Car License Auction: Theory and Experimental Evidences*

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Abstract

In Singapore and many Chinese cities, tens of thousands of people participate in car license auctions each month. In a car license auction, many car licenses are sold but each participant can only bid for one license. We examine the theoretical properties of three auction formats: Shanghai auction, Guangzhou auction, and Singapore auction. Our main results are that (1) No equilibrium of the Shanghai auction can guarantee an efficient allocation, (2) the Singapore auction allocates objects efficiently if and only if a unique market clearing price does not exist, and (3) the Guangzhou auction is efficient if bidders are symmetric. The experimental evidence confirms our theoretical prediction. Our experiment also shows that the learning effects over time are quite different among these auction formats.

JEL classification: C92; D02, D04, D44

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1 Introduction

In the cities of Asian countries (e.g., Beijing, Shanghai, Guangzhou, Tianjing, Singapore), growth in real income has led rapid growth in the use of cars, which in turn has resulted in social problems such as severe smog, frequent traffic jams, and a shortage of parking space. To overcome these problems, local governments have developed various policies to regulate the increasing number of cars.[1] The car license auction is the most widely used policy tool to control the number of cars in cities. However, Shanghai, Guangzhou, and Singapore developed different auction mechanisms. In this paper, we introduce the theoretical models of three auction formats and report on lab experiments conducted to characterize the behaviors and outcomes of these auctions.

We consider the car license auction because of its importance in terms of size and its potential influence on the car-controlling plans of other cities.[2] Singapore implemented auctions to allocate the right to use a car in 1990, and the bidding format gradually changed to an open-bid format by 2001. Shanghai used auctions to assign car licenses starting in the 1990s, while Guangzhou implemented its car-controlling program in 2012.[3] Singapore conducts an auction every two weeks while Shanghai and Guangzhou hold auctions every month. Today, people pay more than $4,000 US, $12,000 US, and $50,000 US for a car license in a Guangzhou, Shanghai, and Singapore auction, respectively. The price of a car license has risen over time in these cities because of people's growth in income.

In car license auctions, thousands of licenses are sold but each bidder can only purchase one object. Furthermore, the Shanghai auction and Guangzhou auction are discriminatory price auctions in which each winner pays her/his final bid for the object. Singapore uses a uniform price auction in which all the winners pay a uniform price for the object. However, these auctions have different features from the classical auction formats. In a Shanghai auction,

[1]Beijing uses a monthly lottery to decide who can own a new car. Shanghai, Singapore, and Guangzhou developed their own auction formats to allocate the rights to purchase a new car. Tianjing and Hanghzou adopted a car license auction similar to Guangzhou's mechanism in 2014. Some other cities in China have tried to solve the problem of traffic congestion by limiting the number of days of car use.

[2]Many cities in China plan to adopt stricter controls on the number of cars.

[3]Actually, the Guangzhou car-controlling program includes both an auction mechanism and a lottery mechanism each month. In this paper, we focus on Guangzhou's car license auction.

bidders can only bid once and only revise their bid price twice, and the revised bid price must be in a narrow price interval based on the current lowest accepted price; in a Guangzhou auction, all the bidders are informed of the current average bidding price twice; in a Singapore auction, the number of objects shrinks to break the tie of bids. The specific goal of this paper is to explain how these features affect the bidding strategy and outcome of the auctions.

Both economists and policy makers have expressed interest in comparing the bidding strategy, the efficiency, and the adaptive learning of these auction formats. However, it is difficult to make a direct comparison among them based on the empirical data because the population densities, income distributions, and traffic conditions are quite different in Shanghai, Guangzhou, and Singapore. Moreover, there is no available data on the willingness-to-pay of bidders in practice. Therefore, lab experiments helped us conduct comparisons and model these auctions.

In this research, we assume that bidders cannot react to the history information instantaneously in Shanghai auctions and Singapore auctions. Due to the variation in bidders' reaction time, the equilibrium of the Shanghai auction cannot guarantee allocation efficiency. The model predicts that subjects with a fast reaction earn higher payoffs than those with a slow reaction in Shanghai auctions. In a Singapore auction, each person submits a last-second bid equal to her/his own value. We also show that the bids submitted to a Guangzhou auction should be the same as those submitted to a discriminatory price sealed-bid auction.

Our claims are not just theoretical. Through an experimental comparison, we find that the Shanghai auction is not as efficient as the Guangzhou and Singapore auctions. Consistent with theoretical predications, late bidding is prevalent in Shanghai and Singapore auctions. The experimental results also show significant learning effects in repeated Guangzhou and Singapore auctions. However, the Shanghai auction cannot reach efficiency even after it has been repeated many times.

Our theoretical analysis is based on several well-developed theories about the uniform price and discriminatory price auctions with single unit demand (e.g. Vickrey, 1961; Ortega-Reichert, 1968; Milgrom and Weber, 1982; Milgrom, 1985; Cox et al., 1984, 1988; Krishna, 2009). The assumption about the reaction time in this paper is related to Roth and Ockenfels (2002) and Ockenfels and Roth (2006), who show that reactions are not instantaneous in Internet dynamic auctions. Moreover, our paper follows a recent strand of literature that uses laboratory experiments to evaluate the efficiency and impacts of public policies (e.g. Plott, 1994; Merlob et al., 2012; Cramton, 2012; Chen and Kesten, 2013). In particular, Liao and Holt (2013) reports a laboratory experiment designed to evaluate the revenue and efficiency of the Shanghai auction. Our experiments show that Shanghai auctions are inefficient, a result similar to Liao and Holt (2013).

Our paper is also related to the literature that analyzes the empirical data of Singapore auctions and Shanghai auctions. Koh and Lee (1994) argues that the Singapore auction should be discriminatory, which would be both more equitable and more politically acceptable. Some literature focuses on the impacts of the Singapore auction changing from sealed bids to open bids in 2001 (Koh, 2003; Chu, 2011; Cheng, 2011). They suggest that the shift leads a lesser volatility in winning price and a better reaction of demand and supply forces. Luo (2008) analyzes the impacts of several mechanism changes in the Shanghai auction.

The remainder of the paper is organized as follows. In the next section, we present the experiment's design. Section 3 summarizes the experimental results. Section 4 describes the theoretical model of car license auctions. Section 5 estimates the bidding strategies and learning effects in our experiments. Section 6 concludes.

2 Models

The car license auction is a special case of a multiple object auction. However, the formats of these auctions differ from classical auction formats in their payment or/and bidding rules. In this section, we develop the models of three auction formats, which are used to explain the inefficiency found by our experiments. We consider the setting of multiple object auctions with K identical objects. In each auction there are N bidders, indexed by i. The bidders only have single-unit demands for objects. The object's value to bidder i, denoted v_i, is private information. Each v_i is an independent draw from the distribution F, where F has strictly positive density on $[0, \bar{v}] \subset \mathbb{R}^+$. Let $\beta_i(.)$ be the bidding strategy of bidder i in a auction. The auction time is between 0 and 1.

Consider an equilibrium of a standard auction $\beta = \{\beta_1, \beta_2, ..., \beta_N\}$. In a standard auction, the efficiency of the auction format demands that the K units be awarded to the K highest of the N values. For the equilibrium to allocate efficiently for every realization of the values, the ranking of the K final bids b_i must agree with the ranking of the K values. In other words, efficiency requires that the final bid b_i is a monotonic increasing function of v_i.

An implication of the monotonicity is that the different components of the bidding strategy must be symmetric across both bidders and objects – that is, for any i and j, $\beta_i(.) = \beta_j(.)$. Otherwise, with positive probability there are situations in which the allocation will be inefficient. In particular, if $i \neq j$, then there will be situations in which $v_i > v_j$, but $\beta_i(v_i) < \beta_j(v_j)$ and bidder i does not win the object she or he should have won on grounds of efficiency.

2.1 Shanghai Auction

Denote that the Shanghai auction occurs in two stages. Each bidder can bid once at any time $t \in [0, 2/3]$ in the first stage, and she/he can revise the bid twice at any time $t \in (2/3, 1]$ in the second stage. Only if bidders submit a bid in the first stage, can they revise the bid in the second stage. Denote H_n^K as the Kth highest bid at $t = n$. Bidders are informed of the real-time H_n^K throughout the auction.

In the first stage of a Shanghai auction, a bidder can submit one bid within the interval $[0, +\infty)$. The revisions at $t = n$ in the second stage must be in the range of $[H_n^K - M, H_n^K + M]$ where $M \ll \bar{v}$. If bidders do not revise their bids in the second stage, the bids in the first stage are regarded as their final bids.

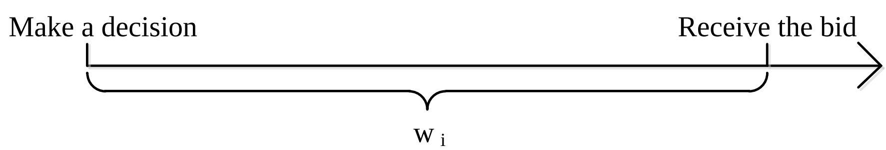
In a Shanghai auction, the payoff of bidder i can be summarized as follows:

$$\pi_i = \begin{cases} v_i - b_i, & b_i > B_{N-1}^K; \\ 0, & b_i < B_{N-1}^K. \end{cases}$$

where B_{N-1}^K denotes the Kth-highest final bids of other $N-1$ bidders. Bidders whose final bid prices are equal to B_{N-1}^K have symmetric probabilities to win the auction.

Here, we apply the reaction time to explain the inefficiency of Shanghai auctions. Assume a bidder i could react to another players bid, but the reaction cannot be instantaneous. The reaction at time $t_{i,n}$ must be strictly after time $t_{i,n-1}$, such that $t_{i,n-1} < t_{i,n}$. The information sets of the game are such that if t is between $t_{i,n-1}$ and $t_{i,n}$ ($t_{i,n-1} < t < t_{i,n}$) then bidder i knows the bid histories up to $t_{i,n-1}$. Furthermore, we assume each bidder's reaction time $w_i = t_{i,n} - t_{i,n-1}$ is independently drawn from a distribution W, where W has strictly positive density on $[0, 1/3] \subset \mathbb{R}^+$. The reaction times vary because of the variation in mental chronometry and/or the variation in Internet and computer speed. As shown in figure 1, the reaction time is the time between when the subject stops updating information and the auctioneer receives the bid.

Figure 1: Reaction time



Because bidders have various reaction times, each bidder's final bid is based on his/her own history information. Denote $H_i^* = H_{1-w_i}^K$ as the last Kth highest bid which bidder i can apply to make a decision before $t = 1$. After $t = 1 - w_i$, bidder i does not have time to react to others' bids or Kth highest bids.

According to the above assumptions, we propose the following:

Proposition 1 *The equilibrium strategy of subject i is to submit at least a bid lower than v_i before $t = 1 - w_i$, and at $t = 1 - w_i$*

1. *If $v_i \geq H_i^*$, submit a bid $H_i^* \leq b_i \leq \min(v_i, H_i^* + M)$ or retain the bid just before as the final bid.*

2. *If $v_i < H_i^*$, retain the bid just before as the final bid.*

It is easy to see that $t = 1 - w_i$ is the last opportunity for the auctioneer to receive subject i's bid before $t = 1$. Thus, any information updating after $t = 1 - w_i$ is useless to subject i. If others adopt the equilibrium strategy, subject i has no incentive to deviate because the Kth highest bid monotonically increases over time.[4] The existence of incremental first revisions in the second stage [5] would not break the equilibrium. With the existence of first revisions, we will observe an increasing trend in the entire second stage but a much more dramatic trend at the end of the second stage.

Proposition 2 *The equilibrium cannot guarantee an efficient allocation in Shanghai auctions.*

Efficiency requires $b_j < b_i$ for any $v_j < v_i$. With positive probability, there will be situations in which there exists two bidders i and j with $w_i = w_j$, where b_i is the Kth highest bid and v_j is just below v_i. A change in w_j to $w'_j < w_i$ allows bidder j to submit his/her final bid after subject i. The Kth highest bid that subject i observes does not change. But if incremental first revisions received between $t = 1 - w_i$ and $1 - w'_j$, subject j would face a different Kth-highest bid $H^*_j > H^*_i$. Then when $H^*_j - H^*_i \geq M$, subject j could submit a higher bid after subject i so that $b_i \leqslant H^*_j < b_j < v_j < v_i$. For such a change, the equilibrium allocation cannot guarantee efficiency. Furthermore, if subject j has zero reaction time, any equilibrium cannot guarantee efficiency because subject j always has time to react and bid more than b_i.

In Shanghai auctions, bidders with a relatively fast reaction can earn higher expected payoff than bidders with a relatively slow reaction. Bidders with shorter reaction times have more flexibility in making decisions, which puts their in a good position in Shanghai auctions. Hence, the heterogeneity of reaction time causes the inequity and inefficiency in the Shanghai auction. By setting each subject's reaction time to 1, the Shanghai auction reduces to a discriminatory price sealed-bid auction. Finally, we can obtain a "soft close"[6] discriminatory price auction by setting each subject's reaction time to 0.

[4]Because each person can only bid once in the first stage, the Kth highest bid monotonically increases in that stage.

[5]The reason for incremental bids includes mistakes, psychological reasons or trying to crowd out potential opponents. See, e.g., Ku et al. (2005) and Ockenfels and Roth (2006).

[6]The "soft close" auction is automatically extended if necessary past the scheduled end time until some number of minutes has passed without a bid (Ockenfels and Roth, 2006).

2.2 Singapore Auction

In the Singapore auction, each bidder can bid at any time in $t \in [0, 1]$. Bidders are informed of the real-time Kth-highest bid in the entire auction. The bids must be higher than the current $K + 1$th highest bid plus m. The Singapore auction is a uniform price auction and the payoff of bidder i in the Singapore auction can be summarized as follows:

$$\pi_i = \begin{cases} v_i - (B_{N-1}^K + m), & b_i \geq B_{N-1}^K + m; \\ \\ 0, & b_i < B_{N-1}^K + m. \end{cases}$$

where B_{N-1}^K denotes the Kth-highest final bids of other $N - 1$ bidders.

Given each bidder bids their value in the Singapore auction, no one has incentive to bid a lower price because it cannot increase the payoff but may reduce the probability of winning. Moreover, a bidder submitting a final bid which is higher than his/her value may cause a negative profit. Again, we assume each bidder's reaction time w_i is independently drawn from a distribution W. If bidder i submits a bid at w_i, the auctioneer will receive the bid at $t = 1$, which is a best reply to incremental bids. Thus, we conclude that:

Proposition 3 *In a Singapore auction, it is a weak dominant strategy of bidder i to bid v_i at $t = 1 - w_i$.*

In a Singapore auction, the price of car licences is equal to the $K + 1$ highest final bid plus a smallest increment m. In particular, the winning price would be strictly higher than the Kth-highest value where the Kth and $K + 1$th highest values are the same. In this case, the actual number of winners in the Singapore auction could be smaller than K. For example, there are four bidders participate in a Singapore auction with two objects. If the values are 200, 100, 100 and 50, then the unique market clearing price is 100. In this case, the winning price will be 110. Thus, only one object can be sold in this Singapore auction. Therefore, the Singapore auction cannot be a standard auction with fixed number of objects sold.

If there are multiple market clearing prices, the final lowest accepted bid is equal to the lowest market clearing price plus a smallest increment m. Thus, the allocation must be efficient because of the market clearing with K objects sold. We acknowledge this in the following proposition:

Proposition 4 *The Singapore auction allocates objects efficiently if and only if the market clearing price is not unique.*

2.3 Guangzhou Auction

The Guangzhou auction is a one-stage auction with two announcements of current average bids. Bidders can bid once and revise their bid twice at any time in $t \in [0, 1]$. Bidders are not informed of real-time bids but rather recieve two announcements of average bids at $t = 1/3$ and $t = 2/3$. In a Guangzhou auction, the payoff of bidder i can be summarized as follows:

$$\pi_i = \begin{cases} v_i - b_i, & b_i > B_{N-1}^K; \\ \\ 0, & b_i < B_{N-1}^K. \end{cases}$$

where B_{N-1}^K denotes the Kth-highest final bids of other $N-1$ bidders. Bidders whose final bid prices are equal to B_{N-1}^K have symmetric probabilities to win the auction.

If all the bidders in Guangzhou auctions submit their bids after $t = 2/3$, no one has incentive to bid early. Hence, Guangzhou auctions could be simplified to sealed-bid auctions. Denote Y_{N-1}^K as the Kth-highest order statistic of N-1 draws from the distribution F. Assuming that bidders are symmetric, we can express an equilibrium strategy of the Guangzhou auctions as follows:

$$\beta(v_i) = E\left[Y_{N-1}^K | Y_{N-1}^K < v_i\right]$$

Thus, one can see that Guangzhou auctions are efficient if bidders are symmetric.

Denote $G(x)$ as the cumulative distribution function (CDF) where Y_{N-1}^K and $g(x)$ is the first derivative of $G(x)$. We offer the following proposition of the bidding strategy in Guangzhou auctions:

Proposition 5 *If bidders are risk neutral, the equilibrium bidding strategy in Guangzhou auctions is to bid* $b_i = \frac{1}{G(v_i)} \int_0^{v_i} x \cdot g(x)\mathrm{d}x$ *after* $t = 2/3$.

In particular, if the values are independently drawn from a uniform distribution from an interval $[0, 1]$, $G(x)$ is the cumulative distribution function of Beta$(N - K, K)$ (Cox et al., 1984).

3 Experiment Design

We simulated Shanghai, Guangzhou and Singapore auction in the lab (The introductions to the three car license auctions are listed in the appendix). In addition, our design also included the uniform price sealed-bid (UPSB) auction, which has not been applied to auction car licences in reality. The UPSB auction was used as a baseline measure for car license auctions. The experiment was conducted at the Finance and Economics Experimental Laboratory (FEEL) of Xiamen University in the spring of 2013. We ran four sessions for each treatment, and each session had 20 subjects for a total of 320 participants. Participants were recruited from a subject pool in the Online Recruitment System for Economic Experiments (Greiner, 2004), which includes both undergraduate students and master students at Xiamen University. A random sample was taken from the subject pool to receive email invitations to a session. Students who responded to our recruiting email were randomly assigned to a session, and no one participated in more than one session. All sessions used an identical protocol. Upon arrival, participants were seated at computer terminals and given a set of instructions, which the experimenter then read aloud.

Every subject participated in 21 rounds of auction. Subjects first performed a practice round, without any payoff, which was followed by 20 rounds with cash motivation. At the end of the experiment, participants received their payoff for these 20 rounds in private. Each session lasted about 1.5 hours. Participants earned an average of 50 CNY (about $8.50 US).

In each round, all 20 subjects participated in an auction with six identical objects. Each subject could purchase at most one unit in a round. For each round, subjects' values were independently drawn from a discrete uniform distribution from an integer interval [0,10000]. To directly compare the impact of institutions, we randomly generated the values for one treatment and then used the same values for the other three treatments. Moreover, the minimum increment of bidding in each treatment was 10. The experiment was programmed and conducted with the software z-Tree (Fischbacher, 2007).

The specific designs for four treatments are as follows:

- **The Shanghai treatment.** Each round of the Shanghai auction had two stages. The first stage lasted for 3 minutes, and each bidder could only submit one bid in this stage. The second stage lasted for 1.5 minutes, and each bidder could revise his or her bid twice. Only if the subject submitted a bid in the first stage could she/he revise the bid in the second stage. In the entire round, subjects could see the current sixth highest bid in real time. The revised bids in the second stage could only range from real-time 6th bid-250 to real-time 6th bid+250. The bidders were sorted by final bid price in descending order, and the first six bidders won the objects and paid their bids. If several bidders had the same final bids, these bidders were sorted by submitting time.

- **The Singapore treatment.** Each round of the Singapore auction lasted for three minutes. Throughout the entire round, a subject could see "the current lowest accepted bid," which was equal to the real-time seventh highest bid price plus 10. Throughout the entire round, each subject could bid multiple times, but the bid had to be equal to or higher than "the current lowest accepted bid." If a subject's bid was not less than the final lowest accepted bid, he or she could obtain an object and pay a price equal to the lowest accepted bid.

- **The Guangzhou treatment.** Each round of the Guangzhou auction lasted for three minutes. In each round, a bidder could submit the bid once and revise it twice. After the auction began, at one minute and two minutes, "the current average bid" was announced to every bidder twice. "The current average bid" was the average of bids in the range of the 10th percentile to the 90th percentile at the announcement time. The bidders were sorted by final bids in descending order, and the first six bidders won the objects and paid their bids. If several bidders had the same final bids, these bidders were sorted by submitting time.

- **The UPSB treatment.** Each round of the UPSB auction lasted for three minutes. In each round, a bidder could only submit one bid. Throughout the entire auction, the bidder had no information about others' bids. The bidders were sorted by bid in descending order, and the first six bidders got the object and paid a price equal to the seventh highest bid. If several bidders had the same bids, these bidders were sorted randomly.

4 General Description of Experimental Results

4.1 Performance

We first address the relative efficiency of the four alternative procedures. In a K-object auction, efficiency means that the objects are allocated to bidders whose values are the K highest values. In car license auctions, the average revenue implies how much bidders need to pay to own a car license. If an auction is efficient, the sum of revenues and consumer surpluses should be maximized. We define the efficient bidders as bidders who successfully purchase an object in an auction and whose value is one of the K highest values in the auction. Thus, efficiency can be measured as follows:

$$\text{Efficiency 1} = \text{The number of efficient bidders}$$

Alternatively, we could also consider efficiency according to the social welfare of auctions. Thus, the efficiency of an auction format could also be measured as follows:

$$\text{Efficiency 2} = \frac{\text{The sum of actual winners' values}}{\text{The sum of } K \text{ highest values}}$$

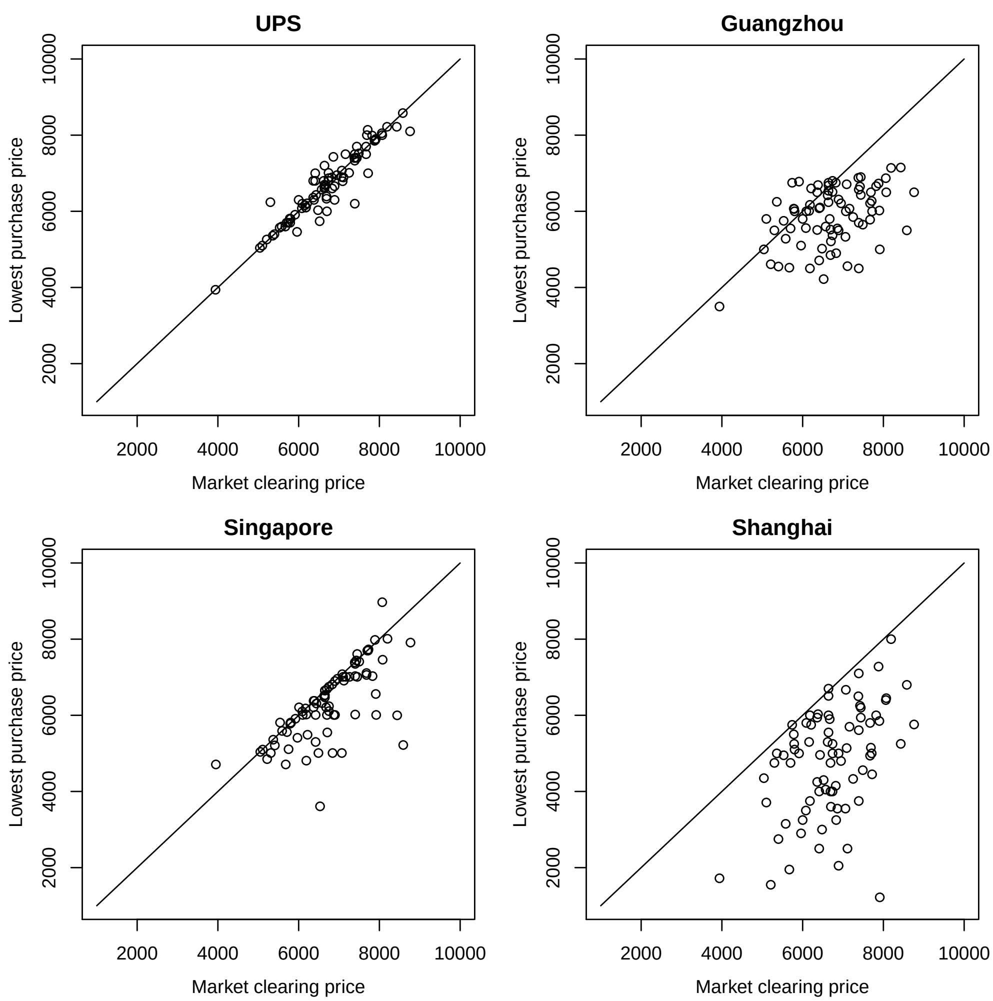
Table 1: The Efficiency of Four Auction Formats

	UPSB		Singapore		Guangzhou		Shanghai
Revenue	6687.00	>	6290.76	<	6388.40	>	5148.50
	(904.38)	***	(960.65)	**	(820.069)	***	(1406.93)
Consumer Surplus	1566.06	<	1759.11	>	1657.48	<	2303.81
	(1168.26)	***	(1437.93)	*	(1172.48)	***	(1646.69)
Social Welfare	49518.38	>	47695.50	=	48275.25	>	44713.88
	(3581.68)	***	(5187.90)		(3727.78)	***	(5162.22)
Efficiency 1	5.56	>	5.15	>	4.93	>	3.81
	(0.55)	***	(0.89)	**	(0.88)	***	(1.03)
Efficiency 2	0.99	>	0.97	=	0.97	>	0.90
	(0.02)	***	(0.05)		(0.03)	***	(0.08)

Note: ***, ** and * denote statistical significance at 1, 5 and 10 percent level of Wilcoxon rank-sum test, respectively.

Both UPSB auctions and Singapore auctions are uniform price auctions. 1 shows that the efficiency of UPSB auctions is significantly higher than that of Singapore auctions. Moreover, the revenue and the social welfare of UPSB auctions are significantly higher than those of Singapore auctions, while Singapore auctions have a higher consumer surplus. Guangzhou auctions and Shanghai auctions are discriminatory price auctions; however, the efficiency of Guangzhou auctions is significantly higher than that of Shanghai auctions. The Shanghai auction has the least revenue and the least social welfare of the four auction formats, and it causes a 10% loss of total social welfare. However, the Shanghai auction has the highest consumer surplus, followed by the Singapore, Guangzhou, and UPSB auctions.

Figure 2: Lowest Purchase Prices versus Market Clearing Price by Auctions



Note: Black dots indicates lowest purchase prices.

Furthermore, the standard deviation of revenue shows the volatility of purchase price in an auction. The price volatility of Shanghai auctions is much higher than the other three auction formats.

We report the lowest purchase prices versus the market clearing prices[7] of four treatments in Figure 2. In the UPSB auctions, there is no significant difference (at the 5% level of significance of the Wilcoxon signed-rank test) between lowest purchase prices and corresponding market clearing prices. The lowest purchase prices are lower than the corresponding market clearing prices (at the 5% level of significance of the Wilcoxon signed-rank test) in Singapore, Guangzhou and Shanghai auctions. This implies that the allocations in UPSB auctions are efficient while bidders in other car license auctions systematically underbid. Figure 2 supports the results of the efficiency comparison.

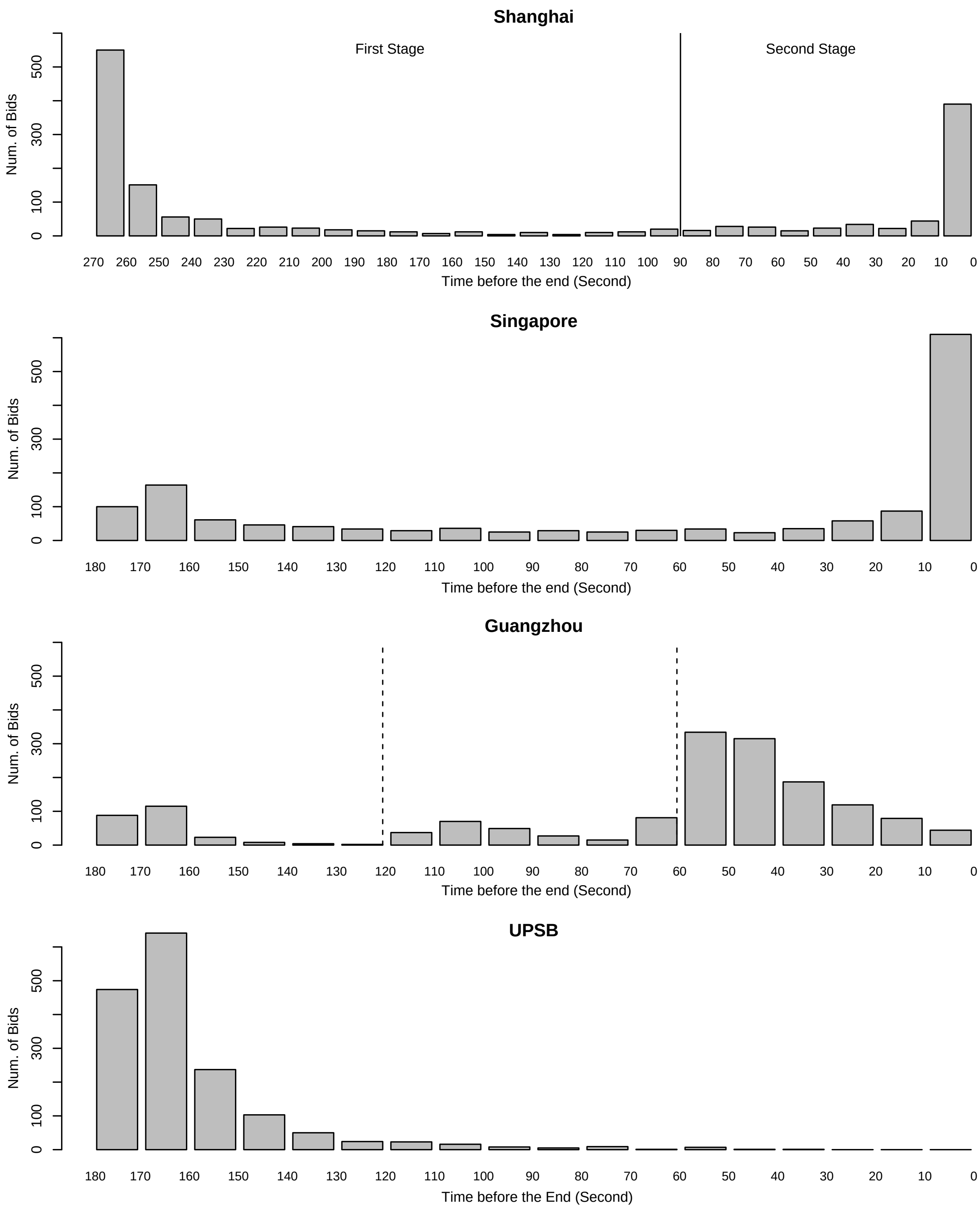
4.2 Bidding Time

The Shanghai and Singapore auctions are dynamic auctions where bidders can observe the real-time lowest accepted price. Late bids are usually found in dynamic Internet auctions (Ockenfels and Roth, 2006; Roth and Ockenfels, 2002). According to 1 and 3, bidders in Shanghai auctions and Singapore auctions would bid very late to have the auctioneer receive these bids at the end of the auctions. In Shanghai auctions, some bidders may give up the chance to revise their bid in the second stage. Thus, some final bids will be received in the first stage of Shanghai auctions. In Guangzhou auctions, the theoretical prediction shows that subjects submit their final bids after the second announcement. The bidding time is not that important in the UPSB auction because of its information structure.

Figure 3 illustrates the timing of the auctioneer receiving the final bids from bidders. The top panel shows that most final bids were received in the first 10 seconds (32.5%) and the last 10 seconds (24%) of Shanghai auctions. The second panel shows that about 40% of all final bids were received in last 10 seconds of Singapore auctions, but this does not reduce the efficiency of the auctions. In Guangzhou auctions, about 70% of all final bids is received in the last 60

[7] An auction can have many market clearing prices. In this paper, we only consider the lowest one when referring to "the market clearing price".

Figure 3: The Receiving Time of Final Bids



seconds. Figure 3 reveals that late bidding is much more prevalent in dynamic auctions than in sealed-bid auctions. The experimental results support the theoretical predictions regarding bidding time.

5 Estimated Bidding Strategies and Learning Effects

Figure 4 shows subjects' actual bids in four treatments. We also include the equilibrium strategy of Guangzhou, Singapore and UPSB auctions in the figure. Although most bids are very close to the equilibrium strategies, some of the bid prices are higher than their corresponding value while some are very close to zero. The equilibrium strategy of Shanghai auctions depends on the dynamic historical information in each auction, so we do not show it in the figure.

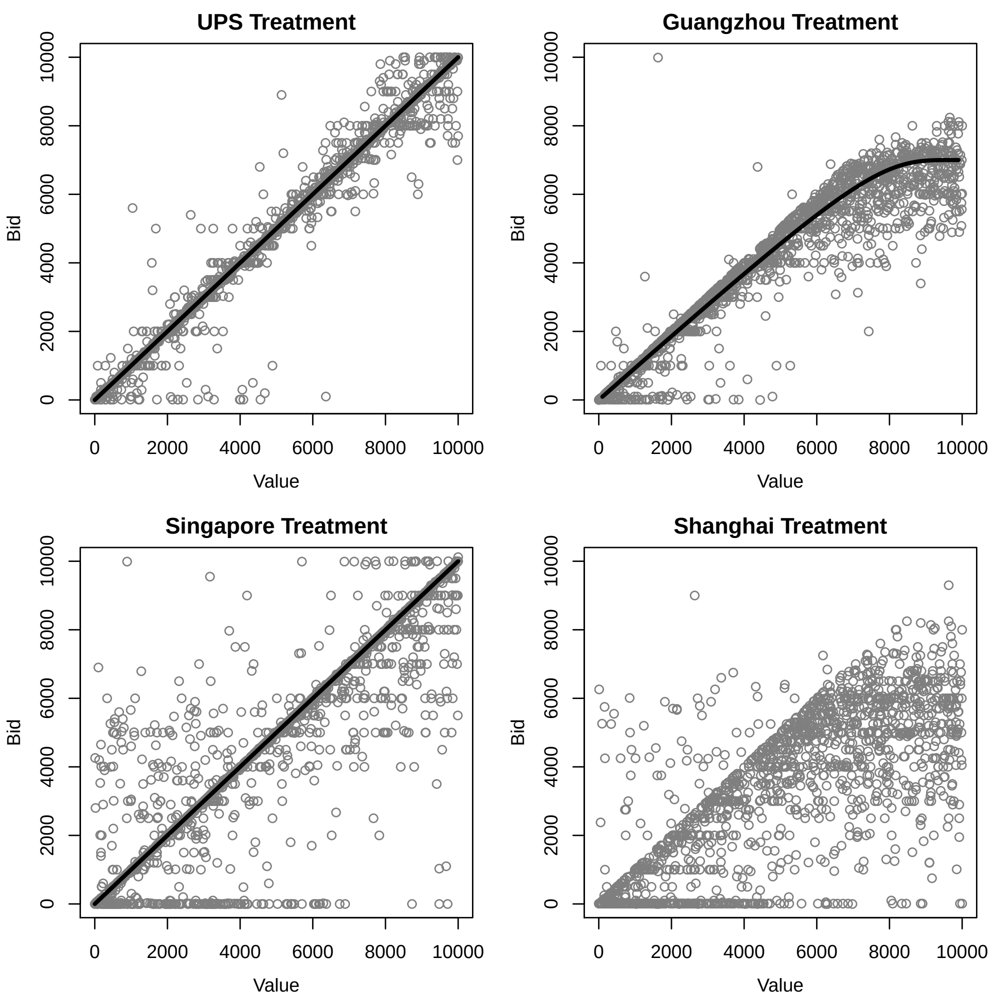
In Shanghai auctions, two characteristics are used to define the types of outcomes. First, the final bids are distinguished by whether the corresponding values are higher than the final lowest accepted bids. Second, the final bids can cause either a win or a lose in an auction. The different types of outcomes in Shanghai auctions are depicted in Table 5.

	$v_{it} > B^K_{N-1,t}$	$v_{it} < B^K_{N-1,t}$
Win	Positive Surplus (PS), 29.88%	Incorrect Bids (IB), 0.12%
Lose	Slower reaction (SR), 23.81%	Low Value (LV), 46.19%

Note: PS and LV include the case that the value is equal to the final bid.

"Slower reaction" indicates that the subject loses the auction, but there was an alternative bid at which he could have won and earned a positive surplus. This implies a relatively large w_i compared to his potential opponents. We refer to "positive surplus" as an outcome in which the subject won and earned a positive surplus and "incorrect bids" indicates an outcome with a negative surplus. "Low value" indicates that there was no other bid at which the bidder could have won and earned a positive surplus. In the Shanghai auctions, the number of slow reactions (23.81%) is quite large compared to the positive surpluses (29.88%). The outcome is rarely "incorrect bids," which shows that subjects do not bid higher than their values. The

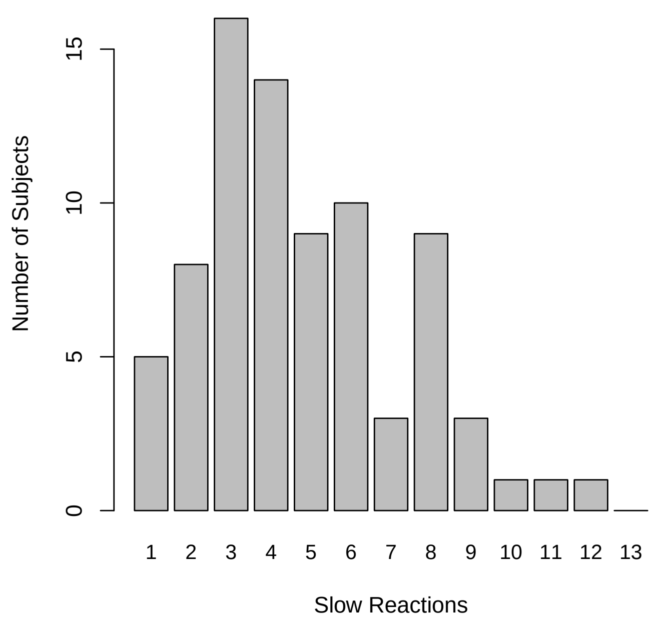
Figure 4: The Bids and Equilibrium Strategies



Note: Solid black lines indicate the theoretical predictions of bidding strategies. Gray dots indicates the actual final bids.

number of slow reactions by subject can be regarded as an indicator of reaction time w_i. Figure 5 indicates that the reaction time distribution of subjects is quite flat. About 25% of subjects lost more than six opportunities to win in Shanghai auctions while some others did not lose any opportunities.

Figure 5: The Number of Slow Reactions by Subjects



We estimate the effects of reaction time on the total profit of subjects. As shown in table 2, subjects with a larger number of SRs have significantly lower total profit in Shanghai auctions. Our estimation results imply that subjects with a relatively fast reaction can earn more than subjects with a relative slow reaction. In Shanghai, a market exists in which agents charge ordinary consumers a fee to bid for licenses. The agents have more experience, faster computers, and faster Internet access than ordinary consumers. The charge for a successful bid [8] is from 3,000 to 7,000 CNY (about \$500 to \$1,200 US).

The equilibrium bidding strategies of UPSB and Singapore auctions are linear, so we estimated the bidding strategies of the two treatments as follows:

$$b_{it} = \alpha_0 + \alpha_1 \cdot v_{it} + \epsilon_{it}$$

[8] Typically, the bid should not exceed the final lowest accepted bid plus M.

Table 2: The effects of Reaction Time on Total Profits

Total Profit (N=80)	Model 1	Sig.	Model 2	Sig.	Model 3	Sig
Intercept	-12670	**	17889.9	***	-12680	***
	(5390)		(1700.7)		(4709)	
Total Value	0.26	***			0.33	***
	(0.05)				(0.05)	
Num. of SRs			-854	***	-1310	***
			(316.7)		(261.1)	
Adjust R2	0.23		0.07		0.41	
F test	24.59		7.27		28.7	

Note: ***, ** and * denote statistical significance at 1, 5 and 10 percent level, respectively.

where b_{it} and v_{it} are the bid price and the value of bidder i in round t respectively, $\epsilon_{it} \sim i.i.d.\ \mathrm{N}(0, \sigma^2)$. If each bidder in the UPSB treatment and the Singapore treatment follows the equilibrium strategy, there must be the intercept term $\alpha_0 = 0$ and the slope term $\alpha_1 = 1$.

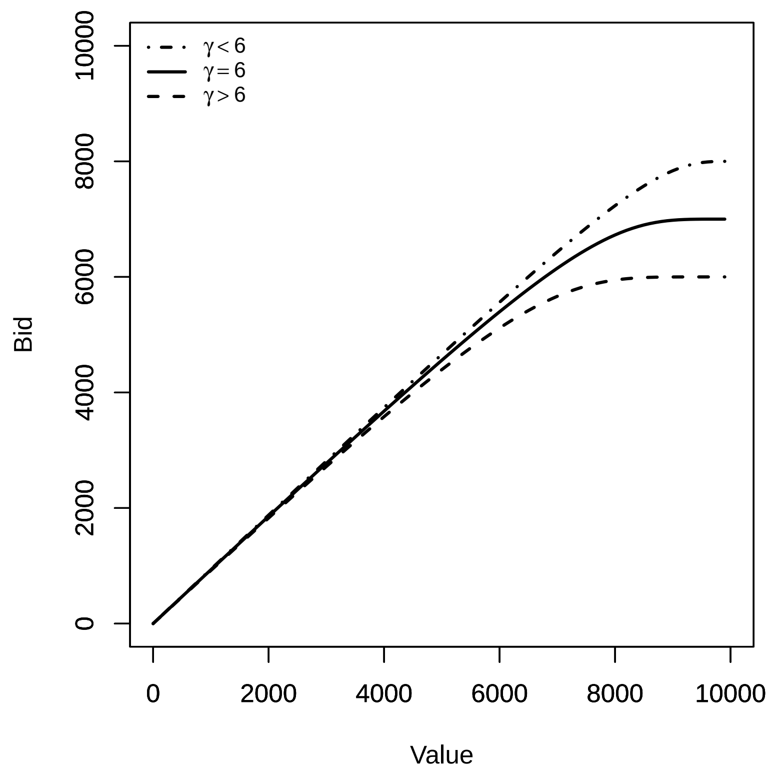
The equilibrium bidding strategy of Guangzhou auctions is nonlinear, so we estimated the bidding strategy as follows:

$$b_{it} = \gamma_0 + \frac{10000}{I_{v_i}(20 - \gamma_1, \gamma_1)} \int_0^{\frac{v_i}{10000}} x \cdot I'_x(20 - \gamma_1, \gamma_1)\mathrm{d}x + \epsilon_{it}$$

where $I_x(\alpha, \beta)$ is a cumulative distribution function of Beta distribution. In the Guangzhou treatment, there must be $\gamma_0 = 0$ and the slope term $\gamma_1 = 6$ if subjects are symmetric risk neutral.

We estimate the coefficients of three models by maximum likelihood estimation (MLE) and summarize the results in Table 3. First, the intercept terms of the three models are not significantly different from 0, which means that subjects would bid 0 when their values are 0. Secondly, we cannot reject the hypotheses that the slope terms are equal to 1 in both Singapore auctions and UPSB auctions. The results support our theoretical model that the equilibrium strategies in the two treatments are to exactly bid the value. However, the equilibrium bidding strategy can predict the bids better in UPSB auctions than in Singapore auctions. Finally,

Figure 6: The theoretical bidding strategies with different γ



we reject the hypothesis that $\gamma_1 = 6$. The coefficient of the beta distribution is significantly lower than the 6 that subjects overbid compared to the risk neutral equilibrium strategy (see figure 6 for an example).

Both economists and policy makers have expressed interest in the learning effect of various auction formats. The equilibrium solution concept relies on the common knowledge of rationality; however, the criterion of common knowledge may only be met after bidders repeatedly interact and analyze the feedback in a series of repeated auctions. Furthermore, because the bidding rules and the information structures are different, various rounds may be needed for bidders to adjust their behavior to achieve equilibrium in the four auction formats.

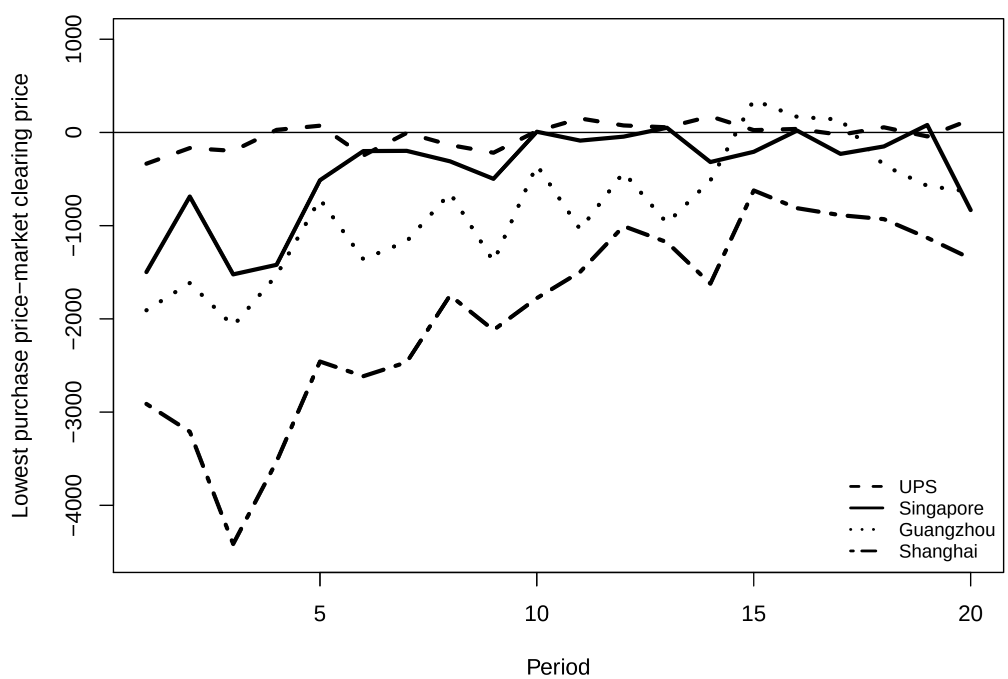
Figure 7 shows how the lowest purchase price converges to the market clearing price over time. When all subjects follow the equilibrium strategy in a UPSB, Guangzhou, or Singapore auction, we should observe an efficient allocation of objects. This implies that the lowest purchase price should be equal or close to the market clearing price in these auctions. Therefore, the average differences between the lowest purchase price and the market clearing price

Table 3: The Bidding Strategies of UPSB, Singapore and Shanghai Auction.

b_{it} (N=1600)	UPSB	Sig.	Singapore	Sig.	Guangzhou	Sig.
Intercept	-50.86		296.35		-19.9	
	(31.75)		(289.63)		(18.73)	
v_{it}	1.00	***	0.96	***	5.96	***
	(0.01)		(0.05)		(0.01)	
σ	633.23	***	5946.21	***	713.72	***
	(11.19)		(104.87)		(13.05)	
Number of Sample	1600		1600		1600	
-LL	12591.82		16168.74		12779.13	

Note: ***, ** and * denote statistical significance at 1, 5 and 10 percent level, respectively.

Figure 7: The differences between the lowest purchase prices and the market clearing prices



measure the proportion of subjects who adopt equilibrium strategies. As shown in Figure 7, the purchase prices in a UPSB auction can immediately converge to the market clearing prices at the beginning of repeated auctions. Singapore auctions converge to efficient allocations around the tenth period while Guangzhou auctions converge around the fifteenth period. The Shanghai auction has the largest difference between the lowest purchase price and the market clearing price at the beginning of repeated auctions. Even after 20 periods, we do not observe a convergence to efficient allocation in the Shanghai auction, which coincides with our theoretical results.

Table 4: The Changes in Bidding Strategies

	UPSB ($\hat{\alpha}_1$)	Singapore ($\hat{\alpha}_1$)	Guangzhou ($\hat{\gamma}_1$)
Period 1 to 5	0.99	0.88	5.84
	(0.01)	(0.05)	(0.02)
Period 6 to 10	1.00	0.96	5.95
	(0.01)	(0.05)	(0.01)
Period 11 to 15	1.00	0.99	6.00
	(0.00)	(0.04)	(0.01)
Period 16 to 20	0.99	0.92	6.03
	(0.01)	(0.06)	(0.01)

Table 4 summarizes the coefficients of bidding strategies in different phases of the four treatments. In all four phases, the bids in the UPSB auction always coincide with the equilibrium strategy. In the Singapore auction, subjects gradually adjust their bidding strategies to the equilibrium strategy. We observe a downward adjustment of bid prices in the Guangzhou auction in which the bidding strategy moves from the overbid side to equilibrium.

The complexity of auction rules may explain the difference in learning in the four formats. The relative coarseness of the action space in the sealed-bid auction rules out the more subtle strategies and signaling that is possible in a dynamic auction. Hence, the convergence of bidding strategies in dynamic auctions is much slower than in sealed-bid auctions. Moreover, the equilibrium strategy in the uniform price auctions is much simpler than in the discriminatory auction. Thus, subjects in the uniform price auction learn much more quickly than in the discriminatory auction. Specifically, the Shanghai auction not only is very complex but also does not have an efficient equilibrium, so it does not have an obvious learning process.

6 Discussion and Conclusion

The central issues discussed in this paper are motivated by an assessment of the performance of car license auctions. One policy goal of car license auctions is to allocate public resources efficiently. Our theoretical analysis generated three main conclusions about efficiency. First, the Shanghai auction cannot be efficient. Second, the Guangzhou auction is efficient when participants are symmetric. Third, the Singapore auction allocates objects efficiently if and only if a tie at the market clearing price does not exist. The experimental results show that the Shanghai auction format is not as efficient as other auction formats.

Another policy goal is that the auction formats should be easy to learn. In practice, a complex auction format will cause significant confusion and many misunderstandings about the mechanism. Our evidence shows that the Singapore auction is easier to learn than either the Guangzhou or the Shanghai auction.

Furthermore, critics of car license auctions claim that the price of a car license is too high. Thus, the government tries to use inefficient auction formats (such as the Shanghai auction) to suppress winning prices. However, the bidders whose values are higher than the winning price do not leave the market. As a result, the accumulation of bidders causes an increase in the winning prices in the long run.

This paper provides both theoretical and experimental analysis of the car license auctions that are used to allocate a kind of limited public recourse: a car license. Our results provide further understanding of the robustness of the auction theory. Our assessment of the auction formats may also help local governments develop or improve their policies on the allocation of car licenses.

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Appendix: The Instructions (Not For Publication)

A1 Shanghai auction

Overview

This is an experiment on multiple object auctions. The instructions are simple, and if you follow them carefully and make good decisions, you may earn a considerable amount of money that will be paid to you privately in cash at the end of this experiment.

It is important that you read these instructions carefully so that you understand the task in the experiment. We will also ask you a series of review questions after you finish reading these instructions. This is to test your understanding of the tasks in the experiment. You will be allowed to refer to the instructions as you answer the questions and as you participate in the experiment.

You are prohibited from talking to other participants. Turn off your mobile phones, and only use the computer to complete the experiment. If you have any questions, you should raise your hand and someone will come to answer them.

How you earn money

In today's experiment, you will participate in a multiple object auction. The entire experiment includes 21 rounds and each period last for about 4.5 minutes. In each round, all 20 bidders will participate in an auction with six objects. You can bid for at most one object in a round, and all the objects are identical. The first round is for practice, and it will not generate any cash profit. You can earn profit from the latter 20 periods, and the profit of each period will be added up to determine your total profit.

In each round, you will receive a random number with a minimum interval of 10 between 0 and 10000. It is equally likely that you receive any number in this range. Your random number is your value of the objects in this round. Only you know your own value; all bidders' values are selected from the range of 0 to 10000 with the same probability. Each round includes two stages:

The first stage lasts for three minutes. After you receive the value of objects, you can submit only one bid in this stage. Only you know your bid, and all bidders are informed of "the current lowest accepted bid" (the real-time sixth highest bid). The second stage lasts for 1.5 minutes. You can revise your bid twice in this stage. If you do not revise your bid, your bid in the first stage will be regarded as your final bid. The revision in this stage can only be in the range of "the current accepted bid" minus 250 to "the current accepted bid" plus 250. After you revise the bid twice in this stage, you cannot revise it again. Only you know your bid, and all bidders are informed of "the current lowest accepted bid" (the real-time sixth highest bid). Your final bid at the end of second stage will be used to determine the winners in the round. After two stages, bidders are sorted by final bid in descending order. If you are one of the first six bidders, you will purchase the object and pay your bid. Once you purchase the object, you will exchange it for experimental currency equal to your value. In this case:

Your profit = Your value - Your bid (Note that your profit may be positive, zero, or negative.)

If you don't purchase the object, your profit in the period is zero. In the event of a tie, the tied bids are sorted in ascending order of submission time. If some bidders have the same final bid and the same submission time, we will randomly sort these bidders. The profit of each period will be added up to determine your total profit. Your total earning is in experimental dollars, and we will convert them to yuan (RMB) at the exchange rate:

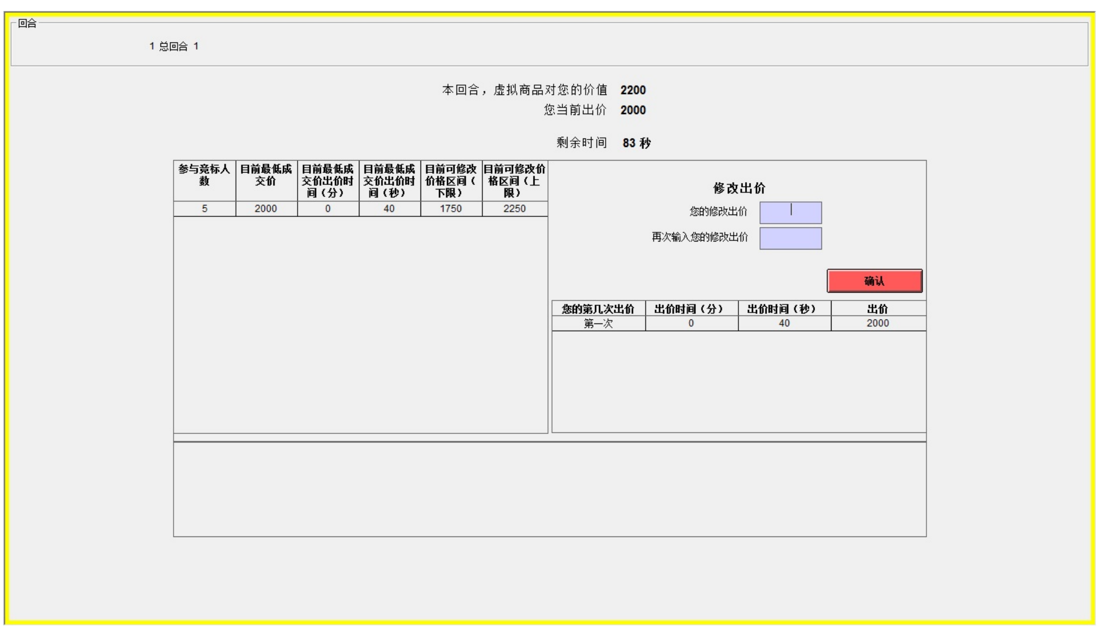
1 Yuan (RMB) = 300 Experimental Dollars.

We will pay you this money plus the 10 yuan (RMB) show-up fee privately at the conclusion of the experiment.

How to use the computer interface

The following figure shows the interface of the first stage. As an example, you can see that your value in this period is 8,900 experimental dollars. You are informed of the current lowest accepted bid, the number of bidders who submit bids, and the remaining time. You need to enter your bid twice and click the "Submit" button to submit your bid.

The following figure shows the interface of the second stage. As an example, you can see your value is 2,200 experimental dollars and your last bid is 2,000. You are informed of the current lowest accepted bid, the number of bids or revisions you have already made, the remaining time, and the number of bidders who submit bids. You need to enter your revised bid twice and click the "Submit" button to submit your revision.



History of Past Periods

In each auction period, you can see your history information at the bottom of the window. Here you will find information about your past values, you past bids, the past winning prices, and your past purchases.

Note: If you do not successfully submit your bid in the first stage of a round, you cannot bid or revise in the second stage or purchase the object in the round.

Review Questions

Please raise your hand if you have any questions. After five minutes we will go through the answers.

1. Suppose you are participating in an auction, 20 bidders' final bids are: 500, 1200, 5600, 9800, 3100, 900, 5300, 7000, 7500, 8800, 4200, 9900, 2700, 7500, 6100, 6900, 8400, 9000, 4800 and 3700. If your final bid is 8800, can you successfully purchase the object? How many objects can you purchase?

   If you can win in this period, what's your winning price?

   How much do you pay for the object?

   If your value is 6000, what is your profit in this period?

   If your value is 8800, what is your profit in this period?

   If your value is 9900, what is your profit in this period?

2. In the second stage, how many times can you revise your bid?

   If the current lowest accepted bid is 5500, what is the range in which to submit your bid?

   If your bid in the first stage is 4900 and you do not bid in the second stage, what's your final bid?

A2 Singapore auction

Overview

This is an experiment on multiple object auctions. The instructions are simple, and if you follow them carefully and make good decisions, you may earn a considerable amount of money that will be paid to you privately in cash at the end of this experiment.

It is important that you read these instructions carefully so that you understand the task in the experiment. We will also ask you a series of review questions after you finish reading these instructions. This is to test your understanding of the tasks in the experiment. You will be allowed to refer to the instructions as you answer the questions and as you participate in the experiment.

You are prohibited from talking to other participants. Turn off your mobile phones, and only use the computer to complete the experiment. If you have any questions, you should raise your hand and someone will come to answer them.

How you earn money

In today's experiment, you will participate in a multiple object auction. The entire experiment includes 21 rounds and each round lasts for about 4.5 minutes. In each round, all 20 bidders will join an auction with six objects to be sold. In each round, each bidder has use for at most one object and the six objects are identical. The first round is a practice round, and it will not generate any cash payoff. You can earn profits from the latter 20 rounds, and the profit from each round will be added up to determine your total profit.

In each round of the auction, you will receive a random number with a minimum interval of 10 between 0 and 10000. It is equally likely that you will receive any number in this range. Your random number is your value of the objects in this round. Only you know your value; all bidders' values are selected from the range of 0 to 10000 with the same probability.

Each round lasts for three minutes. After you receive the value of objects, you can submit a bid in the round. Only you know your bid, and you can submit new bids at any time of the round. The new bid must be higher than your current bid. Your final bid at the end of second phase will be used to determine winners of the auction.

All bidders are informed of the current lowest accepted bid. After three minutes, you purchase the object if your final bid is higher than the final lowest accepted bid. Your price for the object is equal to the final lowest accepted bid. Once you purchase the object, you will exchange it for experimental currency equal to your value. In this case:

Your profit = Your value - The final lowest accepted bid (Note that your profit may be positive, zero, or negative.)

If you don't purchase the object, your profit in the round is zero. The profit from each round will be added up to determine your total profit. Your total earning is in experimental dollars, and we will convert them to yuan (RMB) at the exchange rate of:

1 Yuan (RMB) = 300 Experimental dollars.

We will pay you this money plus the 10 yuan (RMB) show-up fee privately at the conclusion of the experiment.

The current lowest accepted bid

Bidders are sorted by their current bid in descending order. The current lowest accepted bid is equal to the seventh highest bid plus 10. If the number of bidders who have already submitted a bid is smaller than six, the current lowest accepted bid is set to 10.

Note that if two or more than two bidders bid the same sixth highest bids, these bidders are randomly sorted. An example is shown in the following table. The final lowest accepted price is equal to the seventh highest bid plus 10 = 4100+10=4110. Therefore, only four bidders can purchase the objects in this round. Each winner of the auction should pay 4110 to purchase the object.

How to use the computer interface

The following figure shows the interface of the auction. As an example, you can see your value in this round is 6400 experimental dollars. You are informed of the current lowest accepted bid, your past bids, and the remaining time. You need to enter your bid twice and click the

Final bid	Final rank	Purchase
10000	1	Yes
8800	2	Yes
7000	3	Yes
6500	4	Yes
4100	-5	No
4100	-6	No
4100	-7	No
...	...	...

”Submit” button to submit your bid.

History of Past Rounds

In each auction round, you can see your history information at the bottom of the window. Here you will find information about your past values, you past bids, the past winning prices, and your past purchases.

Note: If you do not successfully submit your bids in a round, you cannot bid in the second phase to purchase the object in that round.

Review Questions

Please raise your hand if you have any questions. After five minutes, we will go through the answers.

1. Supppose you are participating in a auction, 20 bidders' final bids are: 500, 1200, 5600, 9800, 3100, 900, 5300, 7000, 7500, 8800, 4200, 9900, 2700, 7500, 6100, 6900, 8400, 9000, 4800 and 3700. If your final bid is 8800, can you successfully purchase the object? How many objects can you purchase?

   If you can win in this round, what's your winning price?

   How much do you pay for the object?

2. Suppose you are the bidder who bids 9000 in Question 1.

   If your value is 6000, what is your profit in this round?

   If your value is 9000, what is your profit in this round?

   If your value is 9900, what is your profit in this round?

3. Suppose you are the bidder who bids 5600 in Question 1.

   If your value is 4000, what is your profit in this round?

   If your value is 5600, what is your profit in this round?

   If your value is 9900, what is your profit in this round?

A3 Guangzhou auction

Overview

This is an experiment on multiple object auctions. The instructions are simple, and if you follow them carefully and make good decisions, you may earn a considerable amount of money that will be paid to you privately in cash at the end of this experiment.

It is important that you read these instructions carefully, so that you can understand the task in the experiment. We will also ask you a series of review questions after you finish reading these instructions. This is to test your understanding of the tasks in the experiment. You will be allowed to refer to the instructions as you answer the questions and as you participate in the experiment.

You are prohibited from talking to other participants. Turn off your mobile phones, and only use the computer to complete the experiment. If you have any questions, you should raise your hand and someone will come to answer them.

How you earn money

In today's experiment, you will participate in a multiple object auction. The entire experiment includes 21 rounds and each round lasts for about three minutes. In each round, all 20 bidders will join an auction with six objects to be sold. In each round, each bidder has use for at most one object and the six objects are identical. The first round is a practice round, and it will not generate any cash payoff. You can earn profits from the latter 20 rounds, and the profit of each round will be added up to determine your total profit.

In each round of the auction, you will receive a random number with a minimum interval of 10 between 0 and 10000. It is equally likely that you will receive any number in this range. Your random number is your value of the objects in this round. Only you know your value; all bidders' values are selected from the range of 0 to 10000 with the same probability.

Each round lasts for three minutes. After you receive the value of objects, you can submit only one bid in this round. Only you know your bid, and your bid will be used to determine winners of the auction.

When a round begins, after one minute and two minutes, the current average bid price will be announced to every bidder. The current average bid is the average of bids between the 10th percentile and the 90th percentile of all bids at that moment. After three minutes, bidders are sorted by final bid in descending order. If you are one of the first six bidders, you purchase the object and pay the amount of your bid. Once you purchase the object, you will exchange it for experimental currency equal to your value. In this case:

Your profit = Your value - Your bid (Note that your profit may be positive, zero, or negative.)

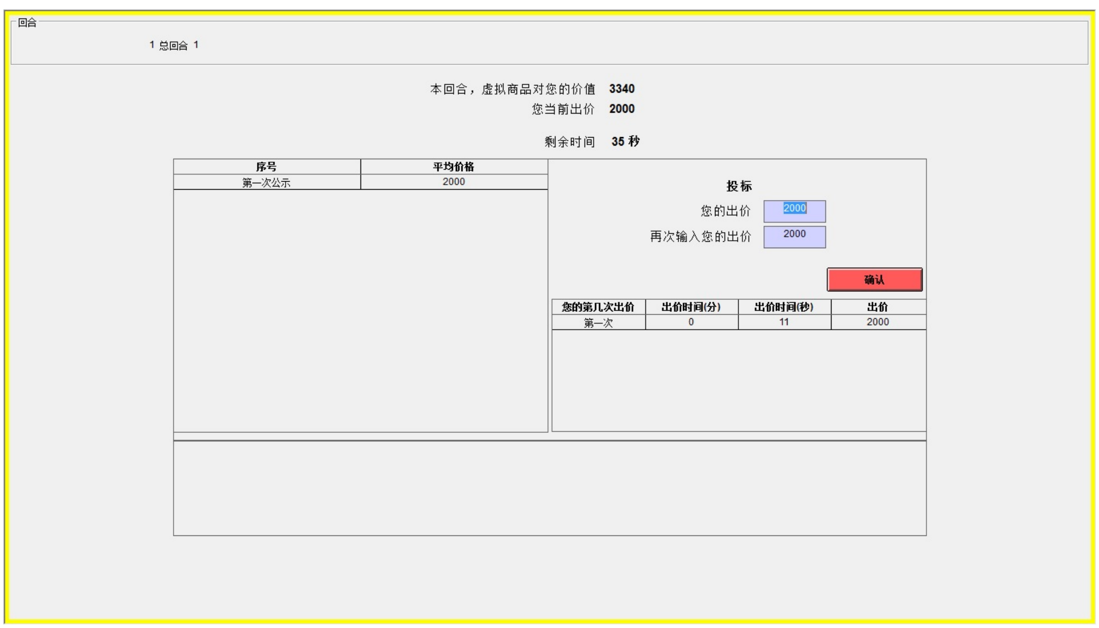
If you don't purchase the object, your profit in the round is zero. In the event of a tie, the tied bids are sorted in ascending order of submission time. If some bidders have the same final bid and the same submission time, we will randomly sort these bidders. The profit from each round will be added up to determine your total profit. Your total earning is in experimental dollars, and we will convert them to yuan (RMB) at the exchange rate:

1 Yuan (RMB) = 300 Experimental dollars.

We will pay you this money plus the 10 yuan (RMB) show-up fee privately at the conclusion of the experiment.

How to use the computer interface

The following figure shows the interface of the auction. As an example, you can see your value in this round is 3340 experimental dollars. You are informed of the current average bid and the remaining time. You need to enter your bid twice and click the "Submit" button to submit your bid or revisions.



History of Past Rounds

In each round, you can see your history information at the bottom of the window. Here you will find information about your past values, you past bids, the past lowest purchase prices, and your past purchases.

Note: If you do not successfully submit your bids in a round, you cannot purchase the object in that round.

Review Questions

Please raise your hand if you have any questions. After five minutes we will go through the answers.

1. Suppose you are participating in an auction, 20 bidders' final bids are: 500, 1200, 5600, 9800, 3100, 900, 5300, 7000, 7500, 8800, 4200, 9900, 2700, 7500, 6100, 6900, 8400, 9000, 4800 and 3700. If your final bid is 8800, can you successfully purchase the object? How many objects can you purchase?

   If you can win in this round, what's your winning price? What's your winning price?

   How much do you pay for the object?

   If your value is 6000, what is your profit in this round?

   If your value is 8800, what is your profit in this round?

   If your value is 9900, what is your profit in this round?

2. In a round, how many times you could submit your bid?

   If your first bid is 4900 and you do not bid later, what's your final bid?