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Discriminatory auctions lead to lower allowance prices: evidence from the United States

Yu Xia
Department of Economics, Syracuse University

Abstract

This study develops an equilibrium strategy for specific auction scenarios by optimizing the Symmetric Independent Private Value model to analyze the behavior of buyers and sellers throughout the auction process, examine the price and quantity proportion of sulfur dioxide auctions, and ascertain the impact of discriminatory auction forms on low auction prices. The results indicate that agents have incentives to lower prices, discriminatory auctions adversely affect allowance prices, and common value and market concentration further undermine the effectiveness of the auction mechanism.

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Contact: Yu Xia - yxia44@syr.edu.
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1. Introduction

In the past few decades, the externalities of pollutant emissions have received increasing attention. However, this externality is not as intuitive as standard goods, and its price is difficult to measure. The properties of sulfur dioxide (SO_2) emissions offer the U.S. government the possibility of performing an auction instead of controversial environmental regulation.

In 1990, the Clean Air Act (CAA) underwent a significant revision in the United States, resulting in the CAA Amendments (see also Schmalensee and Stavins 2019). The CAA Amendments clearly stipulate the trading regulations for storage, transfer, direct sale, and auction of air pollutants, further prompting the U.S. Environmental Protection Agency (EPA) to develop the National Ambient Air Quality Standards (NAAQS), establish the Acid Rain Program (ARP) under Title IV of the 1990 CAA Amendments, and implement the SO_2 emission trading mechanisms. The ARP is the first national cap-and-trade program that introduces the SO_2 allowance auctions to reduce SO_2 emissions through market-based incentives. It was implemented in two phases: the first phase started in January 1995 and ended in December 1999, while the second phase was from January 2000 to December 2010, with the final 2010 SO_2 cap set at 8.95 million tons, a level of about one-half of the emissions from the power sector in 1980 (see also U.S. EPA 2025a).

In March 1993, the EPA held its first public auction of SO_2 emissions trading through the Chicago Board of Trade. The auction adopted a two-way mechanism, where both buyers and sellers simultaneously quoted prices, submitted buy orders (quote + quantity) and sell orders (quote + quantity), and the system automatically matched orders with price and time priority. Ultimately, the SO_2 emission allowances for different units will be awarded to the highest bidder of a single unit. This is a typical form of discriminatory auction.

Since the establishment of the SO_2 allowance auction mechanism and discriminatory auction form, some scholars have discussed whether the discriminatory auction form is applicable to the EPA's SO_2 allowance auctions. Their views are inconsistent. Hausker (1992) believes that the method of allowance auctions can compensate for the inefficiency of the SO_2 emission trading markets to a certain extent. Cason (1993) confirms that, from the perspective of the sellers, the pricing rules of discriminatory auctions lead sellers to choose asking prices below their cost. Joskow *et al*. (1998) argue that the market prices and the allowance prices of discriminatory auctions are close, and the effect of discriminatory auctions is not as bad as predicted. Other scholars have compared discriminatory auctions with other auction forms, such as uniform-price auctions, and analyzed the impact of common value. Wilson (1979) suggests that when people bid for multiple items of the same quality, they tend to give a unit bid lower than their value measurement of the commodity. This is because bidders will measure the marginal utility of each unit to themselves in terms of discriminatory pricing. Cason (1995) proves that, from the perspective of the buyers, discriminatory auctions implemented by the EPA can lead to buyers bidding higher than their valuation, resulting in inefficient auction outcomes, and the common value problem makes things worse. Jackson and Kremer (2007) note that, under common value, the average price paid in discriminatory auctions is often lower than the expected value of the item. Damianov and Becker (2010) come to a similar conclusion that the uniform-price auction brings a higher expected revenue and a higher trade volume for the sellers than the discriminatory-price auction.

Based on the above investigation, this study constructs a theoretical model to analyze the behavior of bidders in the Symmetric Independent Private Value (SIPV) case, examine whether the allowance prices meet expectations, and explore how this situation occurs.

2. Methods

2.1 Model construction

This study primarily employs two theoretical frameworks, such as game theory and auction theory. The essence of a game is a process of change from dynamic competition (bargaining) to relatively static cooperation (game equilibrium). Typically, if we want the auction mechanism to generate expected returns or prices, we can use an equilibrium strategy (see also Nash 1950) to maximize the interests of both buyers and sellers. Meanwhile, information plays an important role in the auction process (see also Atakan and Ekmekci 2024).

In modern auction theory, there are three typical forms of information structure commonly used for item value: private value (see also Vickrey 1961), common value (see also Wilson 1969), and affiliated value (see also Milgrom and Weber 1982). Among them, the discriminatory auction is one of the most widely used auction forms, which is based on the information structure of private value and uses the SIPV model as the benchmark model (see also Krishna 2010).

This study takes the EPA's SO_2 allowance auctions as a case and proposes an equilibrium strategy that simplifies the benchmark SIPV model to suit a specific auction situation.

From the perspective of the sellers, suppose there are Q units of SO_2 allowance, and each allowance is provided by a seller. N sellers engage in this auction by asking price a set as their minimum acceptable price in the EPA's SO_2 allowance auctions. Buyers' bid prices are drawn from a probability distribution $\Phi(\cdot)$, with a lower bound $\underline{b}$ and an upper bound $\overline{b}$. Rank the bid price $b_1 \geq b_2 \geq \ldots \geq b_Q$, and rank the asking price $a_1 \leq a_2 \leq \ldots \leq a_N$. Assume that the cost of emission (or the cost of no longer being able to emit), c, is drawn from the distribution function $H(\cdot)$, in the interval $[\underline{c}, \overline{c}]$. In this model, the auctioneer uses asking prices to rank, but buyers pay the matched bid price in the end. Thus, sellers' payoff would be b-c after b and c are given.

By symmetry, each seller asks for a price according to the function

$$a=a(c) \tag{1}$$

The inverse function is

$$c=c[a(c)] \tag{2}$$

Denote the probability that a seller i's asking price is ranked as the jth lowest asking price as $G_j[c(a)]$. The expression is

$$G_j[c(a)]=\frac{(N-1)!}{(N-j)!(j-1)!}[1-H(c)]^{N-j}[H(c)]^{j-1} \tag{3}$$

Denote the probability that the asking price a is lower than the jth highest bid price b_j as

$$F_j(a)=P_r(a \leq b_j) \tag{4}$$

The conditional payment will be

$$E_j(a)=E[b_j|a \leq b_j] \tag{5}$$

Given the notation above, the expected payoff is expressed as

$$\pi(a)=\sum_{j=1}^{Q}G_j[c(a)]F_j(a)[E_j(a)-c(a)] \tag{6}$$

Solving the first-order condition (FOC) $\pi'(a)=0$, the differential equation is attainable:

$$c'(a)=\frac{\sum_{j=1}^{Q}G_j[c(a)]\{F_j(a)E'_j(a)+F'_j(a)[E_j(a)-c(a)]\}}{\sum_{j=1}^{Q}G'_j[c(a)]F_j(a)[c(a)-E_j(a)]} \tag{7}$$

From the perspective of the buyers, suppose there are Q homogeneous allowances and there are N bidders. The valuations of bidders are distributed according to $H(\cdot)$.

Assume bidder i believes that all rivals bid according to the function

$$b_{-i}=b(v_j) \tag{8}$$

The inverse function would be

$$v_j=\beta^{-1}(b) \tag{9}$$

Like the notations above, the probability that bidding b results in winning is equal to the probability that b is no less than the Qth highest bid at least. Due to the monotonicity of the function $b(v_j)$, this probability can be formally expressed as

$$G(\beta^{-1}(b))=\frac{(N-1)!}{(N-Q-1)!(Q-1)!}\int_0^{\beta^{-1}(b)}[H(v)]^{N-Q-1}[1-H(v)]^{Q-1}h(v)dv \tag{10}$$

Bidders choose b to maximize the expected payoff

$$\Pi(b, v)=(v_i-b_i)\,G(\beta^{-1}(b)) \tag{11}$$

Typically, there is no closed-form solution.

Intuitively, as a special case, for sellers, the optimal situation is that the seller's lowest asking price a matches the buyer's highest bid b. As for the buyer, the ideal situation is just the opposite; that is, the seller's highest asking price a matches the buyer's lowest bid b. But that is not the case.

2.2 Specific examples of the model

Since these models above have no general closed-form solution, this subsection provides some simple examples to illustrate agents' behavior.

2.2.1 Sellers' example

Consider $\overline{b}=\overline{c}=2$, $\underline{b}=0$ and $\underline{c}=1$. Both b and c are uniformly distributed. There are still N sellers, but only 1 unit allowance.

The probability that a is the lowest ask price is

$$G_1[c(a)] = [\frac{\bar{c} - c(a)}{\bar{c} - \underline{c}}]^{N-1} = [\frac{2 - c(a)}{2 - 1}]^{N-1} = [2 - c(a)]^{N-1} \tag{12}$$

The probability that the only bid is greater than a is

$$F_1(a) = \frac{\bar{b} - a}{\bar{b} - \underline{b}} = \frac{2 - a}{2 - 0} = 1 - \frac{a}{2} \tag{13}$$

The conditional expectation is

$$E_1(a) = \frac{\bar{b} + a}{2} = \frac{2 + a}{2} = 1 + \frac{a}{2} \tag{14}$$

Plugging into equation (7) and simplifying, solve the differential equation. By using $\bar{c} = \bar{a} = \bar{b}$, the result is as follows:

$$c(a) = 2 + \frac{N+1}{2N}(a - 2) \tag{15}$$

The asking function in this case is

$$a(c) = 2 + \frac{2N}{N+1}(c - 2) \tag{16}$$

Since $N+1 \leq 2N$, then $c \leq a(c)$, which indicates that the seller has an incentive to put the asking price below the cost in this case.

2.2.2 Buyers' example

For buyers, suppose there are 2 units of allowance and 2 bidders.

Bidder 1 has valuations v_1 and v_2, as well as bids b_1 and b_2, where $b_1>b_2$. The rival, bidder 2, has bids c_1 and c_2, where $c_1>c_2$.

To simplify the general case, denote the marginal distribution function of C_1 as $F_1(\cdot)$. Similarly, $F_2(\cdot)$ for C_2.

Bidder 1 wins both units if $b_2>c_1$. The probability is $F_1(b_2)$.

Bidder 1 wins exactly one unit if $c_2<b_1$ and $c_1>b_2$. The probability is $F_2(b_1)-F_1(b_2)$.

The expected payoff is

$$\Pi(b, v) = F_1(b_2)\,(v_1+v_2-b_1-b_2) + [F_2(b_1)-F_1(b_2)]\,(v_1-b_1) \tag{17}$$

Assume $b_1>b_2$. The FOC indicates that

$$f_2(b_1)\,(v_1-b_1) = F_2(b_{-1}) \tag{18}$$

$$f_1(b_2)\,(v_2-b_2) = F_1(b_2) \tag{19}$$

So, b_{-1} is unrelated to v_2, and b_2 is uncorrelated to v_1. It is the same in the asymmetric case. If $b_{-1} \neq b_2$, it is expected that a rational bidder will bid more aggressively or more conservatively. If there are some rational, strong bidders, they will bid more conservatively. And due to their market power, their behavior may make the market prices biased downward.

3. Results and discussion

To examine the impact of discriminatory auction forms on low auction prices, this study analyzes the data from the EPA's SO_2 allowance auctions and the prices of SO_2 emissions in other markets, including secondary markets.

Since the prices of SO_2 emissions vary from person to person in discriminatory auctions, the clearing prices provided by the EPA are used. The data for the 6-year advance auction in 1993 is missing, so the spot auction prices and 7-year advance auction prices are used. The market prices come from press reports and three organizations: Emission Exchange Corporation, Cantor Fitzgerald and Fieldstone. Note that other markets have quarterly or monthly prices, while the EPA's SO_2 allowance auctions are held once a year. Because there is a certain volatility in permit prices after the EPA auction is held, and the volatility has no correlation with the increment in time, this study treats the market prices after the auction as the prices of next year.

The comparison between the EPA's SO_2 auction prices and other market prices from 1993 to 1996 is shown in Table I.

Table I. Comparison between the EPA's SO_2 auction prices and other market prices from 1993 to 1996.

Year	EPA spot auction	EPA 7-year advance auction	Market prices
	Clearing prices	Clearing prices	
1993	$131	$122	$170–$310
1994	$150	$140	$170–$200
1995	$130	$126	$110–$140
1996	$66.05	$63.01	$60–$130

Source: U.S. EPA (2025b); Joskow *et al*. (1998).

As shown in Table I, in 1993, the first year of the EPA's SO_2 allowance auctions, the auction prices were lower than the market prices. This difference seemed obvious until 1995.

It is worth noting that the auction prices and market prices in 1996 dropped significantly compared with the similar prices in the previous three years. The main reason is that 1995 was the first year of ARP implementation, and both parties in the auction were in the observation period of the ARP implementation process and its effectiveness. Due to the lag of the market, its effect did not emerge until 1996. It can be expected that various prices will gradually rebound to a new stable state after 1997.

We can also find evidence in the comparison between the clearing prices and the average winning prices. They are both on the EPA website, available from 1993 to 1996. The comparison between the EPA's SO_2 auction clearing prices and average winning prices from 1993 to 1996 is shown in Figure 1.

Figure 1 shows the results of the EPA's SO_2 allowance auctions from 1993 to 1996, indicating that the EPA's spot auction clearing prices are getting closer to the EPA's spot average winning prices over time.

Normally, if the agents' value is private, then the EPA auction prices will not closely relate to the market prices, and the clearing prices will not be related to the average winning prices as well. However, Table I and Figure 1 show that the EPA auction prices are getting closer to the market prices over time, and the clearing prices are also getting closer to the average winning prices. We can find evidence of common value in the comparison between the clearing prices and the average winning prices. Under common value, agents tend to avoid the winner's curse by decreasing their bids (see also Wilson 1969), which may lead to lower auction prices.

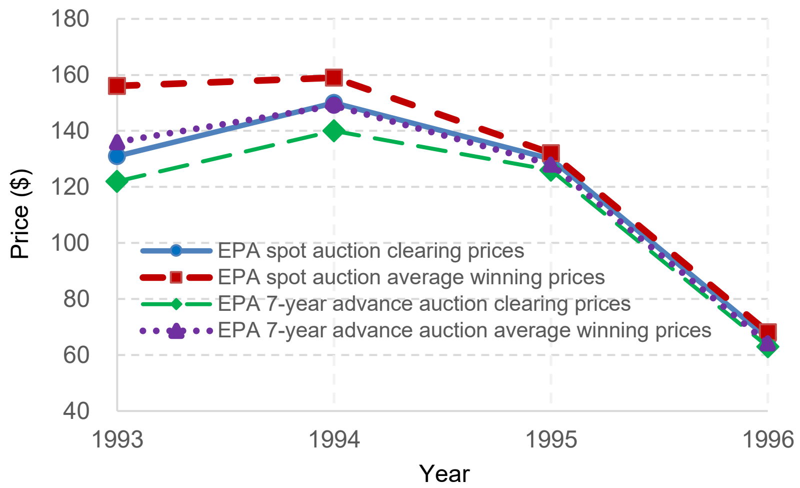

Figure 1. Comparison between the EPA's SO_2 auction clearing prices and average winning prices from 1993 to 1996. *Note*: These four curves describe the trends over time of the clearing prices and the average winning prices provided by the EPA's SO_2 allowance auctions from 1993 to 1996. Among them, these two prices have chosen different observation points, namely the spot auction and the 7-year advance auction.

The EPA also provides the proportion of valid allowance quantity gained from the EPA's SO_2 allowance auctions since 1994. Table II provides the quantity proportion of the EPA's SO_2 allowance auctions from 1994 to 1996.

Table II. Quantity proportion of the EPA's SO_2 allowance auctions from 1994 to 1996.

Year	The 1st largest bidder			The 2nd largest bidder			The 3rd largest bidder		
	EPA SO_2 spot auction	EPA SO_2 6-year advance auction	EPA SO_2 7-year advance auction	EPA SO_2 spot auction	EPA SO_2 6-year advance auction	EPA SO_2 7-year advance auction	EPA SO_2 spot auction	EPA SO_2 6-year advance auction	EPA SO_2 7-year advance auction
1994	36.0%	78.7%	89.3%	25.9%	15.3%	5.0%	24.0%	3.9%	2.0%
1995	35.1%	98.4%	50.2%	15.8%	1.6%	29.9%	15.8%	<0.1%	10.0%
1996	71.5%	68.0%	66.0%	7.7%	24.0%	11.6%	6.7%	8.0%	10.0%

Source: U.S. EPA (2025b).

As shown in Table II, in the initial stage of the EPA's SO_2 allowance auctions, there were bidders who had a good command of the available allowance quantity. Intuitively, because of their control, they have incentives to decrease their bids to gain more payoff without losing too much probability of winning. Thus, market concentration also has a negative impact on the allowance prices.

Through theoretical research and statistical analysis, the study has found that between 1993 and 1996, over time, the EPA auction prices became increasingly close to market prices, and clearing prices also became closer to the average winning prices, which indicates that the marginal effect of discriminatory auction policies for SO_2 is gradually decreasing. It may be predicted that in the future, for a considerable period, unless there are special external factors affecting this trend, the volatility of SO_2 market prices will not be particularly noticeable. For this reason, we did not continue to explore the EPA's SO_2 allowance auctions after 1996.

Hitaj and Stocking (2016) confirm this prediction. They found that the EPA's SO_2 auction market remained relatively inefficient in the initial stage after its launch, and during the observation window (2003–2008), the middle of the second phase of ARP implementation, the volatility of the EPA's SO_2 auction market would increase with the uncertainty of regulatory events. Furthermore, they also raised a special case that affected the volatility of SO_2 market prices: on July 11, 2008, the U.S. Court of Appeals revoked and repealed the Clean Air

Interstate Rule (CAIR). The CAIR was a regional cap-and-trade program that covered 27 eastern U.S. states and was announced by the EPA in 2005 to regulate markets after 2010. On December 23, 2008, the Court of Appeals once again ruled to allow the EPA to continue implementing the CAIR until the EPA issued new rules in July 2010. The unexpected court ruling caused the EPA's SO_2 allowance prices to fall by nearly 60% overnight, bringing much uncertainty to the future of ARP.

To illustrate this situation, Table III presents the comparison between the EPA's SO_2 auction clearing prices and average winning prices from 1993 to 2025.

Table III. Comparison between the EPA's SO_2 auction clearing prices and average winning prices from 1993 to 2025.

Year	EPA spot auction		EPA 7-year advance auction	
	Clearing prices	Average winning prices	Clearing prices	Average winning prices
1993	$131	$156	$122	$136
1994	$150	$159	$140	$149
1995	$130	$132	$126	$128
1996	$66.05	$68.14	$63.01	$64.21
1997	$106.75	$110.36	$102.15	$104.16
1998	$115.01	$116.96	$108.30	$111.05
1999	$200.55	$207.30	$167.55	$179.79
2000	$126.00	$130.69	$55.27	$68.32
2001	$173.57	$174.97	$105.72	$110.75
2002	$160.50	$167.74	$68.00	$81.87
2003	$171.80	$171.81	$80.00	$86.40
2004	$260.00	$272.82	$128.00	$128.00
2005	$690.00	$702.51	$260.00	$297.49
2006	$860.07	$883.10	$241.67	$275.13
2007	$433.25	$444.39	$176.00	$193.35
2008	$380.01	$389.91	$131.50	$136.14
2009	$62.00	$69.74	$6.63	$6.65
2010	$36.20	$37.71	$1.69	$2.07
2011	$2.00	$2.81	$0.16	$0.17
2012	$0.56	$0.67	$0.12	$0.13
2013	$0.17	$0.28	$0.04	$0.04
2014	$0.35	$0.45	$0.04	$0.04
2015	$0.11	$0.11	$0.03	$0.03
2016	$0.06	$0.06	$0.02	$0.02
2017	$0.04	$0.06	$0.01	$0.01
2018	$0.06	$0.06	$0.02	$0.02
2019	$0.04	$0.07	$0.01	$0.01
2020	$0.01	$0.02	$0.01	$0.01
2021	$0.01	$0.01	$0.01	$0.01
2022	$0.02	$0.04	$0.01	$0.01
2023	$0.04	$0.04	$0.02	$0.02
2024	$0.02	$0.02	$0.02	$0.02
2025	$0.01	$0.01	$0.01	$0.01

Source: U.S. EPA (2025b).

As shown in Table III, since the implementation of emissions trading in 1993, the price of SO_2 emissions trading remained relatively stable before the end of 2003, fluctuating within the range of around $100 to $200 per ton. However, starting in January 2004, the trading price soared to $620 per ton. In 2005, the EPA's spot auction clearing price was $690. The main reason is that the U.S. Congress plans to formulate a new cap-and-trade program and intends to consider further reducing the total amount of pollutant emissions by 70%. The implementation of this plan will greatly reduce the tradable emission allowances, while the emission demand for power development will not significantly decrease in the short term, leading to an increase in market trading prices. But, during the period of 2007 to 2010, the later stages of the second phase of ARP implementation, SO_2 market trading prices experienced a sharp decline. Specifically, it reached a historic turning point in 2011, falling below $3 per ton. In fact, after full implementation of the ARP, the EPA's SO_2 allowance prices have symbolically dropped and remained at a level of less than $1 per ton since 2012.

4. Conclusions

In the initial stage of the cap-and-trade program, the EPA designated discriminatory auctions as SO_2 allowance auctions, resulting in lower allowance prices in the auctions. This study developed an equilibrium strategy in a specific auction case, simplifies the SIPV model, discusses the relationship between discriminatory auction forms and low SO_2 allowance prices, compares data intuitively, and draws some exploratory conclusions: (i) In the SIPV case, agents of discriminatory auctions have incentives to hide their bids below their costs, while buyers usually bid on each unit independently, resulting in the real price being often underestimated; (ii) Agents of the EPA's SO_2 allowance auctions are likely to have a common value: allowance bids increase to market prices as time goes by, and auction average winning prices get closer to auction clearing prices as well. Under common value, agents tend to bid lower before they acquire enough information; (iii) The EPA's SO_2 allowance auctions have strong bidders, at least in the first few years, and market concentration decreases allowance prices.

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