RANDOM RESERVATION PRICES AND BIDDING BEHAVIOR IN OCS DRAINAGE AUCTIONS*

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I. Introduction

RECENT surveys of the economic literature on auctions[1] indicate that there has been a great deal of theoretical work on the properties of equilibrium behavior in auctions and on the design of auctions to maximize the seller's revenues in the presence of optimizing bidders. However, there has been very little empirical work, using field data, that attempts to test various behavioral theories or, indeed, to see whether they are of any practical interest. There has been some good experimental work[2] but the relatively small stakes involved in these experimental games, and the relative inexperience of the subjects (given the potential complexity of equilibrium strategies), leave a useful role for the careful study of a detailed field data set. This article analyzes such a data set, the first-price, sealed-bid auctions of drainage and development leases on federal land in

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[1] See Paul R. Milgrom, The Economics of Competitive Bidding: A Selective Survey, in Social Goals and Social Organization (Leonid Hurwicz, David Schmeidler, & Hugo Sonnenschein eds. 1985); Paul R. Milgrom, Auction Theory, in Advances in Economic Theory—Fifth World Congress (Truman Bewley ed. 1987); R. Preston McAfee & John McMillan, Auctions and Bidding, 25 J. Econ. Lit. 699 (1987).

[2] See, for example, John H. Kagel & Dan Levin, The Winner's Curse and Public Information in Common Value Auctions, 76 Am. Econ. Rev. 894 (1986).

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the Outer Continental Shelf (OCS), in which the stakes are large, the rules of the game straightforward, and the players experienced and well funded. The distinguishing feature of a drainage and development lease is that it is located next to tracts where oil and/or gas has been discovered.

In a previous study,[3] we examined the sample of federal drainage and development leases sold in the period 1959–69. For these tracts, we had at least ten years of production data on the productive tracts. This allowed us to construct relatively good proxies for tract value and profit, which is tract value minus the bid and discounted royalty payments. We used these proxies to establish that neighbor firms, which owned the adjacent tracts, were better informed about the value of a drainage or development lease and earned significantly higher profits than nonneighbor firms. The latter result was due to an apparent absence of any competition among neighbor firms. We also documented that nonneighbor firms and neighbor firms bid strategically in ways that were largely consistent with the predictions of an auction model with one informed firm and an arbitrary number of uninformed firms.

In this study, we extend the sample period to 1979 and include auctions of drainage and development leases where the high bid was rejected. One of our objectives is to see whether the conclusions obtained in our previous study concerning bidding behavior hold for the later segment of the sample. There are two reasons why one might expect the results to differ. First, the price increases of 1973 and 1979 caused more firms to participate and significantly raised the averge number of bids in auctions of wildcat leases. (A wildcat lease is located in areas which have not been drilled and on which firms are permitted to acquire only seismic information.) Second, the average number of neighbor firms per tract was higher in the period 1959–69 than in the subsequent period. Both of these factors made later auctions potentially more competitive than earlier auctions.

Our second objective is to examine the effect of a random reservation price on bidding behavior. In our earlier study, we had assumed that the government adhered to its reservation price of $15 or $25 per acre in each auction. In fact, however, the government frequently rejected winning bids above the preannounced price. In the period 1954–79, it rejected the winning bid on 225 of 2,510 wildcat leases and on 94 of 526 drainage and development tracts. Clearly, the preannounced price was simply a lower bound for the reservation price, and the actual reservation price on many tracts was much higher.

[3] Kenneth Hendricks & Robert H. Porter, An Empirical Study of an Auction with Asymmetric Information, 78 Am. Econ. Rev. 865 (1988).

The testable implications of a random reservation price on bidding behavior in a first-price, sealed-bid auction with asymmetric information have been characterized by Hendricks, Porter, and Wilson.[4] The principle implications are: (i) the uninformed firm is less likely to bid than the informed firm, but if it participates, it always bids high rather than low; and (ii) the cumulative probability distribution of an informed bid is less than that of the maximum uninformed bid at bids that have some chance of being rejected and equal for bids that are certain to be accepted.

The intuition underlying these results is straightforward. When the informed firm submits a low bid, the probability of rejection is high, and so its expected profit margin is small. Thus, if an uninformed firm were to win with a low bid, it would do so primarily against informed firms whose valuations were less than that bid. As a result, its expected profits would be negative, and it is better off not participating. The situation is different at high bids. The probability of rejection is relatively small at these bids, and the informed firm responds by shading its bid well below its valuation. The uninformed firm then has an incentive to submit high bids. At this level, there is some chance it can win profitable tracts.

The results of our empirical study can be summarized as follows. The participation and win rates of neighbor and nonneighbor firms for the period 1959–69 were virtually identical to those for the period after 1969. Thus, the price increases and entry of new firms in the later period had no effect on the pattern of competition on drainage and development auctions. On the basis of our analysis of returns on drainage and development tracts sold prior to 1970, this suggests that neighbor firms continued to earn substantial rents on tracts sold in the later auctions. Participation by the nonneighbor firms was at relatively high bids, with 15 percent of the high neighbor bids lying below almost all of the high nonneighbor bids. The distribution function of the high neighbor bid is below that of the high nonneighbor bid. At larger bids, it is approximately identical to the product of the distribution function of the maximum of the nonneighbor bids and the probability the government accepts the winning bid. Thus, the hypothesis that neighbor and nonneighbor firms bid strategically in accordance with the theory of auctions with asymmetric information is strongly supported by the data.

The article is organized as follows. In Section II, we present some evidence on the rejection and reoffer policies of the government and on the pattern of competition. In Section III, we describe a model of bidding

[4] Kenneth Hendricks, Robert H. Porter, & Charles A. Wilson, The Role of Uninformed Bidders in Auctions with Asymmetric Information and Random Reservation Prices (unpublished manuscript, New York Univ. April 1989).

with asymmetric information and a random reservation price. In Section IV, we examine the distribution functions of the high neighbor and nonneighbor bid and relate their properties to the predictions of the theory.

II. Government Behavior and the Pattern of Competition

The theoretical literature on optimal auction mechanisms suggests a wide array of potential rejection rules that the Department of Interior may have employed. In order to focus our theoretical model in the next section, it is useful to first uncover some regularities of the rejection and reoffer policies for OCS drainage auctions. In addition, we also examine the ex post pattern of competition. We are primarily interested in the following questions: (1) Is there any evidence that the reservation prices depended upon the value of the bids submitted? (2) Did the reoffer auction play an important role in bid and rejection decisions? (3) Were the participation rates of neighbor and nonneighbor firms in the period 1959–69 any different from those in the period 1970–79?

The sample consists of all federal drainage and developmental leases, off the coasts of Texas and Louisiana, that were sold in the period 1959–79 for which we can identify a previously sold adjacent neighbor tract and which received at least one bid. Each lease was sold via a first-price, sealed-bid auction, where a bid is a dollar figure that the firm pays to the government at the time of the sale if it is awarded the tract. The terms of the lease are, if no exploratory work is done after five years have elapsed, then ownership of the lease reverts to the government, and if any oil and/or gas is extracted, then one-sixth of the revenues accrues to the government.

Table 1 provides some descriptive statistics for the 385 tracts on which the high bid was accepted, and for the 89 tracts on which it was rejected. The maximum bid by a neighbor firm is denoted by B_I, the maximum nonneighbor bid by B_u, and the high bid on a tract by $B_{\max}$. All bids are in millions of 1972 dollars. The numbers are sample averages, and those in brackets are the standard deviations of the sample means. The number of neighbor bids is represented by N_I, and N_U is the number of nonneighbor bids. The number of neighbor tracts is given by N; D_I is a dummy variable that equals one when the high bid was submitted by a neighbor firm and is zero otherwise.

Clearly, rejected bids were lower than accepted bids, on average, by more than a factor of six. The participation rates were lower on tracts with rejected bids by more than a factor of two. Indeed, the majority of these tracts received only one bid. Note that there is little difference in the number of neighboring tracts. Further, rejected bids were more likely to

TABLE 1

COMPARISON OF ACCEPTED AND REJECTED BIDS

	Accepted	Rejected
B_I	5.54	.89
	(.63)	(.21)
B_U	4.44	.37
	(.45)	(.09)
B_{max}	7.35	1.21
	(.65)	(.21)
N_I	1.12	.84
N_U	1.64	.43
$N_I + N_U$	2.76	1.27
N	3.88	3.83
D_I	.54	.69
No. of tracts	385	89

Note.—All dollar figures are in millions of 1972 dollars. Numbers in parentheses are SDs of the sample means.

have been submitted by firms owning neighboring leases. Finally, note that 18.8 percent of all high bids were rejected in this sample.

Prior to a lease sale, the U.S. Geological Survey computes a "fair market" value for each lease, which the Department of Interior subsequently uses to evaluate the winning bid. One might be tempted to view the presale estimate as the ex ante unannounced reservation price. There are three reasons for not doing so in the empirical work that follows. First, no presale value is available on the sixty-two drainage tracts sold prior to 1968. Second, the presale value was not revealed on tracts with rejected high bids. Finally, the presale value exceeded accepted high bids on thirty-three tracts, or more than 10 percent of the sample with announced presale values. Accordingly, we treat the government's reservation price as a random variable that is a function of some observable variables and an unobservable component, but not a function of the presale value.

Therefore, we estimate a probit equation to determine the factors that influenced the government's rejection rule. The results are displayed in Table 2. We separate the sample into drainage leases and developmental leases, the latter typically being of lower value. The overall rejection rates were virtually identical for the two samples. In the table, the explanatory variables are $\log(A)$, the logarithm of tract acreage; D_I, the dummy indicating that a neighbor firm submitted the high bid; $\log(B_{max})$, the logarithm of the high bid, measured in 1972 dollars; $D_I \cdot \log(B_{max})$, an interaction term; D_R, a dummy variable that equals one when the tract is a reoffered

TABLE 2

PROBIT EQUATIONS FOR REJECTION DECISIONS

Independent Variables	Drainage Tracts	Developmental Tracts
Constant	−7.36	−9.74
	(1.47)	(4.33)
log A	.46	1.29
	(.18)	(.53)
log B_{max}	−.49	−.80
	(.13)	(.17)
D_I	.75	−.40
	(.23)	(.29)
D_I·log B_{max}	−.10	.19
	(.14)	(.23)
D_R	.16	.56
	(.31)	(.31)
log P	1.51	−1.16
	(.44)	(.72)
No. of observations	295	179
No. of accepted bids	237	148
log likelihood	−101.9	−56.8

NOTE.—SEs are displayed in parentheses.

lease; and log(P), the logarithm of the average wellhead price of offshore oil in 1972 dollars. We experimented with a list of variables that characterizes the production and bidding history of the neighboring tract, but they are not significant factors for either sample. Similarly, including the number of bidders, or a dummy variable indicating whether only one firm bid, does not significantly alter the estimates.

The probit equations in Table 2 support the notion that winning bids were much more likely to be rejected when they were low, and this effect is both statistically and economically significant. The logarithm of the high bid (expressed in millions of 1972 dollars) ranged from −3.56 to 4.74, with mean 0.68 and standard deviation 1.64. In other words, high bids were quite variable relative to the magnitude of their probit coefficients.

It is also notable that on drainage leases a given high bid was more likely to be rejected if it was made by a neighbor firm. One explanation is that the government used the identity of the bidder to discriminate against neighbor firms. However, other explanations, which are consistent with the government committing to a reservation price before observing the bids, are possible. For example, neighbor firms may have submitted more bids in the range where rejection was likely than nonneighbor firms. In fact, as we shall see later, this is one of the predictions of the theory.

What became of the tracts with rejected high bids? By the end of 1979, thirty-one of these tracts had been reoffered. On average, they were

TABLE 3

COMPARISON OF REJECTED AND MATCHED REOFFERED TRACTS

	INITIAL OFFERING	REOFFERING	
		Accepted	Rejected
B_I	.61	2.56	1.26
B_U	.58	4.41	.60
D_I	.55	.44	.63
Presale Estimate	...	1.99	...
No. of Tracts	31	23	8

NOTE.—All dollar figures are in millions of 1972 dollars.

reoffered a year and a half later. Seven of the reoffered tracts had their high bids rejected, and were never reoffered again in our sample. One tract was reoffered twice, and the high bid was rejected on each occasion. The remaining twenty-three tracts had their high bid accepted on the first reoffering.

Table 3 provides some descriptive statistics for the reoffered tracts. The notation is that of Table 1. An additional statistic is the presale estimate of the value of the tract that was computed by the U.S. Geological Survey prior to the sale. Recall that this estimate is not revealed on tracts with rejected high bids.

The set of thirty-one reoffered tracts was similar to the larger set of tracts with rejected high bids. The high bid on approximately one-quarter of the tracts was rejected; these bids were on average lower than the accepted bids and were more likely to have been submitted by a neighbor firm. When the tracts were reoffered, they generally received much higher bids. These bids, however, were still lower than those on tracts that were sold in their first offering. Finally, note that the average presale estimate exceeds both high bids in the initial offering, and was less in the reoffering.

Were the neighbor firms bidding competitively, and was there more competition from nonneighbor firms in the later auctions? In our previous article,[5] we argued that, despite the frequent incidence of multiple neighbor firms for drainage and development leases prior to 1970, the distribution function of the high neighbor bid could be explained by a model in which only one serious neighbor firm bid was submitted. Table 4 displays the frequency distributions of the number of neighbor tracts, neighbor bids, and nonneighbor bids for our sample, as well as for the periods

[5] Hendricks & Porter, *supra* note 3.

TABLE 4

FREQUENCY DISTRIBUTIONS

	0	1	2	3	4	5	6	7	8	≥9	Average
All tracts:											
N	0	53	115	83	64	56	35	26	17	25	3.87
N_I	83	294	82	12	3	0	0	0	0	0	1.07
N_U	184	135	70	35	19	10	8	4	2	7	1.42
Before 1970:											
N	0	23	47	24	13	16	3	6	4	1	3.08
N_I	19	97	20	0	1	0	0	0	0	0	1.03
N_U	57	38	17	12	6	0	3	1	0	3	1.37
After 1969:											
N	0	30	68	59	51	40	32	20	13	24	4.19
N_I	64	197	62	12	2	0	0	0	0	0	1.08
N_U	127	97	53	23	13	10	5	3	2	4	1.43

before 1970 and after 1969. It is notable that, despite the increase in the number of neighbor tracts, the distribution of neighbor bids in the latter segment of our sample is similar to that of the earlier segment. The means are virtually identical. Similarly, there is little change in the distribution of nonneighbor bids, although there was widespread entry in wildcat lease auctions in this period. Evidently, neither the rents that neighbor firms earned in the early part of our sample, nor the higher prices of the 1970s, induced entry by either neighbor or nonneighbor firms.

We draw the following conclusions from the evidence presented in this section. First, the purpose of the government's rejection policy was to reduce the incentive that firms might have had to bid the preannounced minimum price on tracts that, on the basis of public information, were regarded as low value tracts. It was *not* to lessen the neighbor firm's informational advantage by rejecting and making public its bid, and then holding a reoffer auction. The instances in which this would have been most rewarding to the government were precisely the ones in which the rejection option was rarely used. Bids over five million dollars on drainage tracts, and over one million dollars on development tracts were almost always accepted. Second, the reoffer auction was probably not a significant factor in the bidding decisions of the firms. Reofferings were infrequent, and a significant amount of time usually elapsed before they occurred. Third, the pattern of competition in drainage and development auctions consists mainly of one neighbor firm bidding against a set of nonneighbor firms.

III. The Model

Our model focuses on the auction of a single drainage tract, and abstracts from any structural or strategic factors that may link a firm's bidding decision in this auction to those made in other auctions. Specifically, we assume that (i) there are no information externalities between tracts sold in the same sale, (ii) each firm is risk neutral, and (iii) the bidding strategy of each firm depends only on the state of information and competition from that tract in the auction at hand. Assumptions (i) and (ii) are relatively innocuous. However, assumption (iii) implies that the informed firm behaves myopically with respect to the event that the high bid is rejected and the tract is reoffered at a later date. The evidence on the reoffer auctions presented in the previous section provides some empirical support for this assumption. (Recall that the probability a tract's high bid was rejected and subsequently reoffered was less than 6 percent, and the average time between the initial sale and a reoffering was a year and a half.)

There is one neighbor firm that observes a private signal X on V, the unknown value of the representative drainage tract. The n nonneighbor firms observe only a public signal Z. The reservation price R is random and distributed independently of (V,X) conditional on Z. Realizations of the random variables will be denoted by lower case letters. In what follows, we treat z as given and are explicit about the dependence of the distributions on its value. However, for notational convenience, we will suppress the dependence of bidding strategies on z.

The essential feature of our model is that the information revealed by on-site drilling of an adjacent tract by a neighbor firm is a sufficient statistic for the information that nonneighbor firms and the government acquire from seismic surveys. The assumptions that the neighbor firm knows the information of the nonneighbor firms and that the reservation price is uninformative conditional on public information are made in order to obtain a precise characterization of the set of equilibria and its properties.[6] The results serve as a useful benchmark for understanding how small changes in the underlying information structure are likely to manifest themselves in bidding behavior.

We have also assumed that the government does not base its reservation price on the bids. The difficulty with assuming otherwise is that a fully rational neighbor firm would realize that its bid may affect the *distribution* of the reservation price and take this into account. This substantially changes bidding incentives and greatly complicates the neighbor firm's decision.

We summarize the information of the neighbor firm by the real-valued, random variable $H = E[V|X,z]$[7] Realizations of X then imply realizations of H. We shall assume that H has an atomless distribution, $F(\cdot;z)$, with finite mean, $\bar{H}$. The strategy of the neighbor firm can then be defined as a function σ, which maps realizations of H into the nonnegative real numbers. We shall assume that $\sigma(h)$ is a differentiable, strictly increasing function on the range $(\underline{R},\infty)$, where $\underline{R} > 0$ is the price below which the government is committed not to accept a bid. The inverse function of σ on this interval is denoted by $\tau(b)$.

The strategy of nonneighbor firm i is a distribution function $G_i(\cdot;z)$ over

[6] Paul R. Milgrom & Robert Weber, Distributional Strategies for Games with Incomplete Information, 10 Math. Operations Res. 619 (1985), prove that the equilibrium correspondence for games like ours is upper hemicontinuous. This implies that the behavioral implications of our model are approximately the same as those of a model in which estimates of nonneighbor firms are based upon noisy, but private, signals of tract value. The latter model, while more descriptive, is not very tractible.

[7] This approach follows that of Paul R. Milgrom & Robert J. Weber, The Value of Information in a Sealed Bid Auction, 10 J. Math. Econ. 105 (1982).

the nonnegative real numbers. Since the neighbor firm knows the exact valuation of each nonneighbor firm, the latter will bid randomly (conditional on participation), rather than follow some predictable bidding strategy. If nonneighbor bids were predictable, the neighbor firm would outbid them when it was worthwhile to do so and not bid otherwise. The nonneighbors could then expect to lose money.

Let the reservation price R have an atomless, differentiable distribution, $J(\cdot;z)$, with finite support $[\underline{R},\bar{R}]$. Define $G(b;z) = J(b;z)G_1(b;z) \ldots G_n(b;z)$ to be the distribution function of the maximum of the reservation price and the bids submitted by the uninformed firms on the tract. Given strategy combination $(G(\cdot), \sigma(\cdot))$, the payoff to the neighbor firm, when its estimate of V is h, is the product of the probability that its bid is highest and its expected value of the tract less its bid:

$$G(\sigma(h);z)(h - \sigma(h)). \tag{1}$$

Note that, since the reservation price is not correlated with V conditional on X, bidding more than the reservation price is *not* an informative event for the neighbor firm. Hence, its expected value of the tract is independent of the event that a winning bid is accepted.

We ignore any production externalities that could cause neighbor and nonneighbor firms to value the tract differently. The expected payoff to nonneighbor firm i, which submits a bid b greater than $\underline{R}$, is

$$E[H - b|b > \sigma(h);z] \cdot F(\tau(b);z) \cdot \Pi_{j\neq i}G_j(b)J(b;z). \tag{2}$$

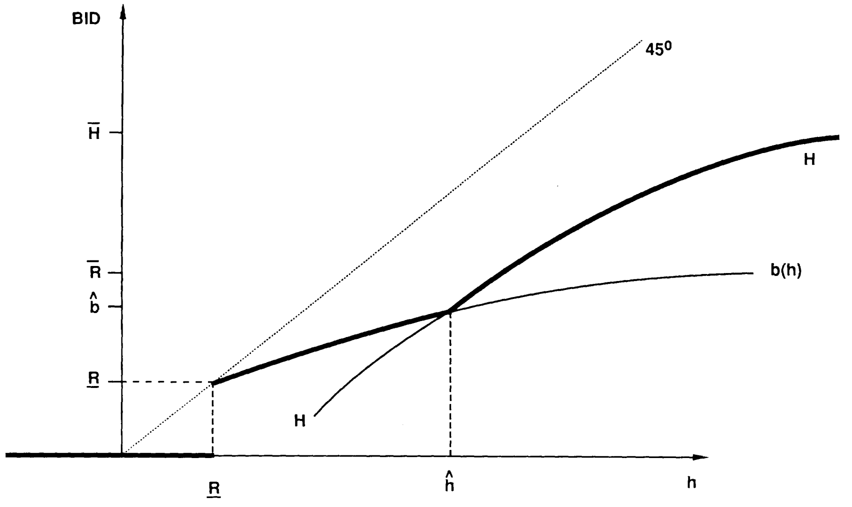
The first term in (2) is expected profits, conditional on the event that b is higher than the bid of the neighbor firm. Given our assumption on the joint distribution of (R,X), there is no need to condition expectations on the event that the bid exceeds the reservation price. The remaining terms represent the probabilities of outbidding the other firms, and of government acceptance. Ties are assumed to be settled by randomization.

A Bayesian Nash equilibrium for the bidding game is a $(n + 1)$-tuple of strategies $(\sigma^*, G_1^*, \ldots, G_n^*)$ such that the expected payoff to each firm conditional on its information is maximized, given the strategies employed by the other firms.

This model is a special case of a more general model analyzed in Hendricks, Porter, and Wilson,[8] and we will apply the results obtained in that article to characterize the set of equilibria. Define the bidding function $b(h)$ to be the solution to

$$J(b;z)(h - b) - J'(b;z) = 0, \tag{3}$$

[8] Hendricks, Porter, & Wilson, *supra* note 4.



BOLD LINE: $\sigma^*(h)$

FIGURE 1.—Neighbor bid strategy

for $h \geq \underline{R}$, and equal to zero otherwise. If no solution to (3) exists, then $b(h)$ is set equal to $\bar{R}$. Thus, $b(h)$ is the neighbor firm's optimal bidding strategy when it is the sole bidder and only concerned about the probability that its bid may be rejected. Also, define $\hat{h}(z)$ to be a solution to the implicit equation $b(h) = E[H|H < h;z]$. We shall assume that if $\hat{h}(z)$ exists, it is unique. This simplifies the notation and appears to be consistent with the stylized facts about F and J.

THEOREM. The $(n + 1)$-tuple $(\sigma^*, G_1^*, \ldots, G_n^*)$ is an equilibrium point if and only if

$$\sigma^*(h) = \max\{b(h), E[H|H < h;z]\},$$

and

$$G^*(b) = \begin{cases} J(b;z) & b < b(\hat{h}), \\ F(\tau(b);z) & b(\hat{h}) \geq b < \bar{H}, \\ 1 & b \geq \bar{H}. \end{cases}$$

Figure 1 depicts the equilibrium. The curve labeled HH is the graph of the function $E[H|H < h;z]$. By construction, it lies below the diagonal, is upward sloping, and has an asymptote at $\bar{H}$. The other curve is the graph of the bid function $b(h)$. It is discontinuous at $\underline{R}$, since the neighbor firm does not bid if its valuation is less than $\underline{R}$. Thereafter, it is increasing in h, and bounded from above by $\bar{R}$. The upper envelope of the two curves represents the equilibrium bidding strategy of the neighbor firm. Thus, at relatively low valuations, the neighbor firm bids marginally against the random reservation price, but at higher valuations the marginal opponent is a nonneighbor firm. This reflects the fact that, if a nonneighbor firm bids, it always submits a bid greater than $b(\hat{h})$. Collectively, the nonneighbors bid randomly in such a way that the best response of the neighbor firm at valuations greater than $\hat{h}$ is to bid according to the schedule HH.

An important implication of the theorem is that, even though the equilibrium strategies of the individual nonneighbor firms are indeterminate, the distribution of the maximum of the nonneighbor bids is essentially unique and can be derived from G. Imposing symmetry on the strategies of the nonneighbors would not provide much guidance for our empirical work since the potential number of nonneighbor bidders is not observable. Note that equilibrium strategies are independent of this number.

The intuition underlying this characterization is relatively straightforward. The difference between the neighbor firm's valuation and its bid is its "shading" factor or, equivalently, its expected profit conditional on winning the lease. In Figure 1, the equilibrium value of this factor at each h is the distance between the 45-degree line and $\sigma^*(h)$. At bids close to $\underline{R}$, the shading factor is quite small, because the probability of rejection is high. Consequently, if a nonneighbor firm submits a bid in this range and wins, the neighbor firm is likely to have a valuation less than the bid. As a result, the expected profit to the nonneighbor firm is negative, and it is better off not participating. At higher bids, the probability of winning against a neighbor firm with valuation greater than that bid increases. This is becasue the value of the shading factor increases as the probability of losing to the government falls. At some bid level, specifically $b(\hat{h})$, the nonneighbor firm on average earns zero profits. Thereafter, to ensure that nonneighbor firms are indifferent among all bids in the support of G, the neighbor firm bids so that the expected profits to the nonneighbor firms are zero. Hence, for valuations above $\hat{h}$, the neighbor firm bids according to the schedule HH.

Mass points in the distribution of the neighbor firm can only occur at $\{0\}$ and at $\{\bar{R}\}$. The former is equal to $F(\underline{R};z)$, and represents the probability that the neighbor firm does not bid. (Its expectation of the value of the lease is less than the announced reservation price.) The latter occurs if there is no intersection of the two curves in Figure 1. This is likely to hold for tracts that, conditional on public information, are believed to be low-value tracts (that is, where $\bar{H}$ is close to $\underline{R}$). If an intersection exists, then G is equal to the distribution of the reservation price for bids below $\underline{R}$ and to the distribution of the maximum nonneighbor bid for bids above $\overline{R}$. A mass point in G occurs only at $\{0\}$, and represents the probability that no nonneighbor firm bids. This probability depends on the distribution of R, but it cannot be less than $F(\hat{h};z)$.

A special case of our model is one in which the distribution of the reservation price is degenerate at $\underline{R}$. This is the fixed reservation price model that has been studied extensively in the literature.[9] In the absence of any competition from the nonneighbor firms, the optimal response of the neighbor firm consists of bidding the reservation price whenever its valuation exceeds that price. In terms of Figure 1, $b(h)$ would be depicted as a horizontal line at $\underline{R}$, and the equilibrium bidding strategy of the neighbor firm would be the upper envelope of this line and the HH curve. The equilibrium distribution function of the neighbor bid would have a mass point at $\underline{R}$ equal to $F(\hat{h}) - F(\underline{R})$, and it would be identical to the distribution function of the high nonneighbor firm bid for bids above $\underline{R}$. Note that, in contrast to the case of a random reservation price, nonneighbor firms would be just as likely to submit low bids as neighbor firms.

The characterization of equilibrium yields a rich set of testable predictions that can be divided into two categories. The first category, which was discussed above, consists of the predictions about the distribution functions of the high neighbor bid and high nonneighbor bid conditional on z (averaging across all realizations of X). For future reference, these are listed below:

1. The probability of no nonneighbor bids is larger than the probability of no neighbor bids.

2. The lower bound of the support of the distribution function of the neighbor bid is $\underline{R}$. The lower bound of the support of the distribution function of the maximum nonneighbor bid is $\hat{b}(z)$, which is strictly larger than $\underline{R}$.

3. The upper bounds of the supports of the two bid distributions are identical and equal to $\overline{H}(z)$.

4. On the interval $[\hat{b}(z),\overline{H}(z)]$, the distribution of the neighbor bid conditional on z is identical to the distribution of the maximum of the nonneighbor bids and the reservation price.

Together, these properties imply that the probability that the neighbor firm's bid is the highest bid is at least one-half.

The second category consists of predictions about profits. Nonneighbor

[9] Richard Engelbrecht-Wiggans, Paul R. Milgrom, & Robert J. Weber, Competitive Bidding and Proprietary Information, 11 J. Math. Econ. 161 (1983); M. Weverbergh Competitive Bidding with Asymmetric Information Reanalyzed, 25 Mgmt. Sci. 291 (1979); Robert J. Wilson, Competitive Bidding with Asymmetric Information, 13 Mgmt. Sci. 816 (1967).

firms should earn zero profits on average, since, in equilibrium, the expected value of the tract conditional on bidding higher than the neighbor firm is equal to the value of their bid. Furthermore, average profits of the nonneighbor firm should be negative on the set of tracts where no neighbor bid is submitted. By contrast, average profits of the neighbor firm should be significantly positive since its expected profit is positive whenever it wins. An additional implication of the random reservation price is that average profits of the neighbor firm on the set of tracts where the winning bid is high should be significantly larger than on the set where the winning bid is low. This follows from the fact that the shading factor is smaller at low bids than at high bids.

The first three predictions about the distribution functions, as well as the prediction about differential profits, stand up well to changes in the underlying information structure. They rely primarily on the assumption that the neighbor firm is better informed about the value of the lease than the government or nonneighbor firms. Prediction 4, however, depends crucially upon the additional assumption that nonneighbor firms and the government do not have private signals. The more general result is that the distribution function of the neighbor bid lies below that of the high nonneighbor bid for bids in the support of the random reservation price. Similarly, the prediction that nonneighbor firms earn zero profits on average holds only approximately if the neighbor firms do not know the valuations of the nonneighbor firms (for example, if nonneighbor firms have some private information sources).

Finally, note that the predictions of this model differ from those of the fixed-reservation-price model,[10] in that the support of the distribution of nonneighbor bids is a strict subset of that of neighbor bids, and there are no mass points in the distribution of neighbor bids (except at zero).

IV. The Evidence

We examined the profitability of tracts won by neighbor and nonneighbor firms for the sample prior to 1970 in our previous article[11] and found that the predictions of the model were confirmed in that data. For the sample of tracts sold after 1970, our estimates of tract profitability are quite poor because of the truncation of production histories at 1980. Consequently, for this sample, we focus primarily on the predictions concerning the properties of the distribution functions of the bids.

Note first that, as we documented in Table 1, winning bids were more

[10] Hendricks & Porter, *supra* note 3.

[11] *Id.*

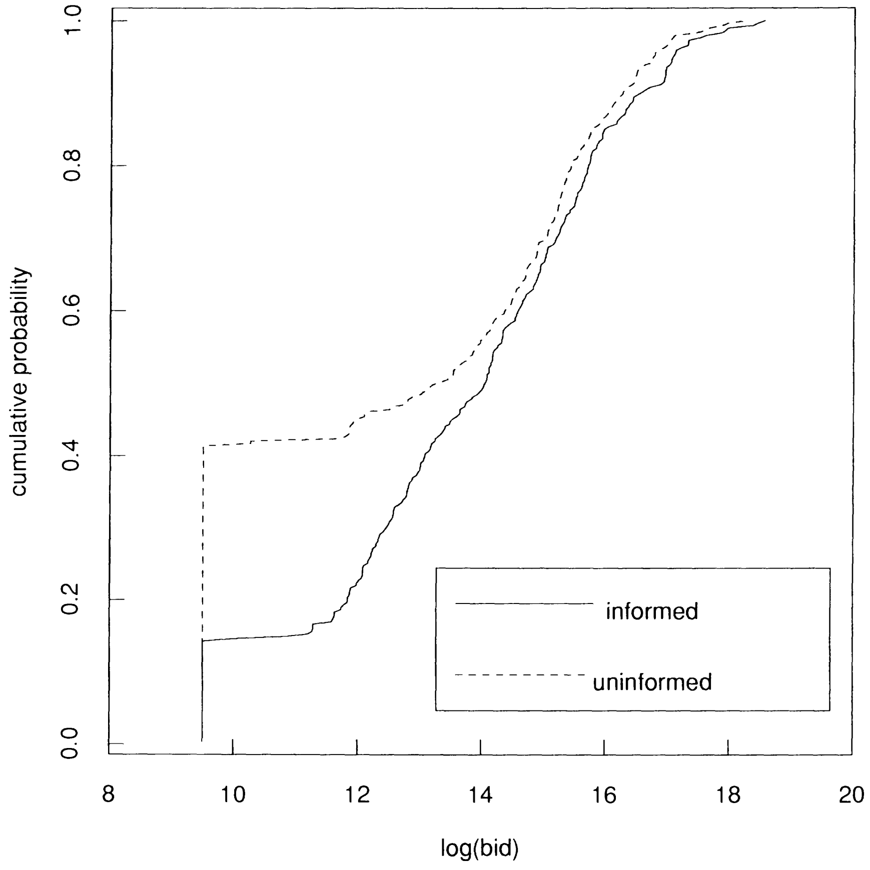


FIGURE 2.—Bid distribution functions: drainage tracts

frequently submitted by neighbor firms, whether they were accepted or not. This is consistent with the distributional implications of our model.

Consider next the participation rates of neighbor and nonneighbor firms and the supports of their bid distributions. Figures 2 and 3 plot the (unconditional) empirical distribution functions of the logarithms of the high neighbor (informed) and high nonneighbor (uninformed) bids for drainage and development leases, respectively.[12] The truncation points on the left

[12] These figures were constructed as follows. Let x_i denote the ith log bid, where $x_i \leq x_{i+1}$, for $i = 1, \ldots, N - 1$. Here $N = 295$ for drainage tracts, and $N = 179$ for development tracts. Then the figures plot the straight lines joining the adjacent points in the sequence (x_1, $1/N$), (x_2, $2/N$), . . . , (x_N, 1). For these figures, bids are expressed in 1972 dollars (and not in millions).

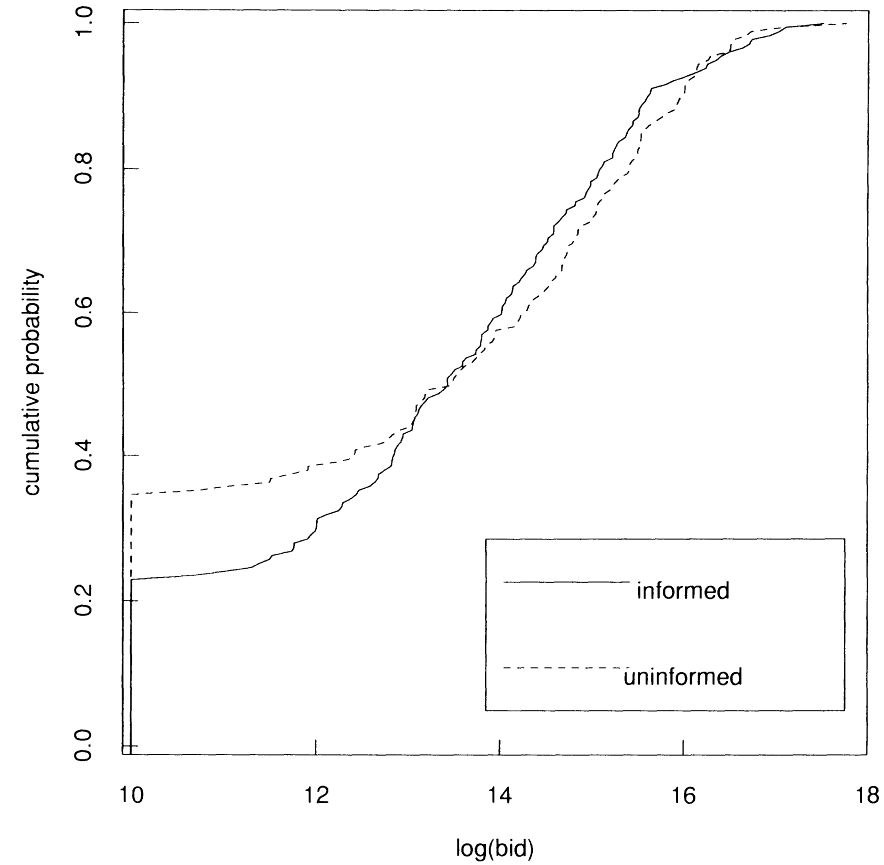


FIGURE 3.—Bid distribution functions: development tracts

side of the figures are below the smallest positive bids, and so their heights represent the probability of no bid. Thus, in accordance with the first prediction of our model, the event of no nonneighbor bids was more frequent than that of no bids by neighbors in both subsets of our sample.

There is also some validity in the second and third predictions about the supports of the distributions, as Figures 2 and 3 demonstrate. A significant fraction, about 15 percent, of the positive high neighbor bids on drainage leases were smaller than almost all of the positive nonneighbor bids in this sample. The corresponding figure for development leases is 10 percent. Recall that the distribution functions are unconditional, in that we have not controlled for any public information variables.

Finally we wish to examine the fourth prediction concerning the shapes of the distribution functions. Let $G_I(b;z)$, denote the distribution function of the high neighbor bid conditional on the public information z, and $G_U(b;z)$ the comparable distribution function of the high nonneighbor bid. If $J(b;z)$ is the probability that the high bid is accepted, conditional on z, then our theory predicts that $G_I = JG_U (\equiv G)$ for $b > b(\hat{h}(z))$, where $\hat{h}(z)$ is as defined in the previous section. (We have suppressed the arguments of the distribution functions for convenience.)

Unfortunately, the distribution functions depicted in Figures 2 and 3 do not correspond to G_I and G_U (or some mixture of them over the same distribution of z). Our sample does not include tracts that received no bids. Let $G_0 = \text{pr}\{B_I = B_U = 0|z\}$, again dropping the z argument of G_0. We observe $H_I = (G_I - G_0)/(1 - G_0)$ and $H_U = (G_U - G_0)/(1 - G_0)$. Then the prediction that $G_I = JG_U$ is equivalent to

$$H_I = JH_U - [(1 - J)G_0/(1 - G_0)], \tag{4}$$

for $b > b(\hat{h}(z))$. We wish to examine this prediction. To do so, we employed the empirical distribution functions of Figures 2 and 3 and a simple nonparametric estimate of the acceptance rule. Figures 2 and 3 are not contingent on z, so we estimated the acceptance equation just as a function of the high bid, $B_{\max}$. As before, drainage and development tracts were treated separately.

We employed Cosslett's distribution-free maximum-likelihood estimator.[13] In our context, this estimator is quite simple computationally since the acceptance rule is specified to depend only on the high bid. The details of the estimation procedure are outlined on page 773 of Cosslett's article. Briefly, high bids are ordered by rank from lowest to highest and assigned the value one if they were accepted and zero if they were rejected. Bids are then assigned into connected groups, in which the highest bid in each group was rejected and the lowest bid in the next (higher) group was accepted. (Whenever a one follows a zero, a new group begins. Thus, every interior group is a string of ones followed by a string of zeros.) Within each group, the estimated probability for acceptance of any bid is the same and equals the fraction of bids in that group that were accepted. These probabilities should be monotonically increasing across groups as bids increase. If not, then consecutive groups that violate this property are combined into larger groups. This process continues until the estimated probabilities are nondecreasing. Between groups the estimated probabilities are arbitrary, so we employed linear interpolation to connect the endpoints. Cosslett shows that this estimator is consistent and pro-

[13] Stephen F. Cosslett, Distribution-Free Maximum Likelihood Estimator of the Binary Choice Model, 51 Econometrica 765 (1983).

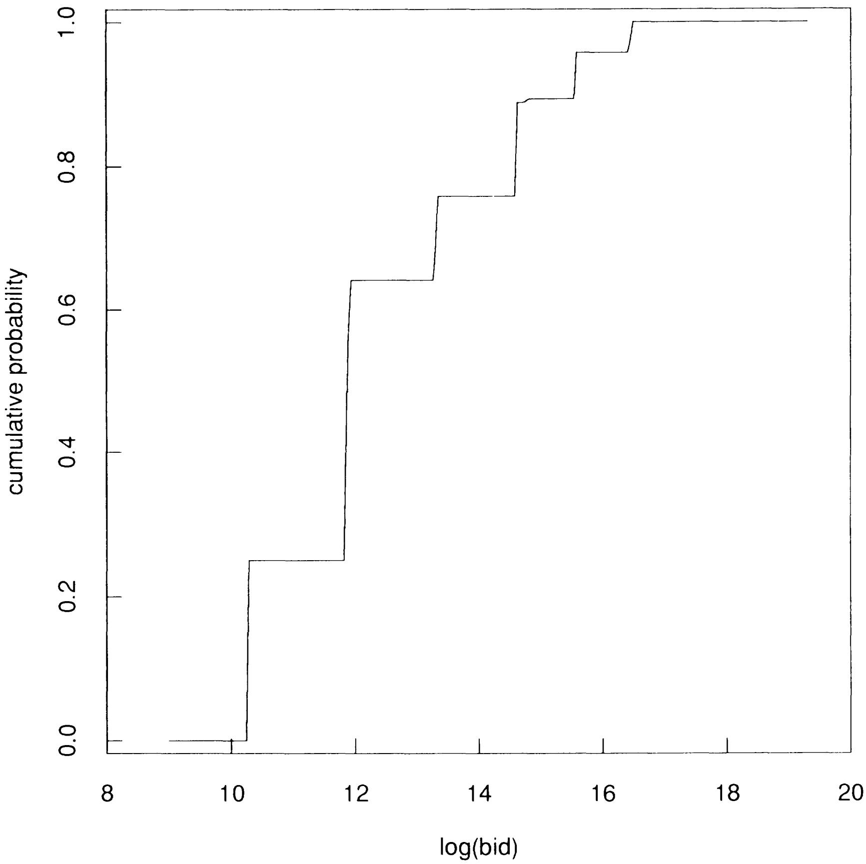


FIGURE 4.—Acceptance distribution: drainage tracts

vides the maximum-likelihood estimator of the acceptance rule. Further, it is relatively efficient for the examples he investigated.

The outcomes of the Cosslett procedure for drainage and for development tracts are depicted in Figures 4 and 5. These are essentially increasing step functions. They add further credence to our previous claim that almost no high bids were rejected. The probability of acceptance is close to one for high bids.

For each bid in the sample, we then multiplied the empirical distribution function of the high nonneighbor bid by the corresponding nonparametric estimate of J. The results are depicted in Figures 6 and 7. The "informed" distribution function is H_I and the "maximum" is JH_U. Again, these are *not* conditioned on the public information.

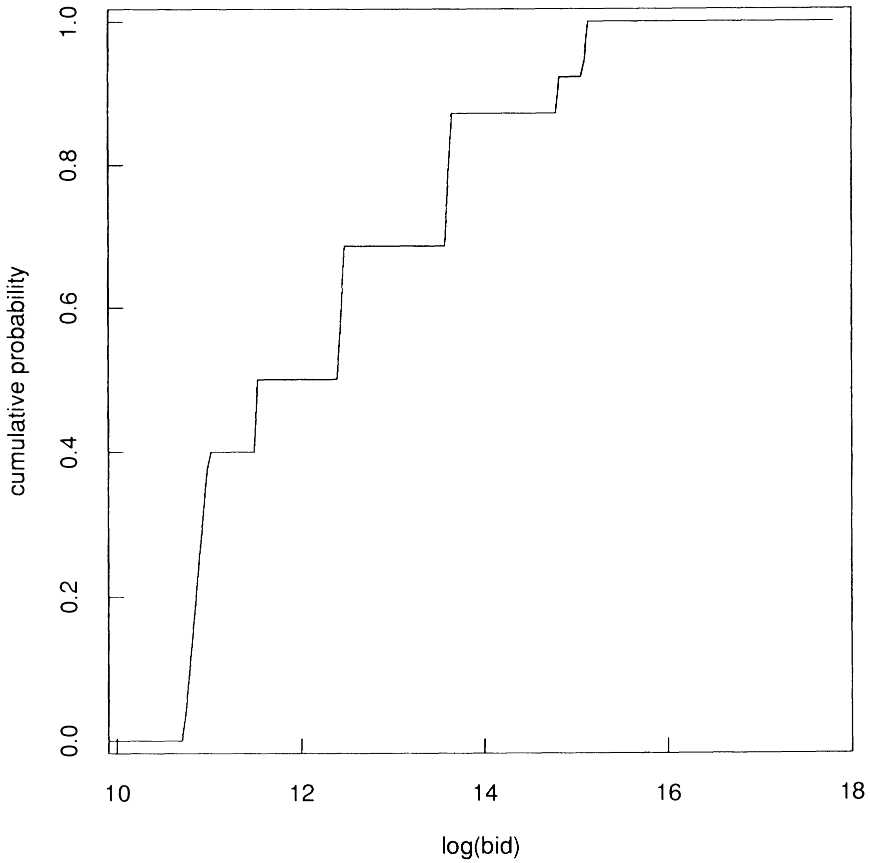


FIGURE 5.—Acceptance distribution: development tracts

Equation (4) suggests that H_I should lie below JH_U on the interval $[b(\hat{h}(z)),\bar{R}]$, but that the difference should be decreasing as the probability of acceptance increases, and small for large bids. For bids in the range where acceptance is certain, H_I should be equal to H_U.The value of G_0 is fixed given z, and the nonparametric acceptance equations shown in Figures 4 and 5 indicate that J is close to unity for large bids.[14] Figures 6 and 7 are strikingly consistent with most of the above predictions. Initially, H_I lies above JH_U, which is contrary to the theory. However, the difference shrinks rapidly, particularly on drainage leases, and, in the range where the acceptance probability is close to one, H_I is approximately equal to H_U.

[14] Further, G_0 should be small for public information z that is "good news," in the sense that the distribution of tract profits given z is more favorable. This should correspond to tracts with high bids.

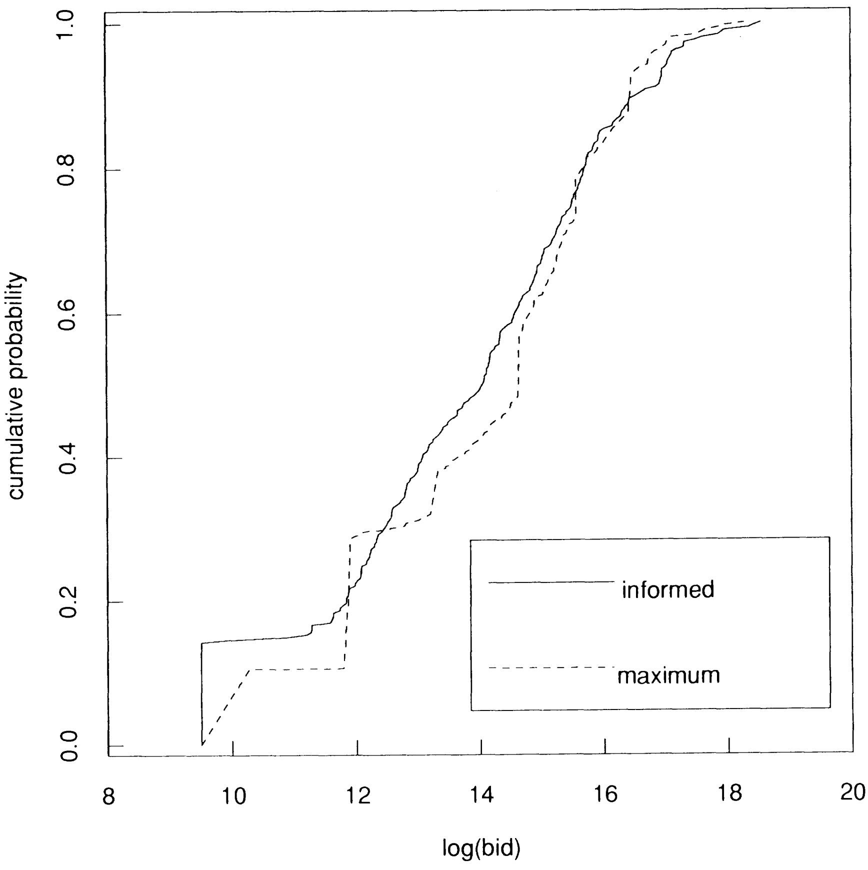


FIGURE 6.—Bid distribution functions: drainage tracts

The graphical analysis given above is suggestive but hardly definitive. The equality restriction was derived for the conditional distribution functions and applies to the unconditional distributions only if $\hat{b}(z)$ is invariant with respect to z. Although we have accounted for the distinction between drainage and development leases, it is unlikely that this condition holds for either subsample. Consequently, what is required is a more sophisticated statistical approach.[15]

A first step is to estimate the distribution functions for the high neighbor and high nonneighbor bid and test whether they are identical. In our

[15] Note, however, that the comparative statics of $\hat{b}$ with respect to changes in z are not unambiguous. Typically, $\hat{b}$ will be increasing in public information variables that are positively correlated with tract value and the random reservation price, so that HH and $b(h)$ in Figure 1 both shift up. However, if HH shifts up much more than $b(h)$ does, $\hat{b}$ will decrease.

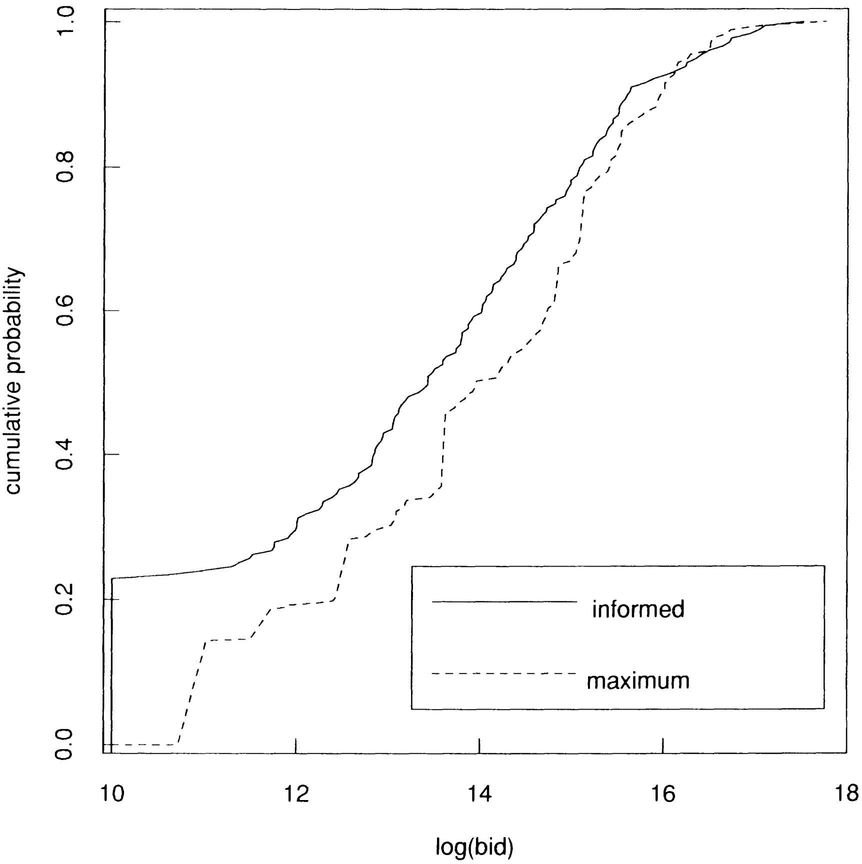


FIGURE 7.—Bid distribution functions: development tracts

earlier article,[16] we conducted this test for the sample of tracts sold in the period 1959–69. Bids divided by announced reserve prices were assumed to be lognormally distributed, with a truncation point at zero, and the sample censoring (there are no data for tracts with no bids) was accounted for. Further, correlation between the errors of the two bid equations was permitted. For that sample, we could construct good estimates of the actual value of tracts, so we had reasonably good proxies of the firms' information sets (in conjunction with other covariates). We could only weakly accept the hypothesis that the coefficients of the bid functions were equal and the point estimates of the coefficients were not very

[16] Hendricks & Porter, *supra* note 3.

similar. However, the test suffered from a selection bias in that we omitted the rejected tracts. Including these tracts in the sample may lead to a rejection of the hypothesis, since the bid distributions are supposed to differ on low-value tracts.

We replicated this estimation scheme for our new sample, treating drainage and development tracts as distinct. (The distinction is strongly supported by a likelihood ratio test of equality of coefficients.) Our covariates list is as follows: a dummy indicating whether the tract was unitized, oil and condensate production on the most recently sold neighbor tract(s), gas production on that (those) tract(s), tract acreage, the number of neighbor tracts, sale year, real oil wellhead price, and a dummy indicating whether the tract was reoffered. The likelihood function is that given in Hendricks and Porter.

We can test the hypothesis that the coefficients of the two bid equations are equal. Our theory predicts that this hypothesis should be rejected because of differences in the probability of submitting a bid and in the probability of submitting low bids. Twice the difference between the unrestricted and restricted log likelihood function values equals eighty-one for drainage tracts and fourteen for development leases. This statistic should have a chi-squared distribution with nine degrees of freedom under the null hypothesis of no differences in the coefficients. We can reject this hypothesis strongly for drainage tracts and, at size .10, for development leases.

These estimated-bid distribution functions could be paired with our probit equation describing the government's rejection rule to test equation (4), but the error terms of our bid equations may be correlated with the error term in our probit-rejection equation. Accordingly, the next step in our research will be to estimate jointly the three distribution functions: G_I, G_U, and J, conditioning on the available public information variables.

V. Conclusion

The data on the offshore drainage and development auctions indicate that neighbor firms were better informed about tract profitability than nonneighbor firms, and that neighbor firms were able to use this informational advantage to earn above-average profits. A key factor underlying the latter result was the striking absence of any competition among neighbor firms. Furthermore, the ability of neighbor firms to coordinate bidding decisions was not affected by the development of OCS federal lands or by the rising oil and gas prices of the 1970s. In this situation, nonneighbor firms bid strategically and appeared to have avoided the affliction known as the "winner's curse." They did not submit low bids, where expected profits conditional on winning were negative, and their behavior at high bids was consistent with breaking even. Neighbor firms also bid strategically, anticipating the competition from the government at low bids and from nonneighbor firms at higher bids.

These results raise some questions about experimental work on the bidding behavior in common-value auctions. All of the studies that we are familiar with report that bidders suffer from the "winner's curse."[17] Whether this is due to the inexperience of the subjects, the relatively small stakes, or structural features of the auction are issues worth pursuing. Certainly, the evidence from drainage and development auctions suggests that oil firms bid quite rationally.

Having established the relevance of theory, it is possible to ask policy questions, such as, Which alternative allocation mechanisms can increase the revenues of the government? The literature on optimal auctions has a great deal to say on this issue. In evaluating the recommendations of this literature, however, it is important not to lose sight of the context in which the drainage and development auction is held. Any information rents that firms expect to earn in a drainage or development auction are likely to have been incorporated into their bids for wildcat leases. Hence, an auction design that successively extracts all of the informational rents from neighbor firms is likely to have an effect on participation and bidding decisions in auctions of wildcat tracts. The auction design may also affect the decision to drill the drainage tract after it has been purchased. For example, letting firms bid royalty rates rather than fixed sums makes the bidding more competitive but reduces the value of the lease since firms are less likely to explore the tract. Any discussion of revenue-maximizing mechanisms for selling drainage and development leases must take into account the entire sequence of decisions that firms have to make.

[17] See, for example, Richard H. Thaler, Anomalies: The Winner's Curse, 2 J. of Econ. Persp. 191 (1988).