{S_1, ..., S_N\}$, $Y(\cdot, S) = [y_1^*(\cdot, S_1), ..., y_N^*(\cdot, S_N)]$, and $p^c(S, Y(\cdot, S))$ is the equilibrium market clearing price.

  - The probability distribution of $p^c(S, Y(\cdot, S))$ is given by

$$G_i(b_{ik}, \overrightarrow{Y_i}) \equiv \Pr\left\{p^c(S, Y(\cdot, S) \le b_{ik} | \overrightarrow{Y_i}\right\}$$

$$\Rightarrow \Pr\left(b_{i,k+1} < p^c(S, Y(., S)) \le b_{ik}\right) = G_i(b_{ik}, \overrightarrow{Y_i}) - G_i(b_{i,k+1}, \overrightarrow{Y_i}).$$

Model: Bidding strategy and equilibrium (cont.)

- The solutions characterize the bidding strategies, a mapping from the space of private signals to the space of bid functions: $\mathcal{S} \rightarrow \mathcal{Y}$.
- The optimal bidding strategy satisfies the following F.O.C. **at each observed bidpoint**:

$$v(y_{ik}, S_i) = b_{ik} + \frac{G_i(b_{i,k+1}, \overrightarrow{Y_i})(b_{ik} - b_{i,k+1})}{G_i(b_{ik}, \overrightarrow{Y_i}) - G_i(b_{i,k+1}, \overrightarrow{Y_i})} - \frac{\frac{\partial G_i(b_{ik}, \overrightarrow{Y_i})}{\partial y_{ik}} \left[\int_{y_{i,k-1}}^{y_{ik}} v(q, S_i) dq - b_{ik}(y_{ik} - y_{i,k-1}) \right]}{G_i(b_{ik}, \overrightarrow{Y_i}) - G_i(b_{i,k+1}, \overrightarrow{Y_i})},$$

for $k = 1, ..., K_i$ and $i = 1, ..., N$.

Empirical strategy: Identification and estimation

- The bid vectors $\left(\overrightarrow{b_i}, \overrightarrow{y_i}, K_i\right)$ $(i = 1, ..., N_t, t = 1, ..., T)$ are observable.
- Two steps to identify the marginal valuation functions:
  1. Estimate marginal valuation at each bidpoint.
  2. Recover entire marginal valuation function for each bidder.

Empirical strategy: Identification and estimation (cont.)

Step 1: Estimate the bounds on the marginal valuation at each bidpoint.

Lower bound:

$$v(y_{ik}, S_i) \geq \underline{v}(y_{ik}, S_i) \equiv b_{ik} + \frac{G_i(b_{i,k+1}, \overrightarrow{Y_i})(b_{ik} - b_{i,k+1})}{\left[G_i(b_{ik}, \overrightarrow{Y_i}) - G_i(b_{i,k+1}, \overrightarrow{Y_i})\right] + \frac{\partial G_i(b_{ik}, \overrightarrow{Y_i})}{\partial y_{ik}}(y_{ik} - y_{i,k-1})}.$$

Upper bound:

$$v(y_{ik}, S_i) \leq \overline{v}(y_{ik}, S_i) \equiv b_{ik} + \frac{G_i(b_{i,k+1}, \overrightarrow{Y_i})(b_{ik} - b_{i,k+1}) - \frac{\partial G_i(b_{ik}, \overrightarrow{Y_i})}{\partial y_{ik}}[\overline{v}(y_{i,k-1}, S_i) - b_{ik}](y_{ik} - y_{i,k-1})}{G_i(b_{ik}, \overrightarrow{Y_i}) - G_i(b_{i,k+1}, \overrightarrow{Y_i})}.$$

- It requires three sub-steps to estimate the bounds non-parametrically:
  1. Estimate $G_i(b_{ik}, \overrightarrow{Y_i})$ and $G_i(b_{i,k+1}, \overrightarrow{Y_i})$, using modification of the resampling approach of Hortaçsu (2002).
  2. Estimate $\frac{\partial G_i(b_{ik}, \overrightarrow{Y_i})}{\partial y_{ik}}$, using the kernel density estimation method (Epanechnikov kernel).
  3. Derive estimated $\underline{v}(y_{ik}, S_i)$ and $\overline{v}(y_{ik}, S_i)$.

Empirical strategy: Identification and estimation (cont.)

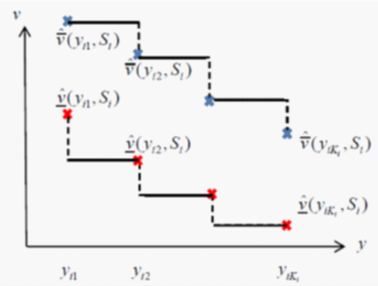
Step 2: Recover lower & upper envelopes of entire marginal valuation functions.

Lower envelope:

$$\widehat{\underline{v}}(q, S_i) = \widehat{\underline{v}}(y_{ik}, S_i), \text{ for } q \in (y_{i,k-1}, y_{ik}].$$

Upper envelope:

$$\widehat{\overline{v}}(q, S_i) = \widehat{\overline{v}}(y_{i,k-1}, S_i), \text{for } q \in [y_{i,k-1}, y_{ik}).$$



Results: Estimated marginal valuations at bidpoints

Figure: Estimated marginal valuations for emitter #1 (PSEG Energy Resources and Trade LLC) in 2004

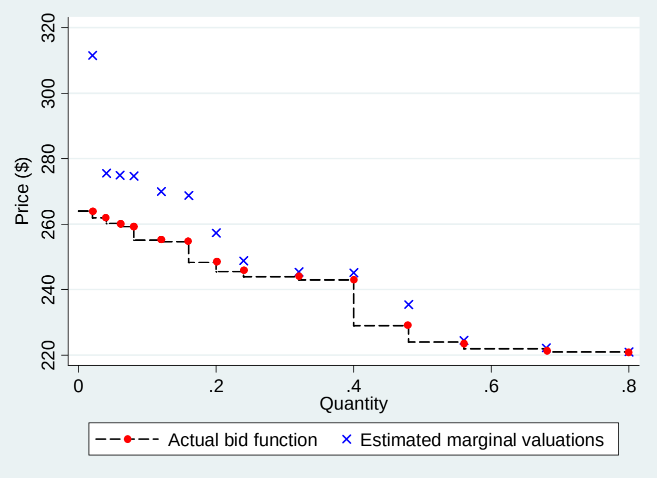
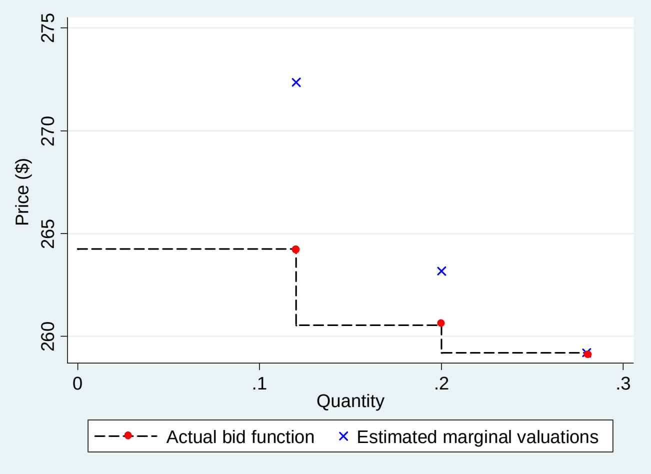


Figure: Estimated marginal valuations for broker #1 (Morgan Stanley Commodities Group, Inc.) in 2004



Results: Average valuation per unit

Table Valuation per unit (unit: dollar)

	Lower bound			Upper bound		
Year	All bidders	Emitters	Brokers	All bidders	Emitters	Brokers
2003	143.46	137.3	159.87	152.97	145.21	173.66
	(38.02)	(43.10)	(13.08)	(29.53)	(27.44)	(29.03)
2004	251.17	246.99	262.29	268.49	268.01	269.75
	(40.39)	(47.01)	(13.01)	(33.96)	(40.12)	(11.38)
2005	636.04	632.1	677.41	652.28	647.28	704.76
	(87.31)	(90.40)	(22.47)	(91.87)	(94.77)	(2.61)
2006	867	893.23	837.85	897.44	928.17	863.29
	(94.05)	(116.58)	(52.87)	(109.46)	(139.36)	(51.16)
2007	480.59	510.1	433.37	510.42	539.9	463.25
	(162.82)	(205.15)	(36.83)	(153.83)	(193.48)	(31.06)
2008	375.7	379.35	373.67	397.92	387.26	403.84
	(185.74)	(234.36)	(169.07)	(191.73)	(235.76)	(178.42)
2009	72.66	172.41	27.32	77.94	176.48	33.15
	(104.73)	(148.63)	(19.50)	(102.97)	(144.96)	(20.88)
2010	57.52	97.74	25.34	60.16	100.22	28.11
	(91.74)	(135.26)	(14.10)	(90.67)	(133.52)	(13.46)

Notes:

1. Standard derivations are in parentheses.
2. Lower bound refers to the results derived based on the lower envelope of the estimated marginal valuations.
3. Upper bound refers to the results derived based on the upper envelope of the estimated marginal valuations.

Evaluate the performance & conduct counterfactual comparisons

Evaluate the performance of the discriminatory SO_2 auction and conduct counterfactual comparisons based on the recovered valuations.

- Efficiency
- Revenue

Efficiency

Table Total surplus (TS) comparison and maximum auction efficiency loss

(unit: thousand dollars)

Year	Lower bound of TS under actual allocation	Upper bound of TS under efficient allocation	Maximum efficiency loss (%)
2003	21,475.00	22,970.32	-6.51
2004	36,849.22	36,956.33	-0.29
2005	91,409.94	91,409.94	0.00
2006	118,355.59	118,741.53	-0.33
2007	66,053.04	66,238.13	-0.28
2008	54,886.82	55,514.75	-1.13
2009	9,677.91	9,916.42	-2.41
2010	4,892.75	4,974.37	-1.64
Mean			**-1.57**

Notes:

1. Maximum efficiency loss (%) = 100% * (Lower bound on TS under the actual allocation - Upper bound on TS under the efficient allocation)/ Upper bound on TS under the efficient allocation.
2. Mean is the average of maximum efficiency loss across years.

Revenue

Table Revenue gain from switching to a uniform price auction with truthful bidding

Year	Lower-bound revenue gain (%)	Upper-bound revenue gain (%)
2003	-0.01 (0.001)	-0.01 (0.001)
2004	-3.54 (0.56)	0.69 (0.62)
2005	-1.75 (0.05)	-0.82 (0.12)
2006	-1.79 (0.03)	1.04 (0.31)
2007	-1.46 (0.15)	1.97 (0.65)
2008	-1.94 (0.09)	4.06 (0.52)
2009	-5.04 (0.42)	4.66 (7.87)
2010	-0.18 (0.41)	2.45 (1.05)
Mean	-1.97	**1.76**

Notes:

1. Jackknife standard errors are in parentheses.
2. The estimates of lower-bound gain (upper-bound gain) assume that bidders truthfully bid the lower envelope (the upper envelope) of the estimated marginal valuations.
3. Revenue gain (%) = 100% * (revenue under the best-case uniform auction – revenue under the discriminatory auction)/ revenue under the discriminatory auction.
4. Mean is the average of revenue gain across years.

Revenue (cont.)

Table Expected revenue gain from switching to a uniform price auction with truthful bidding

Year	Lower-bound expected revenue gain (%)	Upper-bound expected revenue gain (%)
2003	-0.38 (0.07)	2.09 (0.34)
2004	-3.56 (0.72)	1.86 (0.87)
2005	-1.56 (0.05)	0.41 (0.10)
2006	-0.94 (0.33)	1.81 (0.32)
2007	-2.65 (0.48)	4.01 (0.81)
2008	-4.00 (0.71)	1.29 (0.62)
2009	-6.96 (0.64)	1.52 (0.70)
2010	-1.12 (0.44)	4.09 (0.28)
Mean	-2.65	**2.14**

Notes:

1. Bootstrap standard errors are in parentheses.
2. The estimates of lower-bound gain (upper-bound gain) assume that bidders truthfully bid the lower envelope (the upper envelope) of the estimated marginal valuations.
3. Expected revenue gain is the average of bootstrapped revenue gains, where bootstrapped revenue gain (%) = 100% * (revenue under the best-case uniform auction – revenue under the discriminatory auction)/ revenue under the discriminatory auction, based on each resample.
4. Mean is the average of revenue gain across years.

Robustness check

- Assume the number of bidders from each category is unknown, drawn from a Possion distribution.
- The basic conclusions still hold:
    - The average efficiency loss is at most 0.64%.
    - Switching to a best-case uniform auction with truthful bidding would increase the actual revenue and the expected revenue by no more than 1.10% and 3.95%, respectively.

Conclusion

- Theory cannot provide an answer to the question of which mechanism performs better.
- Based on a framework from the auction literature & real bid data, this paper provides some new insights into mechanism choice in a permit auction.
  - The discriminatory SO_2 permit auction performs well. The gain from switching to a uniform mechanism would be very small.
- Regulators can apply a similar framework (methodology) to the study of other permit auctions, e.g., the GHG permit auctions under the EU ETS and the RGGI in the US.