Evaluating car license auction mechanisms

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Evaluating the car license auction formats of Shanghai, Guangzhou and Singapore: theory and experimental evidence

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Abstract

Auctions are widely used to implement a quota system of car ownership in fast growing cities. Three such cities where influential auction formats have been developed for allocating car licenses are the Asian metropolises of Singapore, Shanghai and Guangzhou, with other cities following suit. In this paper, we examine these auction formats theoretically and experimentally. We introduce reaction time as an important non-economic factor to model bidding behaviors in car license auctions. At the theoretical level, reaction time causes inefficient allocations in the Shanghai auction but not in the Singapore or Guangzhou auctions. The experimental results are consistent with our theoretical prediction that late bids prevail in all of these auction formats, but only lead to inefficient allocations in the Shanghai auction. Additionally, we scored the subjects' reaction time in the Shanghai treatment by conducting a number comparison task and we found a positive correlation between winning probability and the score for reaction time.

JEL classification: C92; D44; D91

Keywords: Car license; Multi-unit auction; Experiment; Behavior;

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1 Introduction

Car license auctions have played an important role in recent decades in easing the pressures caused by urbanization. In the large urban centers of Asia (e.g., Singapore, Beijing, Shanghai, Guangzhou and Tianjin), robust population expansion and growing incomes are fueling the rise in car ownership. In 2016, the number of registered motor vehicles in Singapore, Beijing, Shanghai and Guangzhou was 0.96, 5.48, 3.22, and 2.30 million, respectively. The surge in the number of cars has brought many problems, including smog, road congestion and a shortage of parking spaces to name a few. The limiting and auctioning of car license quotas has been a widely used practice¹ since Singapore pioneered the car license auction in 1990. In the early 1990s, Shanghai was the first city in China to assign car licenses using auctions and Guangzhou launched its car-controlling program in 2012. Thousands of licenses were sold in an auction, with a limit of one license per bidder. Purchasing a car license successfully allows the bidder to own a car in that city. Shanghai, Guangzhou and Singapore each use a different auction format, with others cities² following suit with similar versions. Hence, we focus on these three influential auction formats in this paper.

Of considerable interest among policymakers is the efficiency of these auction formats, while economists are more concerned with how people make decisions in auctions in order to come up with ways to design more favorable auction markets. Some of the literature provides an analysis of the empirical data on car license auctions in Singapore and Shanghai. Koh and Lee (1994) argue that the Singapore auction should be discriminatory, in order to make it more equitable and politically acceptable. Several studies focus on the impact of the change from sealed to open bids in the Singapore auction, which took place in 2001 (Koh, 2003; Chu, 2011; Cheng, 2011). They suggest that the shift has led to lower volatility in relation to winning price and better interaction between the forces of supply and demand. Luo (2008) analyzed the impact of the mechanism changes in the Shanghai auction. However, analyzing the empirical auction data of these cities is not our the focus of this study because a direct

¹Some other cities in China, such as Beijing, Wuhan and Chengdu, implement lottery for car licenses and car use restriction.

²Tianjin and Hangzhou adopted the policy similar to Guangzhou's mechanism in 2014.

comparison of car license auction formats cannot be conducted when the willingness to pay of bidders is absent in the empirical data and the cities vary in terms of population density, income distribution and traffic conditions. Hence, a controlled laboratory experiment, like the one used for this study, is an ideal methodology for testing our theoretical predictions regarding the bidding behaviors and efficiencies in the Shanghai, Guangzhou and Singapore auctions.

In our model, we assume that there are incremental bidders and rational bidders in the auctions. Incremental bidders use a naive strategy of bidding one increment above the current auction price, while rational bidders use a sophisticated best response strategy to prior value distributions and others' bids. Moreover, regardless of what type of a bidder is, they cannot react to others' bids instantaneously because of the presence of reaction time.³ In this paper, we name the sophisticated strategy to be late-bid strategy in car license auctions⁴. Furthermore, we found that, the Shanghai auction cannot theoretically guarantee an efficient allocation even among rational bidders due to its bidding constraints and the differences in bidder reaction time. In the Shanghai auction, bidders with a shorter reaction time are theoretically able to bid higher than those with a longer reaction times by using a late-bid strategy. In the Singapore auction, a late-bid strategy not only suggests last-minute bidding right before an auction ends, but also suggests finally bidding their own values, then could end up with an efficient allocation. In the Guangzhou auction, an efficient allocation is achieved by using a late-bid strategy, which actually is the Nash equilibrium bidding strategy deriving from a discriminatory price sealed-bid auction.

We collected behavioral data from our laboratory experiments of real-life car license auction formats and used a theoretical auction format called Uniform Price Sealed-Bid (UPSB) as our baseline treatment (e.g., Plott, 1994; Merlob et al., 2012; Cramton, 2012; Chen and Kesten, 2013). The experimental results show that there are far more inefficient allocations in the

³Roth and Ockenfels (2002) and Ockenfels and Roth (2006) explain that the late bids observed in the internet auctions are caused by delayed reactions and incremental bidders. In their model, the last-second bids are homogeneous and each bid has the same probability of being received by the auctioneer.

⁴Our 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).

Shanghai auctions than in the other three auction formats ⁵. In the Shanghai auction, we found that many high value bidders were not able to win due to their very low bids, which was not observed in the other auction formats. The lack of success of high value bidders may have been caused by their slow reactions. For instance, when the price was pushed up by fast reaction bidders in the last 5 seconds before a Shanghai auction closed, slow reaction bidders might have no time to revise higher bids then. We found evidence to support this by scoring the subjects' reaction times after the Shanghai auction. These scores positively affect the probabilities of winning in the Shanghai auction, which is also consistent with our model, and also explains the existence of agents in Shanghai who bid car licenses on behalf of their customers for a fee of US\$500 to US\$1,500 for each successful bid. In addition, a mass of late bids were observed in the Shanghai, Singapore and Guangzhou auctions, which is consistent with our assumption of late bidding in our model. By analyzing the convergence of bidding processes to equilibrium bidding strategy in the UPSB, Guangzhou and Singapore auctions, we found that learning is much easier in uniform price auctions than in discriminatory price auctions, and also in sealed-bid auctions compared to open auctions.

The remainder of the paper is organized as follows. In the next section, we introduce the three auction formats that are implemented in practice. Section 3 describes the theoretical models of car license auctions. Section 4 presents our experimental design. Section 5 summarizes the experimental results. Section 6 discusses the reaction time effects and learning effects in the experiments. Finally, the conclusion is given in the last section.

2 An overview of car license auctions

The license to use a vehicle is called a Certificate of Entitlement (COE) in Singapore. The auction is conducted every two weeks by the Land Transport Authority of Singapore. A typical auction lasts for about three days, with around 6,000 bidders competing for approximately 3,500 car licenses. A winning price for a COE reached US\$50,000 in July 2017. The auction

⁵Our experiments show a similar result to Liao and Holt (2013), who found that the Shanghai auction is not as efficient as many other classical auction formats.

is run according to an open-bid format, in which bidders can submit/revise bids and receive information about the current price during the entire auction. The current price is the highest $K+1$ th bid plus one Singapore dollar according to the license quota K . All bids and revisions must be equal or higher than the current price. When the auction ends, the bidders with final bids equal to or higher than the final current price win a COE and purchase it at the final current price.

In Shanghai, an online auction platform operated by the Shanghai International Commodity Auction Limited Company conducts a monthly car license auction. In July 2017, 269,189 bidders competed for 10,325 car licenses and the average winning price was around US\$13,660. It is a 1.5 hour open-bid auction and the current price is always publicly announced to all bidders. The current price in the Shanghai auction is the highest K th bid according to the license quota K . The Shanghai auction has two stages: In the first stage, each bidder can submit a bid as long as it is not higher than the cap (warning price); in the second stage, the bidders may revise their bids a maximum of two times within a narrow price interval. A revision in the second stage can only be in the range of the current price of ± 300 RMB. Bidders who bid higher or equal to the final current price win and each winner pays their bid in order to purchase a license.

Guangzhou implemented its car-controlling program in 2012. Guangzhou Enterprises Mergers and Acquisitions Services conducts a monthly online auction, which lasts six hours. In June 2017, the number of car licenses available for private ownership was 3,538, for which 9,505 bidders competed. The average winning price was around US\$3,776. Each bidder can submit a bid and revise it twice at any time during the auction. Unlike the Singapore and Shanghai auctions, no real-time price information is provided in the Guangzhou auction. It only makes two announcements at 11:00 am and 1:00 pm, which are about to the mean of the middle 80% of all bids, ignoring the top and bottom 10%. According to the quota K , licenses are sold to the bidders who submit the highest K final bids. The Guangzhou auction is also a discriminatory price auction, in which every winner pays their bid. Figure 1 shows the timeline for each auction format.

[Figure 1 Timelines and bidding rules in different cities]

3 Models

Car license auctions are essentially multi-unit auctions with bidders who demand only a single unit. However, compared to classical multi-unit auction formats, real-life car license auctions have their own bidding rules and real-time information systems. We consider a setting of an auction with N bidders competing for K identical objects. Each bidder i demands a single unit object with private value $v_i \in [0, \bar{v}]$ which is independently drawn from a distribution F with f being its density function. The auction time is denoted by $t \in [0, 1]$.

Let $\beta_i(\cdot)$ be the bidding strategy of bidder i in an auction. In car license auctions, bidders are allowed to revise their bids several times. We denote b_i as bidder i 's final bid.

Car license auctions are conducted online where the participants submit their bids over the internet. The participants' reactions to the dynamic information cannot be instantaneous and vary depending on their mental chronometry as well as network and computer speed.⁶ Denote w_i as bidder i 's reaction time, which is independently drawn from a distribution W with strictly positive density on $[0, \bar{w}] \subset \mathbb{R}^+$ and $\bar{w} \ll 1/3$.⁷ As shown in Figure 2, reaction time is defined as the time between when a bidder makes a decision and the auctioneer registers the bid.

[Figure 2 Reaction time]

Furthermore, a bidder can either use a best response bidding strategy or an incremental bidding strategy. In incremental bidding, a random minimum amount is submitted, which is one bid higher than the current lowest accepted price as well as lower than its relevant value. Denote bidder i 's type as $\theta_i = 0$ in the case of a best response bidding strategy and $\theta_i = 1$ in the case of an incremental bidding strategy.

Therefore, the type space of bidder i denotes $[v_i, w_i, \theta_i] \in [0, \bar{v}] \times [0, \bar{w}] \times \Theta$.

⁶Roth and Ockenfels (2002) and Ockenfels and Roth (2006) assume the reaction time to be nonzero and a constant across all bidders.

⁷It ensures that each bidder, even the slowest one, is able to submit/revise a bid at any stage of the auction. Shanghai and Guangzhou auctions implement the second stage when the auction time t goes to the last one-third.

3.1 The Shanghai auction

The Shanghai auction has two stages. Each bidder can bid once at any time in the first stage where the auction time $t \in [0, 2/3]$, and they can revise the bid twice at any time in the second stage where $t \in (2/3, 1]$. If a bidder does not bid in the first stage, they cannot proceed to the second stage. Denote H_t^K as the K th highest bid at time t . Bidders are informed of the real-time H_t^K throughout the auction.

In the first stage, a bidder can submit one bid ranging from 0 to a fixed price cap $C \in (0, \bar{v})$.⁸ The price cap is set exogenously and is lower than the market clearing prices.⁹ In the second stage, bidder i can submit two revisions. The revisions submitted to the auctioneer at time t must be one of three options; $H_t^K - M$, H_t^K or $H_t^K + M$ where $M \ll \bar{v}$.¹⁰ If bidders do not revise their bids in the second stage, the bids in the first stage are considered their final bids.

In the Shanghai auction, the payoff of bidder i can be written as:

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

where B_{N-1}^K denotes the K th-highest final bid of other $N - 1$ bidders. The tie is first broken by time priority and randomization is used as a complement if the tie still exists.

Lemma 1 *The current price monotonically increases throughout the entire Shanghai auction.*

Proof. In the first stage, new bids contribute to the increase of the current price. In the second stage, incremental bidders revise their bids higher than the current price, which pushes the price up. Meanwhile, best response bidders have no incentive to revise a bid lower than

⁸This is called the warning cap price in Shanghai auctions.

⁹According to the published information on car license transactions in Shanghai, the lowest purchase price at each auction is always higher than the corresponding warning price.

¹⁰In practice, M is smaller than 0.5% of $\bar{v}$. Although bidders can submit one of five options in real-world Shanghai auctions, we only consider the following three for purposes of $H_t^K - M$, H_t^K or $H_t^K + M$.

the current price since it would only result in zero profit. To summarize, all bids and revisions would increase the current price. ■

With the assumption of reaction time, best response bidders must reserve enough time to successfully submit their final bids before the auction ends. For instance, a bidder i with reaction time w_i has one last chance to make a revision at time $t = 1 - w_i$, before t goes to 1. At time $1 - w_i$, bidder i could increase their bid as high as $H_i^* + M$ where $H_i^* \equiv H_{1-w_i}^K$. Hence, bidders may have different H^* due to their different reaction times.

We propose the following:

Proposition 1 (Late-bid strategy in the Shanghai auction) *The late-bid strategy of rational bidders in the Shanghai auction is given by*

1. *In the first stage, bidder i is to submit their bid b_{i0} at $t = 2/3 - w_i$:*

$$b_{i0} = \begin{cases} C, & v_i \geq C \\ v_i, & v_i < C \end{cases}$$

2. *In the second stage, bidder i is to submit their revision b_i at $t = 1 - w_i$:*

$$b_i = \begin{cases} H_i^* + M, & v_i \geq H_i^* + M \\ b_{i0}, & v_i < H_i^* + M \end{cases}$$

Proof. Recall that the warning price C is the upper bound of bids in the first stage, but there are at least $K + 1$ bidders with values higher than C . Therefore, high value bidders (higher than C) have no incentive to bid lower than C and take the risk of competing against low value but fast-reaction bidders, while low value bidders (lower than C) have no incentive to submit bids higher than their values. Thus, rational bidders have no incentive to deviate from the late-bid strategy in the first stage.

In the second stage, bidder i cannot react to the information updating after $t = 1 - w_i$ so the moment at $t = 1 - w_i$ is the last chance to make a revision in a Shanghai auction. Since the K th highest bid monotonically increases over time (See Lemma 1), bidder i with a value higher than $H_i^* + M$ would submit a bid of $H_i^* + M$ at time $1 - w_i$ to increase the probability of winning. ■

In the Shanghai auction, bidders are allowed to revise their bids twice in the second stage, which could encourage bidders to submit incremental first revisions.¹¹ It is obvious that the K th highest bid H_t^K increases over time as the result of numerous incremental bids, so that the fast-reaction bidders (with small w_i) are able to make higher final revisions than the slow reaction bidders. Hence, fast bidders are more likely to win than slow bidders.

Proposition 2 *In the Shanghai auction, $\rho(v_i, w_i) \in [-1, 1]$ is Spearman's rank-order correlation of values and reaction times of rational bidders, then*

- (i) *If $\rho(v_i, w_i) = -1$, Shanghai auctions can guarantee objects to be allocated efficiently among rational bidders using the late-bid strategy;*
- (ii) *If $\rho(v_i, w_i) \neq -1$, Shanghai auctions cannot guarantee objects to be allocated efficiently among rational bidders using the late-bid strategy.*

Proof. In the second stage, combining with Lemma 1, an increasing trend of the H_t^K would be caused by incremental bidding, thereby facilitating the faster bidders to make higher revisions. In this case, Spearman's rank-order correlation of $\rho(v_i, w_i) = -1$ implies that the bidders with the K highest values are also the K fastest bidders in the Shanghai auction, thereby insuring final revisions of increasing value by means of a late bid strategy and the success of the K highest value bidders. When $\rho(v_i, w_i) \neq -1$, given two bidders i and j with values $v_i > v_j$ and reaction times $w_i > w_j$, bidder j is able to submit their final bid after bidder i .¹² Bidder i observes H_i^* and submits the final bid $H_i^* + M$ at time $1 - w_i$ while bidder j waits to time

¹¹The reasons for incremental first bids include mistakes, psychological reasons or trying to crowd out potential opponents. See, for example, Ku et al. (2005) and Ockenfels and Roth (2006).

¹²Even if bidder j submits the bid after bidder i , the auctioneer would receive both at $t = 1$.

$1 - w_j$ and submits $H_j^* + M$. Since the H_t^K increases over time, it has $H_i^* \leq H_j^*$, which results in bidder j 's final bid b_j not being less than bidder i 's, where $b_i \leq b_j < v_j < v_i$. Hence, an efficient allocation cannot be approached in Shanghai auctions because the K highest final bids may not be made by the bidders with the K highest values. ■

In the Shanghai auction, the reaction time becomes a constraint for submitting the second-stage revisions. Bidders with shorter reaction times are able to make decisions later than those who have relatively longer reaction times. Regardless of whose value is higher, the faster bidders are more likely to win by submitting higher revisions than the slower ones. Ultimately, it leads to an inefficient allocation.

3.2 The Singapore auction

In the Singapore auction, each bidder can bid at any time $t \in [0, 1]$. Bidders are informed of the current lowest accepted bid in the auction. The current lowest accepted bid equals the current $K + 1$ th highest bid plus a small amount m . New bids cannot be less than the current lowest accepted bid. The Singapore auction is a uniform price auction and the payoff for bidder i in the Singapore auction can be summarized as follows:

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

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

Proposition 3 (Late-bid strategy in the Singapore auction) *In the Singapore auction, it is a weakly dominant strategy of rational bidder i to make his bid $b_i = v_i$ at $t = 1 - w_i$.*

Proof. Given that each bidder bids their value in the Singapore auction, there is no incentive to bid a lower price because it cannot increase the payoff and reduces the probability of winning. Moreover, a bidder submitting a final bid higher than their value may cause a negative payoff.

Again, we assume bidder i 's reaction time w_i is independently drawn from a distribution W . If bidder i makes a decision after $1 - w_i$, the auctioneer cannot receive the bid. For bidder i , any bids made before the time $1 - w_i$ may cause some incremental revisions from other bidders. Hence, the bidders in the Singapore auction would submit bids at $t = 1 - w_i$. ■

In the Singapore auction, the purchase price of car licenses is equal to the $K + 1$ th highest final bid plus the smallest increment m . Suppose v_i and v_j are, respectively, the K th and $K + 1$ th highest values/bids with $v_j < v_i < v_j + m$. In this case, the purchase price $v_j + m$ is strictly higher than v_i . As a result, the actual number of winners in a Singapore auction could be smaller than K .

We acknowledge this in the following proposition:

Proposition 4 *In Singapore auctions, objects are allocated efficiently among rational bidders if the difference between the K th and $K + 1$ th highest values is no less than m .*

Proof. For example, there are four bidders in a Singapore auction with two objects. If all of them bid their values at 200, 100, 100 and 50, the price will go to $100 + m$. This results in an inefficient allocation since only one object can be sold in this auction.

When the difference between the K th and $K + 1$ th highest values is larger than m , the K objects are sold to the K highest value bidders with the price equal to $K + 1$ th highest value plus m . In addition, the reaction time cannot affect the final bids. Thus the allocation is efficient. ■

3.3 The Guangzhou auction

The Guangzhou auction has only one stage with two announcements of current average bids. Bidders can bid and then revise their bids twice at any time in $t \in [0, 1]$. Bidders are informed of average bids at $t = 1/3$ and $t = 2/3$. In the Guangzhou auction, the payoff of bidder i can

be summarized as follows: ¹³

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

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

We offer the following proposition of the bidding strategy in Guangzhou auctions:

Proposition 5 (Late-bid strategy of the Guangzhou auction) *If bidders are risk neutral, the late-bid strategy in Guangzhou auctions is to make a bid*

$$b_i = \frac{1}{G(v_i)} \int_0^{v_i} x \cdot g(x) dx$$

at $2/3 \leq t \leq 1 - w_i$.

Proof. The Guangzhou auction can be treated as a sealed-bid auction with only rational bidders, which can be expressed as an equilibrium strategy of the Guangzhou auction as follows (Krishna, 2009):

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

where Y_{N-1}^K is the K th-highest value in $N - 1$ bidders with distribution of G and $g(x)$ is the first derivative of $G(x)$.

In particular, if the values are independently drawn from a uniform distribution, $G(x)$ is the cumulative distribution function of $\text{Beta}(N - K, K)$ (Cox et al., 1984). ■

4 Experiment Design

We conducted Shanghai, Guangzhou and Singapore auctions in the lab (the instructions for the three car license auctions are included in the appendix). In addition, our design also

¹³There is no incremental bidder in the Guangzhou auction because the auctioneer does not announce the current price during the auction.

included the uniform price sealed-bid (UPSB) auction as a baseline treatment, which has not been applied to auction car licenses in practice. The experiment was conducted at the Finance and Economics Experimental Laboratory (FEEL) of Xiamen University. 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 using the Online Recruitment System for Economic Experiments (Greiner, 2004).

Each session included 21 rounds of auction and lasted about 1.5 hours. The first round was for practice and the following 20 rounds had cash payments. At the end of the experiment, participants received their payoffs in private and the average earnings were 60 CNY (about 10 USD).

Each round of auction lasted three minutes, where 20 subjects bid for six identical objects and a purchase limit of one object each. The value of each bidder was independently and uniformly drawn from an integer interval $[0, 10000]$. The sequence of realized values was the same across treatments. The minimum increment of bidding in each treatment was 10. Each bid had to be entered twice for confirmation in order to mimic the real car license auctions.

Further details about each round of auctions in the four treatments are given below:

- *The Shanghai treatment.* Each round had two stages. The first stage lasted for two minutes and the second stage for one minute. During the entire auction, the bidders were publicly informed of the current price, which was the latest sixth highest bid. In the first stage, the bidders had to submit one bid without exceeding the warning price of \$5000. In the second stage, the bidders could only revise their bids a maximum of two times, and each revision had to be within the range of the current price minus \$250 to the current price plus \$250. If a bidder did not submit a bid in the first stage, they were not allowed to proceed to the second stage. The six highest final bids won an object and paid the bids.
- *The Singapore treatment.* The subjects could submit an unlimited number of bids in each round. The current price was the real-time seventh highest bid price plus \$10, and was announced publicly throughout the auction. The bids or revisions could not be less

than the current price. The final bids higher than or equal to the current price each won an object and uniformly paid the current price.

- *The Guangzhou treatment.* In each round, a bidder could submit a bid once and revise it twice. The current average price was announced twice to every bidder at one minute and two minutes after the start of the auction. The current average price was the average of the bids in the 10th percentile to 90th percentile range at the time of announcement. The six highest final bids won the objects and paid their bids.
- *The UPSB treatment.* Each bidder could only submit one bid in each round. Throughout the entire auction, the bidders had no information about the bids of the other participants. The bidders were sorted by bid in descending order, and the first six bidders got the object and paid a uniform price equal to the seventh highest bid.

The treatment of the Shanghai auctions included an addition test to score the subjects' reaction times. In a 90-second test, the subjects were asked to choose the largest of four numbers. The set of questions was identical for all subjects. To answer each question, the subjects were required to enter the number twice, which was consistent with the bidding submission mode in car license auctions. The subjects earned 1 CNY for each correct answer. The average earnings were 17.35 CNY (about 3 USD).

5 Experimental Results

5.1 Performance

We start by summarizing aggregate performance in order to provide an overview of allocative efficiency in the four treatments. The efficiency of allocations is displayed by two variables: A ratio of realized social welfare to potential social welfare and the number of efficient winners. An efficient winner denotes a winner with one of the six highest values. The UPSB treatment is our baseline to compare the other three auction formats. Table 1 summarizes the statistics of our four treatments with uniform price auctions shown in the first two columns and

discriminatory price auctions in the last.

[Table 1 Aggregate performance]

In the four treatments, the UPSB treatment has the highest purchase price, captures the most social welfare, and has the most efficient winners. The Singapore and Guangzhou treatments are not as efficient as the UPSB treatment, but their realized social welfare is still high at nearly 97%. In comparing the Singapore Guangzhou treatments, the prices are not significantly different (two-sided paired t test, p -value=0.29), but the efficient winners are weakly significantly different (p -value=0.07). The Shanghai treatment has the lowest price so the bidders earn more. However, less than 4 out of 6 objects are allocated efficiently. Only 88.57% of the potential social welfare in the Shanghai treatment is realized, which is much lower than the other treatments.

5.2 The bidding strategies

Now we examine the bidding behavior relative to the strategies in our four treatments. Figure 3 provides scatter diagrams of the final bids and the late-bid/equilibrium strategies for our four treatments.

[Figure 3 Bids and late-bid/equilibrium strategies]

The equilibrium strategies in UPSB and late-bid strategies in Singapore auctions are straightforward to bid values. In Figure 3, it can be observed that the UPSB bidding data are following the 45-degree line, whereas more noise is present in the Singapore treatment. In the UPSB and Singapore treatments, 84.94% and 64.24% of the final bids respectively do not deviate from the 45-degree line by more than \$500 (5% of $\bar{v}$). The slopes of the linear estimations of the final bids in the UPSB and Singapore treatments are 1 and 0.96 respectively and the intercepts are not significantly different from 0¹⁴(see the first two columns of Table 2).

[Table 2 Bidding strategies of UPSB, Singapore and Shanghai auctions]

The equilibrium bidding strategy in the Guangzhou auction is not a linear function of value,

¹⁴The results are consistent with a previous experimental study on UPSB auction conducted by Smith et al. (1985).

which is plotted in Figure 3(c). The final bids in the Guangzhou treatment are gathered according to an bidding equilibrium bidding strategy although mild overbids can still be observed, and 74.06% of them do not deviate from the the equilibrium line by more than \$500. To estimate the bidding strategy in the Guangzhou treatment, we write the symmetric equilibrium strategy as

$$b_{GZ} = \gamma_0 + \frac{10000}{I_v(20 - \gamma_1, \gamma_1)} \int_0^{\frac{v}{10000}} x \cdot \frac{dI_x(20 - \gamma_1, \gamma_1)}{dx} dx$$

where $I_x(\alpha, \beta)$ is a cumulative distribution function of the beta distribution. We can estimate parameters γ_1 and γ_2 from the data on bids and values. γ_1 can be thought of as a measure of a bidder's risk attitude: bidders are risk averse if $\gamma_1 < 6$ and risk loving if $\gamma_1 > 6$. When $\gamma_0 = 0$ and $\gamma_1 = 6$, the bidders are risk neutral and follow the equilibrium strategy exactly. The estimation shows $\gamma_0 = 0$ and $\gamma_1 = 5.96 < 6$, which implies that the overbids in the Guangzhou treatment are caused by risk-averse bidders.

In the Shanghai auction, the late-bid strategy of a rational bidder in the first stage is drawn as a 45-degree line which is right censored at \$5000 (see Figure 3 (d)). In the second stage, rational low value bidders (less than \$5000) did not revise the bids submitted in the first stage, so the first bids remain as final bids along the 45-degree line. Actually, only 39.97% of the final bids made by low value bidders gathered along the 45-degree line had an absolute deviation of less than \$500. and 28.61% equaled \$10. The mass of underbids made especially by low value bidders pushed down the current price way below the warning price of \$5000 at the end of the first stage which, combined with the bidding restriction in the second stage, resulted in the final bids gathering around \$5500. Hence, bidders with high values but slow reaction times cannot submit a higher final revision than those with fast reaction times, therefore they are more likely to lose in the Shanghai auction. That is why we observed a high number of relative low bids made by very high value bidders. In the next section, we discuss the relationship between reaction time and the probability of winning in Shanghai auctions.

5.3 Bidding and market failures

This section classifies the bidding outcomes and discuss the market failures in the four treatments. For final bids in auctions, we use two dimensions to classify bidding outcomes: (1) whether the value v_{it} exceeds the lowest purchase price P_t^L and (2) whether the final bid leads to a win. Table 3 lists the four types of classifications.

Table 4 summarizes the four types of bidding outcomes observed in each treatment. If there is no bidding failure, the percentages of Positive-Win (PW) and Negative-Lose (NL) should be 30% and 70% respectively, which are very close approximations of the percentages in the UPSB auctions. The Singapore and Guangzhou auctions have a small percentage of Positive-Lose (PL) outcomes due to underbidding by high value bidders. However, more than one-quarter of the final bids classified as PL in the Shanghai auctions were cases where numerous high value bidders failed to bid higher. A Negative-Win (NW) was rarely observed in any of the treatments.

[Table 3 The classification of bidding outcomes]

[Table 4 Summary of bidding outcomes]

Moreover, many of the bidding failures observed indicate that the purchase prices may deviate from the market clearing prices. We plotted the lowest purchase prices versus the market clearing prices ¹⁵ of the four treatments in Figure 4. In the UPSB auctions, there was no significant difference (p -value=0.88 in the Wilcoxon signed-rank test) between the purchase prices and corresponding market clearing prices. The purchase prices were lower than the corresponding market clearing prices in the Singapore, Guangzhou and Shanghai auctions (p -values are all less than 0.01 in the one-tailed Wilcoxon signed-rank test).

[Figure 4 Lowest purchase prices versus market clearing prices]

In considering the bidding and market failures, the UPSB treatment has the best performance of our four treatments, whereas the Shanghai treatment is the one with the most failures. This also explains why the Shanghai auction did not allocate objects as the others.

¹⁵An auction can have multiple market clearing prices. In this paper, we only consider the lowest one when referring to “the market clearing price.”

5.4 Late bidding

All late-bid strategies in the Shanghai, Singapore and Guangzhou auctions suggest that rational bidders submit final bids as late as they can when the information is updating. According to Proposition 1, 3 and 5, rational bidders would submit their final bids at the very end of the Shanghai and Singapore auctions and at any time after the second announcement in Guangzhou auctions. Unlike real-life car license auctions, the UPSB auction is a strict sealed-bid auction so the bids may be submitted very quickly at the beginning of an auction.

Figure 5 illustrates the timing of the final bids in each treatment. The top two panels show that 65% and 40% of the final bids were received in the last 10 seconds in the Shanghai and Singapore treatments respectively; in addition, we also found evidence of incremental bids throughout the auctions. In the Guangzhou treatment, 70% of the final bids were made after the second announcement. In the UPSB treatment, 93.88% of the bids were submitted in the first 50 seconds. These results are consistent with the late-bid strategies previously discussed in the theoretical models.

[Figure 5 Receiving time of final bids]

6 Discussion

6.1 Reaction time in the Shanghai auction

After the auction experiment in the Shanghai treatment, we made an unexpected announcement to the subjects telling them that they should proceed to the second task of choosing and inputting the largest of four numbers. There was a monetary incentive for the subjects to do this task as fast as they could. In this 90-second task, each subject could earn 1 CNY for each correct answer. We denoted the number of correct answers answered by a subject as *reaction score*.

Figure 6 shows the distribution of the subjects' reaction scores in the Shanghai treatment. Although the subjects were given the exact same set of questions, the fastest subject was able to answer 28 questions while the slowest only answered 7. The bell-shaped distribution shows

the large diversity of reaction scores across subjects.

[Figure 6 Reaction scores of subjects]

The estimation results based on the logit model show how reaction time affects the probability of winning in Shanghai auctions. As shown in Table 5, subjects with higher scores have a significantly higher probability of winning. The result is quite stable even when the values are controlled (see Model 2). Giving the same value, the difference in winning probability between the fastest and slowest subjects could be 18%.

In the second stage of Shanghai auctions, fast-reaction bidders are able to submit final bids after the slow-reaction bidders. Hence, those bidders with fast reactions take systemic advantage of bidding high. The effects of reaction time may also provide an explanation for the mass of underbids in Figure 3(d) as well as the high percentage of PL outcomes in Table 4. In real-world Shanghai car license auctions, auction agents can charge their customers more than US\$ 1,500 for a successful bid from their customers. Experienced agents with fast computers, internet accesses and even quick hands are more likely to win a license than ordinary bidders.

[Table 5 Effects of reaction scores on winning probability]

6.2 Learning effects

Our solution concept relies on the common knowledge of rationality, which can only be fulfilled after several rounds with the subjects being able to learn from feedback. Since the bidding rules and information structures are varied across auction formats, the number of rounds needed for bidders to learn a late-bid strategy could differ across treatments.

If bidders implement Nash equilibrium bidding strategy in UPSB auctions and implement the late-bid strategy in Guangzhou and Singapore auctions, the lowest purchase price should converge to a market clearing price in these auctions. As shown in Figure 7, the purchase price converges to a market clearing price very quickly in the first 3 rounds of the UPSB auction, while in the Singapore auctions it converges after 10 rounds and after 15 rounds in the Guangzhou auctions.

[Figure 7 Differences between the lowest purchase prices and the market clearing prices]

Employing a late-bid strategy in Shanghai auctions cannot ensure that the lowest purchase price will converge to a market clearing price, which may result in inefficient allocations. As shown in Figure 7, the line of the Shanghai auction lies in the range of -\$1500 and -\$4000 throughout the 20 rounds and there is no trend to converge to \$0. Therefore, even though the subjects gained more experience and developed faster reactions through repetition in the Shanghai auction, it did not really result in an efficient allocation.

Table 6 summarizes the coefficients of a bidding strategy at every 5 rounds of each treatment. In all four phases, the bids in the UPSB auction always coincide with the equilibrium strategy. In the Singapore auction, the subjects gradually adjust their bidding strategies to bidding a value after 5 rounds. In the Guangzhou auction, we also observed subjects' bidding strategies gradually converging to an equilibrium bidding strategy.

[Table 6 Changes in the coefficients of bidding strategies]

The different learning processes across auction formats may be due to the complexity of auction rules. Firstly, the equilibrium strategy in the uniform price auctions is much simpler than in the discriminatory price auctions. Thus, we observed that the subjects in the UPSB and Singapore auctions learned much more quickly than in the Guangzhou auction. Secondly, sealed-bid auctions rule out strategic bidding behavior. Therefore, we observed that the convergence of bidding strategies is much slower in Singapore auctions than in UPSB auctions.

7 Conclusion

In this paper, we investigated three car license auctions that are currently implemented in Singapore, Guangzhou and Shanghai both have theoretically and experimentally. The key focus of this study was assessing the performance of these car license auctions. One of policy goals of implementing these auctions is to allocate car licenses efficiently. The Singapore and Guangzhou auctions are more likely to achieve an efficient allocation than the Shanghai auction if bidders implement the late-bid strategy. This is consistent with the experimental results, which show that the Shanghai treatment is less efficient than the others. Another

policy goal is that the auction formats should be easy to learn. In practice, a complex auction format could be confusing and misleading for bidders. Our experimental evidence shows that uniform price auctions are easier to learn than discriminatory price auctions and sealed-bid auctions are easier to learn than open-bid auctions.

On the one hand, the existence of incremental bids suggests that rational bidders should submit their final bids later if information is still being updating in the auction. We observed that a large portion of final bids were submitted very late in the Shanghai, Guangzhou and Singapore auctions. On the other hand, both our theoretical and experimental findings show that Singapore and Guangzhou auctions are more efficient than Shanghai auctions because of the varying reaction times among subjects. Moreover, we found a significant relationship between the subjects' winning probabilities and their reactions in the Shanghai treatment.

Our investigation of these auction formats could also be useful for social planners who are considering using auctions to allocate other public resources such as mineral rights or forest property rights. For instance, since high price of selling car licenses could draw strong public criticism, cities may be keen to use inefficient auction formats (such as the Shanghai auction) to suppress winning prices. Although they successfully control the winning price in the short term, additional costs such as those associated with professional agent fees in these auction formats are rising. Besides, the accumulation of high value bidders who have not won in previous auctions will push the prices much higher in the long run.

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Figures of "Vehicle License Auctions: Theory and Experimental Evidence"

Figure 1: Timelines and bidding rules in different cities

Figure 2: Reaction time

Figure 3: Bids and late-bid/equilibrium strategies

Note: The red lines indicate the theoretical predictions of bidding strategies. The black circles indicate the actual final bids.

Figure 4: Lowest purchase prices versus market clearing prices

Note: The black circles indicate the lowest purchase prices. We have 80 observations for each treatment (4 sessions $\times$ 20 rounds).

Figure 5: Receiving time of final bids

Note: The solid line indicates the end of the first stage in Shanghai auctions. The dashed lines indicate the two announcements of average prices in Guangzhou auctions. Each bar shows the number of final bids within a ten-second period.

Figure 6: Reaction scores of subjects

Figure 7: Differences between the lowest purchase prices and the market clearing prices

Tables of "Vehicle License Auctions: Theory and Experimental Evidence"

Table 1: Aggregate performance

	UPSB	Singapore	Guangzhou	Shanghai
Price	6687.00 (308.02)	6286.63 ^{††} (314.03)	6388.40 ^{††} (317.42)	4578.90 ^{†††} (254.71)
Consumer surplus	1566.06 (199.50)	1758.71 ^{††} (171.00)	1657.48 (192.55)	2780.60 ^{†††} (135.33)
Number of efficient winners	5.56 (0.14)	5.18 [†] (0.25)	4.93 ^{†††} (0.23)	3.78 ^{†††} (0.37)
% of realized social welfare	99.30% (0.35)	96.86% ^{††} (1.09)	96.80% ^{†††} (0.53)	88.57% ^{†††} (2.80)

Note: (1) A session is a unit of analysis. (2) Two-sided paired t test for the difference from UPSB ([†] $p < 0.1$, ^{††} $p < 0.05$, ^{†††} $p < 0.01$). (3) Standard deviations are shown in parentheses.

Table 2: Bidding strategies of UPSB, Singapore and Shanghai auctions

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

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

Table 3: The classification of bidding outcomes

	$v_{it} > P_t^L$	$v_{it} < P_t^L$
Win	Positive-Win (PW)	Negative-Win (NW)
Lose	Positive-Lose (PL)	Negative-Lose (NL)

Note: (1) v_{it} is bidder i 's value at round t and P_t^L is the lowest purchase price in round t . (2) PW and NL include the case of $v_{it} = P_t^L$.

Table 4: Summary of bidding outcomes

	PL	NL	PW	NW
UPSB	3.31%	66.69%	28.75%	1.25%
Singapore	6.5%	56.75%	28.63%	2.44%
Guangzhou	11.88%	57.94%	29.75%	0.25%
Shanghai	26.94%	42.75%	29.94%	0.06%

Table 5: Effects of reaction scores on winning probability

Win (N=1600)	Model 1	Sig.	Model 2	Sig
Intercept	-1.29 (0.23)	***	-4.66 (0.35)	***
Score	0.03 (0.01)	**	0.03 (0.01)	**
Value			5.53×10^{-4} (3.02×10^{-5})	***
-LL	975.38		710.36	

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

Table 6: Changes in the coefficients of bidding strategies

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

Appendix: Experimental Instructions (Shanghai auctions)

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 2 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 bid in this stage can only be lower or equal to the upper limit price 5000, and a bid higher than the upper limit would not be accepted by the auction system.

The second stage lasts for 1 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.