

# Do Buyer-Size Discounts Depend on the Curvature of the Surplus Function? Experimental Tests of Bargaining Models

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**Abstract:** A number of recent theoretical papers have shown that for buyer-size discounts to emerge in a bargaining model, the total surplus function over which parties bargain must have certain nonlinearities. We test the theory in an experimental setting in which a seller bargains with a number of buyers of different sizes. Nonlinearities in the surplus function are generated by varying the shape of the seller's cost function. Consistent with the theory, we find that quantity discounts emerge only in the case of increasing marginal cost, corresponding to a concave surplus function. We provide additional structural estimates to help identify the source of remaining discrepancies between experimental behavior and theoretical predictions (whether due to preferences for fairness or other factors such as computation errors).

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# 1 Introduction

The topic of large-buyer discounts has generated considerable interest among antitrust policymakers, business journalists, and academic economists. The conventional wisdom is that large buyers are somehow better bargainers than small buyers in price negotiations with a seller. Theoretical analyses of such a bargaining model (Horn and Wolinsky 1988, Stole and Zwiebel 1996, Chipty and Snyder 1999, Inderst and Wey 2003, Raskovich 2003) concluded that large-buyer discounts are not guaranteed but depend on the curvature of the total surplus function over which the parties bargain.

Figure 1 captures the logic behind the theoretical argument. Suppose for simplicity that buyers are final good consumers or are downstream firms which sell their output on separate markets. The total surplus over which the parties bargain,  $W(Q)$ , is equal to total benefits (downstream consumer surplus or revenue) minus total costs (upstream and downstream production costs) as a function of the quantity,  $Q$ , sold to buyers who reach an agreement with the seller. Suppose a buyer with demand for  $q$  units trades with the seller. Assuming that others come to an efficient agreement with the seller, the buyer may be regarded as the marginal player, contributing marginal surplus  $A$  to the total. In Figure 1A, in which the total surplus function is concave,  $A$  is quite small, and so whatever the sharing rule implicit in the bargaining process, the buyer will not obtain very much surplus per unit. Now consider a second buyer who is twice as big as the first, having demand for  $2q$  units. The relevant marginal surplus over which the large buyer and seller bargain becomes  $A + B$ , which is much greater per unit than  $A$  due to the concavity of the surplus function. The large buyer's greater per-unit surplus translates into a lower per-unit price than paid by the small buyer.

Contrast this result with the case of a linear total surplus function in Figure 1B. Taking the small buyer to be the marginal player, the surplus over which he bargains to satisfy his  $q$  units of demand is  $A$ . Taking the large buyer to be the marginal player, to fulfill his  $2q$  units of demand,

he bargains over the surplus  $A + B$ , which is twice as large as  $A$  by the linearity of the surplus function. Thus, the large and small buyer contribute the same marginal surplus per-unit and, as a result, pay the same per-unit price.

The case of a convex total surplus function in Figure 1C is more complicated. The surplus over which the small buyer bargains,  $A$ , is much larger per unit than that over which the large buyer bargains,  $A + B$ . Hence we might expect large-buyer premia to emerge in equilibrium. However, buyers' contributions to surplus at the margin may be so high that the low prices they pay as a result are insufficient to cover the seller's costs. Multiple equilibria may arise with one buyer or another paying more to prevent the seller from taking his outside option not to produce. As our analysis in Section 3 will show, the set of equilibrium outcomes may range from large-buyer premia, to prices independent of size, to large-buyer discounts.<sup>1</sup>

We test this theory in an experimental setting with three treatments corresponding to markets with concave, linear, and convex total surplus functions. We generate curvature in the surplus function by varying the seller's marginal cost function, with increasing marginal costs leading to a concave total surplus function, constant marginal costs leading to a linear total surplus function, and decreasing marginal costs leading to a convex total surplus function.

Our results support the qualitative predictions of the theory for buyer-size discounts. Substantial large-buyer discounts are observed in the increasing marginal cost treatment (i.e., concave total surplus function). Large buyers' per-unit bids are 12 percent lower on average than small buyers' in this treatment. Sellers are also more likely to accept low bids from large buyers. Thus, the large-buyer discount is larger, 14 percent, for accepted bids. In the cases of constant and decreasing marginal costs, large and small buyers bid virtually the same per-unit price on

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<sup>1</sup>Alternative theories can generate buyer-size discounts in the absence of curvature of the surplus function. In Katz (1987) and Scheffman and Spiller (1992), large buyers' credible threat of backward integration limits prices charged to them. In Snyder (1996, 1998), collusion is difficult to sustain in the presence of larger buyers. In McAfee and Schwartz (1994), Dobson and Waterson (1997), and Chen (2003), downstream product market competition affects firms' negotiations with an input supplier. In Chae and Heidhues (2004) and DeGraba (2005), sellers favor large buyers because of risk aversion.

average, and sellers' acceptance probabilities do not differ between them.

The fact that buyer-size discounts emerge in the cases predicted by theory and only those cases is notable for several reasons. First, the underlying bargaining game involves a considerable amount of strategic uncertainty. Buyers must form conjectures about the simultaneous bids of other heterogeneous buyers and the sequential rationality of the seller's response to these bids. The solution concept employed by the theoretical papers we test, typically subgame-perfect equilibrium, effectively requires buyers to regard themselves as marginal in just the right way depending on their size. The solution concept may not be a good predictor of observed outcomes in our experimental setting. Indeed, observed buyer bids differ markedly from the corresponding theoretical predictions for a number of cases (average bids are higher than theory predicts for the constant and decreasing marginal cost treatments; small-buyer bids are lower than theory predicts for the increasing marginal cost treatment). Despite the fact that the theory's quantitative predictions concerning buyer-bid levels do not always hold in the experiments, the theory's qualitative predictions concerning buyer-size discounts do hold. Second, the experimental bargaining literature underscores that fairness and equity concerns may inhibit convergence to the subgame-perfect equilibrium in settings such as the ultimatum game, even with repeated play and high stakes (see, e.g., Slonim and Roth 1998). Despite the latitude for fairness considerations and their ability to account for some observed divergences from equilibrium play in our experiments, buyer-size discounts nonetheless emerge only where predicted by the theory.

To our knowledge, ours is the first direct test of the bargaining literature cited in the first paragraph. A few empirical papers have provided indirect tests (Ellison and Snyder 2002, Sorensen 2003). In the particular industries studied, large-buyer discounts were found in markets with competing suppliers but not with monopoly suppliers. Although this result does not support the bargaining literature cited above, it is not a direct rejection since the theory does not say large-buyer discounts must emerge in equilibrium—large-buyer discounts may not emerge if the total surplus function is not concave. Chipty and Snyder (1999) estimate the curvature of the total

surplus function in cable television. Their estimates could be used to determine which case from the bargaining theory applies to cable television, but their paper is not a direct test of the theory since they have no data on prices paid by buyers.

While ours is the first experimental study of size as a source of buyer discounts, previous experimental papers have studied other sources of buyer discounts. Ruffle (2000) examines buyers' ability to extract price concessions from competing sellers through demand withholding. Davis and Wilson (2006) analyze the impact of strategic buyers on market outcomes after a seller merger. Engle-Warnick and Ruffle (2005) show that two buyers achieve significantly lower prices against a monopoly seller than do four buyers. None of these studies varies buyer size within a market to measure buyer-size discounts, nor do they vary the shape of the total surplus function to test the bargaining theories cited in the first paragraph, as we do in the present paper.

## 2 Experimental Design

To test for the relationship between the curvature of the surplus function and buyer-size discounts, we designed three separate markets or treatments. The three treatments differ only in the shape of the seller's marginal cost function: a treatment with an increasing marginal cost function (IMC), constant marginal cost function (CMC), and decreasing marginal cost function (DMC). In each market, three buyers face a single seller. Two of the buyers are small, with unit demand for the fictitious commodity, and the other buyer is large, with demand for two units.<sup>2</sup>

The buyers' per-unit gross surplus is  $v_i = 100$ , implying total gross surplus of  $V_i = 100$  for a small buyer and  $V_i = 200$  for the large buyer. The seller can supply up to four units to the buyers, so there is no binding capacity constraint. We control for the total cost of supplying all

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<sup>2</sup>Exogenous variation in buyer size allows for a simple, direct test of the theory but is also of practical relevance for wholesale and intermediate-good markets in which a monopolist sells to independent local buyers whose size is exogenous, reflecting varying downstream demand that each buyer faces in its local market. It is also of relevance in markets in which buyers are chain stores whose size is determined by the number of retail outlets in the chain.

four units by setting it equal to 80 in all three treatments. In the IMC treatment, the seller's first unit of production costs 0, the second unit costs 5, the third unit 15, and the fourth 60. The DMC treatment uses the same numbers but in reverse order, so the first unit costs 60, the second unit 15, the third 5, and the fourth 0. In the CMC treatment, all four units have the same marginal cost of 20. Combining the gross surplus and cost parameters yields the total surplus functions graphed in Figure 2. The IMC treatment leads to a concave surplus function, CMC to a linear one, and DMC to a convex one.

Twelve subjects participate in each experimental session. After reading the instructions, nine of the subjects are randomly selected to play the role of buyer and three to play the role of seller. This role remains fixed throughout the experiment.

The experiment consists of 60 rounds. In each round, all three markets are simultaneously conducted (one IMC, one CMC and one DMC market) and with probability 1/3 each subject is assigned to each of these markets. Thus, over the course of the 60-round experiment, all subjects participate in each of the three markets. This design feature permits within-subject comparisons across markets. Further, we used a random matching scheme. That is, the cohort of three buyers and one seller that constitutes a market each round is randomly determined. We selected this design feature to minimize repeated-game effects.<sup>3</sup> A final random element in the design is the designation of the large and two small buyers in each market. In a each market, two buyers are randomly assigned the role of small buyer and one buyer the role of the large buyer in each of the 60 rounds. The randomization scheme was performed once, prior to conducting any of the experiments. The outcome of the randomization scheme was used for all six sessions. In this way, we minimize between-session differences unrelated to behavior.

Trading takes place in a posted-bid market (first analyzed by Plott and Smith 1978), involving the following sequence of events. First, each subject is informed of the market to which he has

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<sup>3</sup>Subjects who play together repeatedly even for a known, fixed number of rounds sometimes exhibit supergame-style strategies, especially when the number of rounds is large (Selten and Stoecker 1986).

been assigned and buyers are told whether they have a demand for one or two units that round. Each buyer  $i$  then privately and independently chooses a bid,  $p_i$ . A small buyer's bid reflects the price he is willing to pay to fulfill his unit demand, while the large buyer's bid reflects the per-unit price he is willing to pay for the bundle of two units. The large buyer is not given the option of bidding separate amounts for the two units. The seller observes each buyer bid for  $x_i \in \{1, 2\}$  units and decides whether to accept ( $a_i = 1$ ) or reject ( $a_i = 0$ ) each one. The seller does not have the discretion to supply one of the large buyer's two units and reject the other.<sup>4</sup>

Buyers earn a payment equal to net consumer surplus  $a_i x_i (v_i - p_i)$ , and sellers earn a payment equal to total revenue,  $\sum_i p_i a_i x_i$ , minus the total cost of producing realized sales. Rejected bids yield zero profit for the buyer and the seller; the seller does not incur the cost of unsold units.

Buyers' valuations, seller costs, and the structure of the market are all made common knowledge by reading aloud the subjects' instructions (available from the authors upon request). As mentioned, subjects are told that cohorts would be randomized in each round, but were not told with whom they were playing in a market. Feedback at the end of a round is minimal, again with the aim of minimizing repeated-game effects or possible collusion. Each buyer learns only whether his bid was accepted and his resulting payoff. Buyers do not observe any other buyers' bids in their own or the other two markets, nor the sellers' decisions on other bids.

At the completion of 60 rounds, all subjects were paid their experimental earnings in cash. All subjects were given an initial endowment of 1,000 experimental "points" at the beginning of the experiment. For every 250 points accumulated, the subject received £1. In total, 72 subjects participated in one of six experimental sessions conducted in the Experimental Economics Laboratory at Royal Holloway, University of London. Each session, including the instructions,

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<sup>4</sup>Our choices to exclude large buyers from bidding different prices for its two units and sellers from supplying large buyers with only one unit follow from an effort to simplify subjects' task. These design features maintain the same decision problem for the buyer whether large or small—he simply chooses one bid in either case—and the same decision problem for the seller whether it faces a large or small buyer—he simply chooses to accept/reject the bid in either case. With subjects playing in different treatments during a session, buyers alternating size and with considerable strategic uncertainty about other buyers' play, our experimental setting is already quite complex.

five practice rounds, and a post-experiment questionnaire, lasted between 120 and 160 minutes. On average, sellers earned £22 and buyers £19 each, including the initial endowment.

### 3 Theoretical Predictions

In this section, we derive the pure-strategy, subgame-perfect equilibria of our experimental game. Our experimental setting differs slightly from any of the related theoretical papers because we have adopted a different bargaining game. Rather than Nash bargaining (as in Horn and Wolinsky 1988, Chipty and Snyder 1999, and Raskovich 2003), or specific bargaining procedures giving rise to the Shapley value (as in Stole and Zwiebel 1996 and Inderst and Wey 2003), we adopt a simpler, and thus more tractable, bargaining game for an experimental setting, namely one in which parties make take-it-or-leave-it offers. The equilibrium outcomes are qualitatively similar to those in these other papers, but to derive the equilibria formally requires new propositions. Since these propositions are of some independent interest, we first prove a general version of them, and then proceed to derive their implications for the specific parameters used in our experiment.

Suppose there are  $N$  buyers indexed by  $i = 1, \dots, N$ . Let  $B = \{1, \dots, N\}$  denote the set of buyers. Each buyer  $i$  has inelastic demand for  $x_i \in \mathbb{N}$  units, with  $V_i$  representing the buyer's total gross surplus for the bundle of  $x_i$  units, and  $v_i = V_i/x_i$  representing the buyer's gross surplus per unit. Let  $X = \sum_{i \in B} x_i$ . In the first stage of the bargaining game, each buyer  $i$  makes a simultaneous offer of a bid per unit  $p_i \in [0, \infty)$  to the single seller in the market. In the second stage of the bargaining game, the seller decides whether to accept the bid of each buyer  $i$ , the decision denoted  $a_i \in \{0, 1\}$ . Equivalently, the seller chooses the set of accepted buyer bids  $A = \{i \in B | a_i = 1\}$ . Market sales are  $Q = \sum_{i \in B} a_i x_i$ .

Denote the seller's total cost of producing  $Q$  by  $C(Q)$ , its marginal cost of producing the last of  $Q$  units by  $MC(Q) = C(Q) - C(Q - 1)$ , its incremental cost of producing  $Q_2$  on top of  $Q_1$  by  $IC(Q_2, Q_1) = C(Q_1 + Q_2) - C(Q_1) = \sum_{j=1}^{Q_2} MC(Q_1 + j)$ , and its average incremental cost



of producing  $Q_2$  on top of  $Q_1$  by  $AIC(Q_2, Q_1) = IC(Q_2, Q_1)/Q_2$ . Normalize  $C(0) = 0$ .

A full characterization of the subgame-perfect equilibria of this game for general parameter configurations turns out to be quite complicated. In our experiments, we chose the parameters so that all buyers are served in equilibrium. This simplifies the characterization of equilibria considerably. We will thus restrict attention to the case in which all buyers are served for the remainder of the section. The following proposition provides a sufficient condition for all buyers to be served in equilibrium. The proofs of all propositions appear in the appendix.

**Proposition 1.** *All buyers are served (formally, the set of buyers whose bids are accepted  $A$  equals the set of all buyers  $B$ ) in any pure-strategy, subgame-perfect equilibrium if, for all  $i \in B$ ,*

$$v_i > \max_{\{Q \leq X\}} MC(Q). \quad (1)$$

Condition (1) specifies that all buyers' per-unit valuations exceed the marginal cost of producing any unit. If condition (1) holds, but not all buyers are served in a particular outcome, the outcome cannot be an equilibrium. Rather than earning zero profit, an excluded buyer could offer a bid between its valuation and the incremental cost of being served that would be strictly profitable for the seller to accept regardless of which other buyers were also being served. This accepted bid would generate positive profit for the buyer. Note that the condition in the proposition is satisfied by the experimental parameters since  $v_i = 100$ , which is greater than 60, the highest marginal cost of producing any unit in the experiment.

The next set of propositions characterize the pure-strategy, subgame-perfect equilibria in which all buyers are served for marginal cost functions of different shapes.

**Proposition 2.** *Suppose marginal costs are non-decreasing, i.e.,  $MC(Q + 1) \geq MC(Q)$  for all  $Q \in \{1, 2, \dots, X\}$ . Buyer bids  $\{p_i | i \in B\}$  form a pure-strategy, subgame-perfect equilibrium in which all buyers are served if and only if, for all  $i \in B$ ,*

$$p_i = AIC(x_i, X - x_i) \leq v_i. \quad (2)$$

**Proposition 3.** *Suppose marginal costs are strictly decreasing, i.e.,  $MC(Q + 1) < MC(Q)$  for all  $Q \in \{1, 2, \dots, X\}$ . Buyer bids  $\{p_i | i \in B\}$  form a pure-strategy, subgame-perfect equilibrium*

in which all buyers are served if and only if  $p_i \leq v_i$  for all  $i \in B$  and, for all subsets  $S \subseteq B$ ,

$$IC\left(\sum_{i \in S} x_i, X - \sum_{i \in S} x_i\right) \leq \sum_{i \in S} p_i x_i \leq C\left(\sum_{i \in S} x_i\right). \quad (3)$$

Proposition 2 subsumes the cases of strictly increasing marginal costs and everywhere constant marginal costs, which correspond to two of our experimental treatments, as well as marginal cost functions that are strictly increasing over some regions and constant over others. In view of Proposition 2, characterization of the equilibrium with all buyers being served under constant or increasing marginal costs is quite simple. Each buyer bids an amount that exactly covers the incremental cost of being served on top of the other  $N - 1$  buyers' purchases. Any less than this and the seller would gain by rejecting the bid; any greater than this and the buyer could profitably lower the bid and still not have it rejected by the supplier.

As Proposition 3 shows, characterization of equilibria under decreasing marginal costs is more complicated. There is a continuum of equilibria. Within the bounds provided by condition (3), any set of bids summing exactly to the total cost of serving all buyers forms an equilibrium in which all buyers are served. The first inequality in (3) ensures that the seller does not have an incentive to reject a subset of buyer bids. The second inequality in (3) ensures that a buyer does not have an incentive to lower his bid because it would be rejected by the seller. To see this, note that if a buyer deviated to a lower bid, the second weak inequality would become strict for all subgroups containing the deviating buyer, implying that the seller would earn negative profit if it accepted the bids of any subgroup containing the deviating buyer. The seller would earn more (zero rather than negative profit) by simply rejecting all bids.

Figure 3 summarizes the implications of Propositions 2 and 3 in the case of our experimental parameters. The 45-degree line represents equal average large-buyer and small-buyer per-unit bids; large-buyer discounts are found in the region below the 45-degree line, and small-buyer discounts above it. For the IMC treatment, Proposition 2 implies that small buyers bid  $p_{s_i} = AIC(1, 3) = 60$  in equilibrium while the large buyer bids  $p_l = AIC(2, 2) = 37.5$ . The seller

accepts all bids in equilibrium and earns 115, small buyers each earn a profit 40, and the large buyer earns 125. The large buyer obtains a substantial discount of 22.5. For the CMC treatment, Proposition 2 implies that the small buyers' equilibrium bids,  $p_{s_i} = AIC(1, 3) = 20$ , are the same as the large buyer's,  $p_l = AIC(2, 2) = 20$ , and the seller accepts all bids and earns zero. Thus, there is no buyer-size discount since the large and small buyers make the same per-unit bids equal to the constant marginal cost. Small buyers each earn a profit of 80 while the large buyer earns 160. In the DMC treatment, as Figure 3 indicates, there exists a continuum of equilibria.<sup>5</sup> Equilibria may involve large-buyer discounts, small-buyer discounts, or equal per-unit prices for large and small buyers. All buyers are served in equilibrium. Buyers' payoffs depend on the equilibrium; the seller earns zero in all cases.

To summarize the predictions for the three treatments, large-buyer discounts should be observed in the IMC treatment and no discounts observed in the CMC treatment. The DMC treatment may exhibit a range of outcomes including no discounts. Average bids are predicted to be higher in IMC than the other treatments. Only in the IMC treatment is the seller predicted to earn positive profit; in the CMC and DMC treatments, buyers' bids sum exactly to the seller's total cost of 80.

## 4 Results

In this section, we test the implications of the theory concerning buyer-size discounts based on the six experimental sessions we conducted. Section 4.1 focuses on tests of the comparative-statics predictions of the theory, that is, predictions of the theory for differences between large and small buyers. Section 4.2 focuses on explaining observed deviations from equilibrium behavior.

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<sup>5</sup>Proposition 3 states that condition (3) must hold for all possible subsets of buyers. Translated into our experimental setting, for a subset of one small buyer, condition (3) implies  $0 \leq p_{s_i} \leq 60$ , for a subset of one large buyer  $5 \leq 2p_l \leq 75$ , for a subset of two small buyers  $5 \leq p_{s_1} + p_{s_2} \leq 75$ , for a subset of one large and one small buyer  $20 \leq 2p_l + p_{s_i} \leq 80$ , and for all the buyers  $80 \leq 2p_l + p_{s_1} + p_{s_2} \leq 80$ . Combining these inequalities yields the set of equilibria labeled DMC in Figure 3.

## 4.1 Buyer-Size Discounts

Our analysis of buyer-size discounts in each of the three treatments (IMC, CMC, DMC) proceeds by first examining the extent to which the discounts show up in descriptive statistics reported in Table 1 and using the regression results in Table 2 to test whether the discounts are statistically significant. Although the tables also report results based on all 60 rounds, we direct attention to the last 30 rounds of play throughout the discussion in this subsection. This choice follows from the insight that experimental data may be noisy in the early rounds as subjects familiarize themselves with the environment and learn how rivals play. We will investigate these and other dynamic effects more formally in the next subsection but note for now that all of the qualitative results discussed in this subsection are robust to considering the entire 60 rounds of play.

Regarding the IMC treatment, the summary statistics in the first two rows of part (b) of Table 1 point to an appreciable large-buyer discount. The mean large-buyer bid is 39.5 (median = 40.0), about five points less than the mean small-buyer bid of 44.8 (median = 45.0). The random-effects regression in part (a) of Table 2 shows that this discount is statistically significant.<sup>6</sup> The standard errors are corrected for possible non-independence of observations across multiple rounds of play for the same buyer (by clustering each buyer's observations) and are robust to possible heteroskedasticity (following White 1980). The regression includes dummy variables for the IMC and DMC treatments, labeled *IMC* and *DMC*, respectively, with CMC as the omitted treatment. To assess the magnitude of buyer-size discounts or premia, interaction terms between each of the treatments and buyer size are included,  $IMC \times LARGE$ ,  $CMC \times LARGE$ , and  $DMC \times LARGE$ . The dummy variable *LARGE* equals one for bids made by large buyers. The coefficient of  $-4.84$  (significantly different from zero at the one-percent level) on the interaction term  $IMC \times LARGE$  in part (a) indicates nearly a five-point large-buyer discount in this treatment.

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<sup>6</sup>Our experimental design obviates the need for fixed buyer effects because the buyer's size and the treatment in which the buyer plays is chosen at random each round. Indeed, the coefficients on the variables of interest are virtually identical across fixed- and random-effects specifications. A Hausman test cannot reject the appropriateness of random effects.

The existence and magnitude of the large-buyer discount in IMC are striking when contrasted with the absence of buyer-size discounts in the other two treatments. Theory predicts that the mean large- and small-buyer bids should be identical in the CMC treatment. The descriptive statistics in part (b) of Table 1 bear this out: the mean large-buyer bid in this market is 34.6 (median = 35.0) compared to 34.5 (median = 35.0) for small buyers. In the random-effects regression in part (a) of Table 2, the coefficient of  $-0.86$  on  $CMC \times LARGE$  is not significantly different from zero. Turning to the DMC treatment, we again find no difference between large and small buyers' bids. The mean large-buyer bid for the DMC treatment reported in part (b) of Table 1 is 40.9 (median = 40.0) compared to 40.2 (median = 40.0) for small buyers. In the random-effects regression in part (a) of Table 2, the coefficient of  $-0.44$  on the interaction term  $DMC \times LARGE$  is not statistically different from zero.

The results are if anything stronger if we consider the subsample of accepted bids. The justification for focusing on accepted bids is that these would be the prices observed by the empirical researcher in a typical non-experimental market; one would not observe prices for trades that were not executed due to a breakdown in bargaining. Summary statistics for accepted bids are provided in the last six rows of Table 1. Comparing the large- and small-buyer bids in part (b) of the table for the IMC treatment shows that the mean large-buyer discount increases to about seven points and the median rises to about nine points when just accepted bids are considered. Similarly, the regression coefficient of  $-5.81$  on  $IMC \times LARGE$  in part (b) of Table 2 is larger (by about one point) than the corresponding coefficient for all bids reported in column (a). By contrast, the means and medians of large and small buyers' bids remain virtually unchanged for the CMC and DMC treatments when we restrict attention to accepted bids and the corresponding regression coefficients measuring a buyer-size discount continue not to be significantly different from zero.

We next turn to an analysis of the impact of buyer size on sellers' acceptance decisions. In the IMC treatment, theory predicts that the seller accepts a large buyer's bid whenever it would accept

an equal small buyer’s bid, at least in the range of bids in our data set, but the converse is not true.<sup>7</sup> In the CMC treatment, theory implies that there should be no difference in the accept/reject decision for large- and small-buyer bids since both provide the same per-unit surplus for a given bid. There are no strong theoretical predictions for the DMC treatment in this regard because of the multiplicity of equilibria.

The descriptive statistics in part (b) of Table 1 provide some evidence on the seller’s acceptance decision. Comparing the number of accepted bids in the last six rows of the table to the total number of bids in the first six rows, the disproportionate number of rejected bids made by small buyers in the IMC treatment stands out. For the other buyer types, rejection rates range from two percent (large buyers in DMC) to 17 percent (large buyers in CMC). In the case of small buyers in IMC, the rejection rate is 40 percent, with 143 out of 360 bids rejected. Compare this with large buyers in the same treatment whose bids are rejected at the rate of only ten percent (18 out of 180), despite bidding significantly lower than their small-buyer counterparts.

A more formal analysis of the seller’s accept/reject decision is provided by Figure 4. We ran a probit to determine the reduced-form probability of seller acceptance as a function of a buyer’s bid for each of the six different buyer-size/treatment combinations.<sup>8</sup> To aid interpretation, rather than report a table of coefficient estimates, we provide in Figure 4 a graph of the seller’s acceptance decision based on coefficient estimates. As the figure shows, the seller acceptance functions are similar for the large and small buyers in both the CMC and DMC treatments.

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<sup>7</sup>Consider equal large- and small-buyer bids  $p_\ell = p_{s_1} = p$ . Let  $Q_{s_2} \in \{0, 1\}$  be the quantity supplied to the second small buyer. Both bids are accepted if  $p > IC(3, Q_{s_2})$  and both are rejected if  $p < IC(1, Q_{s_2})$ . Accepting the large-buyer bid and rejecting the small-buyer bid yields a profit of  $2p - IC(2, Q_{s_2})$ . Accepting the small-buyer bid and rejecting the large-buyer bid yields a profit of  $p - IC(1, Q_{s_2})$ . But  $2p - IC(2, Q_{s_2}) > p - IC(1, Q_{s_2})$  if and only if  $p > MC(Q_{s_2} + 2)$ . Note that  $MC(Q_{s_2} + 2) \in \{5, 15\}$  for our design. Since we do not observe any small-buyer bids less than 15 in IMC, accepting the small buyer and rejecting the large buyer is never optimal for the range of bids in our data set.

<sup>8</sup>The dependent variable in the probit is an indicator for the seller’s accept/reject decision; regressors include a full set of dummies for buyer-size/treatment combinations and interactions between these and the buyer’s bid. We use the results based on the last 30 rounds of bids; results based on all rounds of bids are similar. All formal statistical tests related to this probit cited below are based on robust standard errors from a population-averaged panel-data model, clustering on sellers (to account for possible correlation in the errors for the same seller across multiple rounds).

However, the acceptance function for the IMC small buyers lies well below that of IMC large buyers, indicating that the seller is much more likely to accept a large-buyer bid than an equal small-buyer bid. The figure highlights the seller's distinct treatment of IMC small buyers' bids. For example, a bid of 40 by a small buyer in the IMC treatment has less than a 50 percent chance of being accepted, while this same per-unit bid is accepted with near certainty when submitted by each of the other five buyer types. In all five comparisons of the probability of acceptance with small buyers in IMC, the difference is significantly different from zero at better than the one-percent level in pairwise  $\chi^2$  tests.

To sum up, the results for buyer-size discounts are qualitatively consistent with the comparative-static predictions of the theory. Large buyers bid lower and sellers accept these lower bids in the IMC treatment. There are no price discounts and sellers' acceptance behavior is alike across large and small buyers in the CMC treatment. These findings are all predicted by the theory. Theory predicts a broad range of possible outcomes for the DMC treatment, including the possibility that large and small buyers pay equal per-unit prices and sellers' acceptance behavior is alike across large and small buyers. Consistent with this latter possibility, large and small buyers' bids are about equal in the DMC treatment in our experimental data and sellers' acceptance behavior is about the same across large and small buyers.

## **4.2 Explanations of Deviations from Equilibrium**

While the theory correctly predicts the direction of buyer-size discounts in the experiment, there remain some discrepancies between bid levels in certain treatments and the corresponding theoretical predictions that merit investigation. For ease of comparison, Table 3 juxtaposes the mean bids from the experimental data from Table 1 and the theoretical predictions from Figure 3. In the IMC treatment, the average large-buyer bid of 39.5 is close to the theoretical prediction of 37.5. The random-effects regressions from Table 2 can be used to provide a statistical test of the

difference as well as the other differences discussed below in this section: the estimated large-buyer bid in the IMC treatment—given by the sum of the coefficients on the constant, *IMC*, and  $IMC \times LARGE$  from column (b)—is not significantly different from 37.5 at the ten-percent level in a two-tailed *t* test. On the other hand, the average small-buyer bid of 44.8 is lower than the theoretical prediction of 60, significantly different at the one-percent level. (Indeed, the absence of buyer-size discounts in the CMC and DMC treatments coupled with small buyers' below-equilibrium bidding in IMC make large-buyer discounts in this treatment all the more striking.) While large and small buyer bids in the CMC treatment—34.6 and 34.5, respectively—are not significantly different from each other, they are higher than the theoretical prediction of 20 for both, significantly different at the one-percent level. Although large- and small-buyer bids in the DMC treatment cannot be compared to their theoretical counterparts individually because there is not a unique theoretical prediction for them, the average across large and small buyer bids can be compared to theory. The average in column (a) of about 40 is higher than the theoretical prediction of 20, significantly different at the one-percent level.

We begin with a preliminary analysis of whether the buyers, the sellers or both are responsible for the discrepancies between bid levels and theoretical predictions. To help determine whether buyer play is rational—"rational" will be used throughout the discussion in the narrow sense of maximizing own monetary payoffs in a one-shot game—for each treatment and buyer-size combination, we calculate buyers' monetary-payoff-maximizing best responses to others' experimental play. A divergence between mean bids and these best responses would suggest possible departures from buyer rationality. We use the results underlying Figure 4 as an input in the calculation. Multiplying the acceptance probability from Figure 4 times the buyer's payoff conditional on acceptance for each bid level results in the expected buyer payoff function conditional on others' experimental play, displayed in Figure 5. The peak of a function is a payoff-maximizing buyer's best response to others' experimental behavior, recorded in column (c) of Table 3.

Comparing columns (a) and (c), we see a divergence between experimental best responses and



mean bids in three of the six rows: for small-buyer bids in IMC and for large- and small-buyer bids in DMC. This suggests some deviation from rational play on the buyer side at least in these cases. On the other hand, comparing columns (b) and (c), experimental best responses diverge from theoretical predictions in three of the six rows: for small-buyer bids in IMC and for large- and small-buyer bids in CMC. This raises the possibility of departures from rational play on the seller side as well, as will be examined below.

More direct evidence on the rationality of seller play can be obtained from an analysis of individual seller acceptance decisions. A sequentially rational seller would best respond to the set of observed bids in each round (which do not necessarily correspond to the equilibrium bids predicted by theory, as just seen). Focusing on the last half of the rounds in each session (periods 31–60), for each treatment we have 180 seller decisions to analyze (30 periods times six sessions) involving 540 buyer bids. In the IMC treatment, 149 out of 180 sellers' decisions (83 percent) are rational. Half of the irrational decisions are acceptances of all three bids when the seller should have rejected one small-buyer bid. In CMC (where sellers' decisions on all 540 bids can be analyzed separately), we found 481 rational seller decisions (89 percent). Seven of these are rejections of bids less than 20. All 59 irrational decisions are rejections of bids larger than 20, albeit relatively low bids: the average rejected bid was 28.7, significantly less than large and small buyers' average bids. No bid above 40 is rejected. Finally, in DMC, bids were sufficiently high that it is rational for sellers to accept all bids in all cases. Out of 180 sets of decisions in DMC, 170 are rational; ten involve an irrational rejection of at least one bid.

A number of possible factors may account for the departures from rational play by buyers and sellers. Players may care about fairness in addition to monetary payoffs; they may make calculation errors; they may slowly learn about others' experimental play; they may manipulate their short-run play in a dynamic strategy to affect future outcomes, and so forth. A preference for fairness has some intuitive appeal as an explanation. For example, a preference for fairness on the part of sellers might explain why they reject 59 bids in the CMC treatment greater than

20: even though accepting would have increased sellers' monetary payoff, the bids may have been low enough to give them a small share of the payoff relative to the buyer. A preference for fairness on the part of buyers might explain why they bid more on average in the DMC treatment than the monetary-payoff-maximizing best responses, since the latter would leave the buyer with a disproportionate share of the surplus relative to the seller.

To investigate more formally the importance of fairness relative to the other factors, we estimate a structural fairness model. A variety of different theories of fairness have been proposed (see Fehr and Schmidt 2006 for a survey). Perhaps the most influential is Fehr and Schmidt's (1999) model of inequality aversion. Unfortunately, even though the Fehr-Schmidt model is relatively simple, it is still intractable to compute the equilibrium in our setting.<sup>9</sup> We proceed by estimating the model on sellers in isolation. Since sellers moves second in the stage game, conditional on the bids they receive, their behavior can be characterized as a simple discrete-choice problem.

Sellers must decide whether to accept or reject each of three bids, leading to a choice among  $2^3 = 8$  possible acceptance configurations. Seller  $i$ 's utility from choosing acceptance configuration  $k$  from among the eight possibilities, is

$$u_{ik} = x_{ik} - \frac{\alpha_i}{N-1} \sum_{j \neq i} \max(x_{jk} - x_{ik}, 0) - \frac{\beta_i}{N-1} \sum_{j \neq i} \max(x_{ik} - x_{jk}, 0) + \frac{\epsilon_{ik}}{\lambda}, \quad (4)$$

where  $x_{ik}$  is seller  $i$ 's monetary payoff from decision  $k$ ,  $\alpha_i$  measures the disutility from payoff disadvantages relative to the buyers (indexed by  $j$ ) from whom seller  $i$  receives bids,  $\beta_i$  measures the disutility from seller  $i$ 's payoff advantages relative to these buyers,  $\epsilon_{ik}$  is a logit error term,  $\lambda$  is a term scaling the precision of the error, and  $N$  is the number of players in the market (four in our experiments). Fehr and Schmidt's (1999) model is reproduced in the first three terms on the

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<sup>9</sup>In our setting, the seller may accept multiple offers and the total surplus function is potentially nonlinear. The sequential-move games for which Fehr and Schmidt (1999) explicitly derive equilibria all have the flavor of the simpler ultimatum game.

right-hand side of (4). Seller  $i$  enjoys a higher monetary payoff but dislikes inequality relative to its transacting partners. Including separate coefficients  $\alpha$  and  $\beta$  allows the disutility from earning less surplus than transacting partners to potentially differ from the disutility of earning more. The last term,  $\epsilon_{ik}/\lambda$ , has been appended to the Fehr-Schmidt model in the spirit of McKelvey and Palfrey's (1998) quantal response equilibrium. This last term allows for tractable estimation of the model. It captures any sort of deviation from seller rationality including computation errors and dynamic strategies to affect future play beyond the stage game. The smaller is  $\lambda$ , the more important are these other factors relative to fairness in explaining deviations from seller rationality.

Table 4 presents maximum-likelihood estimates of the  $\hat{\alpha}$ ,  $\hat{\beta}$ , and  $\hat{\lambda}$ , assuming parameters are constant in the population.<sup>10</sup> Focusing on the results for all treatments in part (b) of the table (using the last 30 rounds of data), estimates of both fairness parameters  $\hat{\alpha} = 0.068$  and  $\hat{\beta} = 0.133$  are positive, and  $\hat{\beta}$  is significantly different from zero. There is some instability among the fairness parameters across treatments:  $\hat{\beta}$  is significantly greater than zero for most subsamples, and  $\hat{\alpha}$  is significantly positive in DMC.<sup>11</sup>

These estimates thus provide some evidence that fairness plays a role in deviations by sellers from payoff maximization. However, analysis of the relative magnitudes of the estimated parameters suggests that the overall role of fairness is dwarfed by other factors. The error term  $\epsilon_{ik}/\lambda$ , which in our setting has the interpretation of deviations from rational play caused by factors beside fairness, has a standard deviation of  $\pi/\lambda\sqrt{6}$ . Substituting  $\hat{\lambda} = 0.130$ , this standard deviation equals 10. A standard deviation this high would be generated by adding noise in the

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<sup>10</sup>We also estimated (4) allowing  $\hat{\alpha}$  and  $\hat{\beta}$  to vary across the 18 different sellers. The procedure failed to converge or failed to generate an invertible covariance matrix for a number of the subsamples. For those that did (for example, the subsample of all treatments and the last 30 rounds), a likelihood ratio test strongly rejected the equality of parameters across sellers. The resulting  $\hat{\lambda}$  was quite close to that reported in Table 4, so the estimates in the table provide a view of the importance of fairness relative to other factors on average in the sample.

<sup>11</sup>The parameter instability across treatments indicates possible misspecification in the fairness model. Searching for the best-fitting among the large set of alternative fairness models is beyond the scope of this paper. We estimated several alternative models that produced a better fit than Fehr and Schmidt (1999), but the overall picture that fairness plays only a limited role in explaining deviations from rationality was unchanged.

form of an equal chance of adding or subtracting 10 points from each seller decision. A rise or fall of 10 payoff points dominates any estimated fairness effects. For example, considering the estimate  $\hat{\alpha} = 0.068$  (insignificantly different from zero, but we will still take the point estimate for the sake of this exercise), for the seller to be willing to give up 10 payoff points, each buyer's advantage over the seller would have to be reduced by over 146 points ( $146 \approx 10/\hat{\alpha}$ ). This is an order of magnitude greater than buyer-seller advantages observed on average in the data (18.1). Similarly, considering the estimate  $\hat{\beta} = 0.133$ , for the seller to be willing to give up 10 payoff points, each buyer's payoff would have to be increased 74 points to narrow their shortfall relative to the seller, over 2.5 times higher than seller-buyer advantages observed on average in the data (29.5).

Another way to gauge the relative importance of fairness versus other factors in explaining deviations from rationality is to look at the buyer side. Since sellers were selected randomly from the pool of subjects, we can assume that their fairness parameters are representative of the population, and thus that buyers share the same parameters.<sup>12</sup> We will see how much a buyer's best responses to others' experimental play changes if we alter the buyer's utility function to reflect this amount of fairness. The best response to others' experimental play for a buyer with fairness preferences can be computed following the same steps used to derive column (c) of Table 3 but substituting the new utility function. The resulting best responses are given in column (d). Including fairness in the utility function hardly changes the best responses from column (c). The greatest change is for small-buyer bids in IMC. Even there, the change of 1.4 points accounts for only 14 percent of the discrepancy between the payoff-maximizing best response of 54.8 in column (c) and the mean bid of 44.8 in column (a).

By this measure, at most 14 percent of players' (specifically buyers') deviation from rational play is accounted for by fairness. Indeed, the raw data itself suggests limits to how much fairness

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<sup>12</sup>Given the instability of parameters across treatments, it is quite possible that estimates of buyers' fairness parameters would differ from those in Table 4. However, the exercise of simulating buyer best responses with these fairness parameters still is a useful exercise to gauge the economic magnitudes of  $\hat{\alpha}$  and  $\hat{\beta}$ .

would emerge from any empirical model. As mentioned, only a minority of observations involve irrational play. Among these, fairness preferences do not seem to be consistent across treatments. Irrational seller play in IMC consists of accepting bids that a payoff-maximizer would reject, while in CMC it consists of rejecting profitable bids.

Some evidence on the contribution of other factors besides fairness to departures from rational play comes from examining the  $\hat{\lambda}$ . Restricting attention to the results for all treatments in Table 4, and comparing  $\hat{\lambda}$  in part (a) to that in part (b), we see a substantial increase in  $\lambda$  between the first and last 30 rounds, statistically significant at the one-percent level. This increase in  $\lambda$ , equivalent to a fall in the scaled error  $\epsilon_{ik}/\lambda$  in equation (4), suggests that factors causing departures from rational play other than fairness decline in importance as experimental play progresses. One explanation would be that sellers make fewer computation errors as they learn to play the game better over time. Another would be that as the end of the game draws nearer, there is less value in distorting stage-game play in order to gain a dynamic advantage. For example, in a model in which sellers' fairness parameters  $\alpha_i$  are private information, a seller might reject more offers than statically optimal in order to signal a high value of  $\alpha_i$  and raise buyer offers in future rounds. Such signaling would be less useful over time as buyers' posteriors on the distribution of fairness parameters become tighter and as the future horizon over which to earn a return from signaling shrinks. Since players were shuffled anonymously between markets, the benefit of such signaling or other dynamic strategies is considerably reduced; but such strategies remain a possibility.

Comparing the  $\hat{\lambda}$  across treatments, the lowest value is 0.076 for the DMC treatment in part (a) of the table, suggesting that factors other than fairness led to the biggest departures from seller rationality in early-round play of the DMC treatment compared to others. This pattern is consistent with computation errors. As suggested by the lengthy proof of Proposition 3, which applies to the DMC case, compared to relatively shorter proof of Proposition 2, which applies to the IMC and CMC cases, computations are more difficult for DMC than the other treatments, with few shortcuts to the brute force method of computing the payoff from all eight acceptance

configurations to ensure an optimal decision.<sup>13</sup> On the other hand, it is hard to see why dynamic strategies would be more important in the DMC treatment than others, although this possibility cannot be ruled out in the absence of a general dynamic theory.

Table 4 provides evidence on the dynamics of seller behavior. Evidence on the dynamics of buyer behavior is provided by Table 5, which reports a single random-effects regression of bids on lagged bids and lagged seller rejections. Each regressor is interacted with a dummy variable for the first 30 rounds of play (column (a)) and the last 30 rounds (column (b)), with the difference between these two reported in the final column. The coefficient on “bid last round played same treatment” falls significantly between the first and the second 30 rounds, whereas the coefficient on “bid last round played same treatment and size role” increases significantly. These opposite trends suggest that buyers learn the difference between markets and size roles over time, playing more consistently within them and differentiating their strategies across them. Buyers respond to rejections by increasing their bids. The response is sharpest for closely related past experience (same size role and treatment). For example, the coefficient of 0.134 in the last row of column (a) suggests that a rejection in the same size role and treatment leads to a 13.4 percent increase in a bid in the first 30 rounds of play. The buyer does respond to a rejection in the last round even for unrelated roles although less so. A comparison of column (b) with column (a) reveals that buyers respond less to rejections over time, a decline that is significant in two of the three cases. This reduced sensitivity suggests that they become more confident in their strategies and learn less from seller responses over time.

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<sup>13</sup>Among other shortcuts, in IMC and CMC, it is optimal for a payoff-maximizing seller to accept all bids if each exceeds the relevant marginal cost conditional on all others being accepted. This simple check does not suffice for DMC, as can be shown in the example in which one small buyer bids 80 and the other two buyers bid 4 per unit each.

## 5 Conclusion

An accumulation of results from theoretical bargaining models links the existence of buyer-size discounts to the curvature of the total surplus function over which the seller and buyers negotiate. In theory, large-buyer discounts emerge if the total surplus function is concave; there are no discounts if the total surplus function is linear, and a range of possible outcomes if it is convex. We test the theory in markets in which large and small buyers bargain simultaneously with a single seller. The markets differ in the curvature of the total surplus function. By varying the seller's marginal cost function, we obtain concave, linear, and convex surplus functions from increasing, constant, and decreasing marginal cost curves, respectively. Our results support the qualitative predictions of the theory. Large-buyer discounts are observed where predicted—in the treatment with the concave total surplus function—and only where predicted.

The main deviation from theory is that the levels of certain bids differ from the theoretical predictions. Structural estimates of a formal model of inequality aversion provide evidence that preferences for fairness lead to some deviations from payoff maximization in the stage game, but other factors including possibly computation errors or dynamic strategies in a repeated-game context seem to be more important.

Some implications for real-world industries can be drawn from our experimental results. According to our results, large-buyer discounts that stem from the bargaining theory we test should arise in industries in which the seller's cost function exhibits increasing marginal cost (i.e., decreasing returns). Empirical estimates of cost functions provide examples of decreasing returns, at least for large enough production levels, in residential water supply (Kim 1985), electricity generation (Pollitt 1995), electricity distribution (Kwoka 2005), trucking (Spady and Friedlaender 1978), and for some automobile manufacturers (Friedlaender, Winston, and Wang 1983). In industries with constant or increasing returns, alternative theories, including those discussed in the Introduction, may account for any observed large-buyer discounts.

## Appendix

**Proof of Proposition 1** Suppose  $v_i > \max_{\{Q \leq X\}} MC(Q)$  for all  $i \in B$ . Consider any outcome in which there are some buyers whose bids are not accepted by the seller; i.e.,  $B - A$ , the complement of  $A$  in  $B$ , is nonempty. Let  $i \in B - A$ . Buyer  $i$  earns zero profit in this outcome since its bid per unit,  $p_i$ , is rejected. If  $p_i > \max_{\{Q \leq X\}} MC(Q)$ , the seller's rejecting  $p_i$  cannot be subgame perfect. By accepting, the seller could increase its profit by

$$\begin{aligned} p_i x_i - IC\left(x_i, \sum_{j \in A} x_j\right) &= x_i \left[ p_i - \frac{1}{x_i} \sum_{k=1}^{x_i} MC\left(k + \sum_{j \in A} x_j\right) \right] \\ &> x_i \left[ p_i - \max_{\{Q \leq X\}} MC(Q) \right], \end{aligned}$$

which is positive by assumption.

Assume therefore that  $p_i \leq \max_{\{Q \leq X\}} MC(Q)$ . The buyer could raise so that it is in the interval  $(\max_{\{Q \leq X\}} MC(Q), v_i)$ . If the seller's strategy is subgame perfect, it would accept such a bid by the calculations in the previous paragraph. This bid would be profitable for the buyer since it is strictly less than  $v_i$ . *Q.E.D.*

**Proof of Proposition 2** Assume

$$MC(Q) \geq MC(Q - 1) \quad \text{for all } Q \in \{1, 2, \dots, X\}. \quad (\text{A1})$$

To prove necessity, consider a set of buyer bids  $\{p_i | i \in B\}$  forming a pure-strategy, subgame-perfect equilibrium in which all buyers are served. If the seller deviates by rejecting buyer  $i$ 's bid, its profit falls by

$$p_i x_i + C(X - x_i) - C(X) = x_i [p_i - AIC(x_i, X - x_i)].$$

For this deviation to be unprofitable,  $p_i \geq AIC(x_i, X - x_i)$ . An argument similar to the proof of Proposition 1 shows that  $p_i \leq AIC(x_i, X - x_i)$  or else buyer  $i$  could deviate by lowering its price and be assured that this bid is still accepted. Combining these two inequalities yields  $p_i = AIC(x_i, X - x_i)$ . Finally, for buyer  $i$  not to deviate by dropping out of the market (equivalently, bidding  $p_i = 0$ ),  $p_i \leq v_i$ . This proves (2) must necessarily hold in a pure-strategy, subgame-perfect equilibrium in which all buyers are served.

To prove sufficiency, suppose  $AIC(x_i, X - x_i) \leq v_i$  for all  $i \in B$ . Consider the proposed equilibrium in which buyer  $i$  bids  $p_i = AIC(x_i, X - x_i)$  for all  $i \in B$  and the seller accepts the set of bids giving it the highest profit (in case of ties, assume the seller accepts the largest set of such bids). We will argue that this proposed equilibrium is subgame perfect, and the seller serves all the buyers. It is tautological that the seller's strategy is part of a subgame-perfect equilibrium. There remain two claims to be proved: first, that buyers have no incentive to deviate given the seller's strategy and second that the players' strategies lead all buyers to be served. We will prove



these claims in reverse order.

To show the seller's strategy leads it to accept all bids, we have to show that the seller cannot gain from rejecting a subset  $S \subseteq B$  of them. The change in the seller's profit from so doing is

$$\begin{aligned} IC\left(\sum_{i \in S} x_i, X - \sum_{i \in S} x_i\right) - \sum_{i \in S} p_i x_i &\leq \sum_{i \in S} IC(x_i, X - x_i) - \sum_{i \in S} p_i x_i \\ &= \sum_{i \in S} x_i [AIC(x_i, X - x_i) - p_i]. \end{aligned}$$

The first line holds by (A1). The second line holds by algebraic manipulation. The last expression is zero since  $p_i = AIC(x_i, X - x_i)$ .

To show the buyers have no incentive to deviate given the seller's strategy, note first that buyers have no incentive to raise bids because they are all accepted in equilibrium. Buyer  $i$  has no incentive to lower its bid since this would lead the seller to reject it by the argument in the second paragraph above. *Q.E.D.*

**Proof of Proposition 3** Assume marginal costs are strictly decreasing, i.e.,

$$MC(Q) < MC(Q - 1) \text{ for all } Q \in \{1, 2, \dots, X\}. \quad (\text{A2})$$

To prove necessity of the conditions in Proposition 3, consider a set of buyer bids  $\{p_i | i \in B\}$  forming a pure-strategy, subgame-perfect equilibrium in which all buyers are served. As argued in the proof of Proposition 2,  $p_i \leq v_i$  is a necessary condition. We then need to show that the two inequalities in (3) are necessary conditions. The seller can deviate by rejecting a subset  $S \subseteq B$  of buyer bids. For this deviation to be weakly unprofitable,

$$IC\left(\sum_{i \in S} x_i, X - \sum_{i \in S} x_i\right) \leq \sum_{i \in S} p_i x_i. \quad (\text{A3})$$

Thus, the first inequality in (3) is a necessary condition.

To prove that the second inequality in (3) is also necessary, we will proceed in several steps. The first step is to show that the seller makes zero profit in a subgame-perfect equilibrium in which all buyers are served. Suppose to the contrary  $\sum_{i \in B} p_i x_i - C(X) > 0$ . Let  $p_i = \max\{p_j | j \in B\}$ . Then this highest-bidding buyer  $i$  can deviate to a lower bid  $p_i - \epsilon$ , where

$$\epsilon = \frac{1}{2} \min \left\{ \frac{1}{x_i} \left[ \sum_{j \in B - \{i\}} p_j x_j - C(X) \right], \{MC(Q - 1) - MC(Q) | Q = 1, 2, \dots, X\} \right\} \quad (\text{A4})$$

and still have it accepted. To see this, let  $S'$  be the set of buyers whose bids are accepted after the deviation by  $i$ . The definition of  $\epsilon$  in (A4), in particular that  $\epsilon < [\sum_{j \in B - \{i\}} p_j x_j - C(X)]/x_i$ , implies that the seller continues to make strictly positive profit if it continues to accept all buyer bids. Hence  $S'$  is nonempty. If  $i \in S'$ , then  $i$ 's deviating bid is accepted and we are done. If

$i \notin S'$ , then for all  $j \in S'$ ,

$$p_i - \epsilon \geq p_j - \epsilon \quad (\text{A5})$$

$$\geq AIC\left(x_j, \sum_{k \in S'} x_k - x_j\right) - \epsilon \quad (\text{A6})$$

$$> AIC\left(x_i, \sum_{k \in S'} x_k\right). \quad (\text{A7})$$

Condition (A5) holds since  $p_i$  is the weakly highest bid. Condition (A6) holds since  $j \in S'$ , so accepting  $p_j$  must give the seller a nonnegative profit at the margin. Condition (A7) holds since

$$\epsilon < MC\left(\sum_{k \in S'} x_k\right) - MC\left(1 + \sum_{k \in S'} x_k\right) \quad (\text{A8})$$

$$\leq AIC\left(x_j, \sum_{k \in S'} x_k - x_j\right) - AIC\left(x_i, \sum_{j \in S'} x_j\right). \quad (\text{A9})$$

Condition (A8) holds by (A4). Condition (A9) holds because the average incremental cost of producing a bundle is weakly less than the marginal cost of the first unit in the bundle and weakly more than the last unit in the bundle by (A2). We have thus shown that  $i$ 's deviating price exceeds the expression in (A7). But then the seller would gain from accepting buyer  $i$ 's bid in addition to the bids in  $S'$ . Hence buyer  $i$ 's deviating bid is profitable since it would be accepted. We have thus established that the seller earns zero profit in a pure-strategy, subgame-perfect equilibrium in which all buyers are served.

Combining the fact that  $\sum_{i \in B} p_i x_i = C(X)$  with the fact that (A3) must hold for the set  $B - S$ , we have

$$\sum_{i \in S} p_i x_i \leq C\left(\sum_{i \in S} x_i\right).$$

Thus, the second inequality in (3) is a necessary condition for a pure-strategy, subgame-perfect equilibrium in which all buyers are served.

To show sufficiency, consider a proposed equilibrium in which buyers bids are  $\{p_i | i \in B\}$  satisfying  $p_i \leq v_i$  and condition (3) and in which the seller accepts the subset of bids giving it the highest profit (in case of ties, assume the seller accepts the largest set of such bids). We will argue that the proposed equilibrium is subgame perfect, and the seller serves all the buyers. It is tautological that the seller's strategy is part of a subgame-perfect equilibrium. There remain two claims to be proved: first, that buyers have no incentive to deviate given the seller's strategy and second that the player's strategies lead all buyers to be served. We will prove these claims in reverse order. To show the seller's strategy leads it to accept all bids, we have to show that the seller cannot gain from rejecting a subset  $S \subseteq B$  of them. But this is ensured by the first inequality in (3). To show that the buyers have no incentive to deviate given the seller's strategy, note first that buyers have no incentive to raise bids since they are all accepted in equilibrium.

If buyer  $i$  deviates to a lower price  $p'_i < p_i$ , for any subset of buyers  $S$  including  $i$ ,

$$\begin{aligned} p'_i x_i + \sum_{j \in S - \{i\}} p_j x_j &< \sum_{i \in S} p_i x_i \\ &\leq C \left( \sum_{i \in S} x_i \right). \end{aligned}$$

The first line holds since  $p'_i < p_i$  and the second by the second inequality of condition (3). Therefore, it is better for the seller to reject all bids (giving it zero profit) rather than accepting the bids in  $S$ . Since this is true for all  $S$  containing  $i$ , the deviating buyer's bid would be rejected, and so his deviation would be unprofitable. In sum, no buyer deviation would be accepted by the seller, establishing sufficiency. *Q.E.D.*

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Table 1: Descriptive Statistics for Buyer Bids

	(a) All Rounds				(b) Last 30 Rounds			
	Mean	Median	Std. Dev.	Obs.	Mean	Median	Std. Dev.	Obs.
All Bids								
IMC Large Buyer	39.8	40.0	11.4	360	39.5	40.0	10.1	180
IMC Small Buyer	43.4	42.0	11.9	720	44.8	45.0	9.9	360
CMC Large Buyer	34.1	35.0	10.4	360	34.6	35.0	10.0	180
CMC Small Buyer	34.7	35.0	10.1	720	34.5	35.0	8.8	360
DMC Large Buyer	41.7	40.0	13.6	360	40.9	40.0	11.7	180
DMC Small Buyer	42.0	40.0	13.8	720	40.2	40.0	12.1	360
Accepted Bids								
IMC Large Buyer	41.7	40.0	10.4	316	41.1	40.0	8.9	162
IMC Small Buyer	47.6	50.0	10.8	436	48.0	49.0	9.4	217
CMC Large Buyer	35.9	35.0	9.8	298	36.3	35.0	9.4	149
CMC Small Buyer	35.9	35.0	10.2	617	35.3	35.0	8.7	325
DMC Large Buyer	42.4	40.0	13.5	340	41.1	40.0	11.7	177
DMC Small Buyer	42.7	40.0	13.7	673	40.5	40.0	12.1	347

Table 2: Buyer-Bid Regressions

	All Buyer Bids		Accepted Buyer Bids	
	All Rounds (a)	Last 30 Rounds (b)	All Rounds (c)	Last 30 Rounds (d)
Constant	34.60*** (1.22)	35.02*** (1.14)	35.45*** (1.22)	35.52*** (1.12)
<i>IMC</i>	8.73*** (1.32)	9.31*** (1.17)	10.96*** (1.39)	10.53*** (1.29)
<i>DMC</i>	7.69*** (1.72)	5.69*** (1.56)	7.24*** (1.74)	5.40*** (1.52)
<i>IMC</i> × <i>LARGE</i>	-3.62*** (0.88)	-4.84*** (0.93)	-5.55*** (1.09)	-5.81*** (1.09)
<i>CMC</i> × <i>LARGE</i>	-0.08 (0.71)	-0.86 (0.69)	0.37 (0.75)	-0.33 (0.72)
<i>DMC</i> × <i>LARGE</i>	-1.11 (1.04)	-0.44 (0.90)	-0.83 (1.01)	-0.54 (0.90)
<i>N</i>	3,240	1,620	2,680	1,377
<i>R</i> <sup>2</sup>	0.09	0.12	0.11	0.14

Notes: Omitted treatment dummy is *CMC*, so coefficients on *IMC* and *DMC* reflect the difference between small-buyer bids in these treatments and the *CMC* treatment. All columns are random-effects regressions accounting for random buyer effects. Standard errors reported in parentheses below coefficient estimates are heteroskedasticity-robust (following White 1980) and are clustered by buyer. Coefficient significantly different from zero in a two-tailed test at the \*\*\* one-percent level, \*\* five-percent level, \* ten-percent level. *N* is the number of observations.

Table 3: Comparison of Observed, Predicted, and Experimental-Best-Response Bids

	Mean Bid (a)	Theoretical Prediction (b)	Best Response to Others' Experimental Behavior	
			Monetary Payoffs (c)	Utility with Fairness (d)
IMC Large Buyer	39.5	37.0	37.0	36.9
IMC Small Buyer	44.8	60.0	54.8	53.4
CMC Large Buyer	34.6	20.0	36.8	37.6
CMC Small Buyer	34.5	20.0	33.3	34.2
DMC Large Buyer	40.9	*	25.5	26.3
DMC Small Buyer	40.2	*	18.6	19.9

Notes: Entries in columns (a), (c), and (d) based on data from last 30 rounds of play. Column (a) is taken from Table 1. Column (b) is based on Figure 3. Column (c) is based on Figure 5. Column (d) computed multiplying acceptance probabilities from Figure 4 by the utility function incorporating fairness using the parameters from part (b) of Table 4. \*Theoretical prediction is not unique; can be any number in the interval  $[2.5, 37.5]$  with four unit bids averaging 20.



Table 4: Structural Model of Seller Fairness

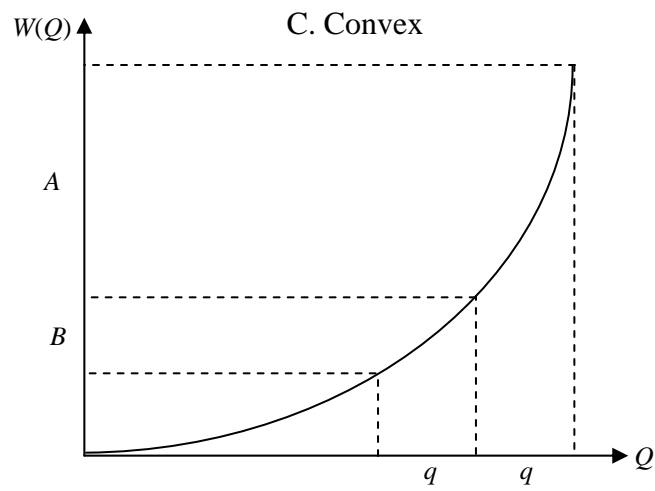
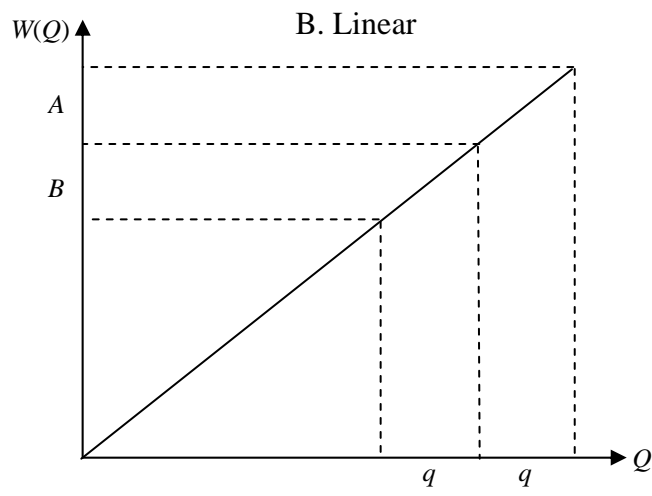
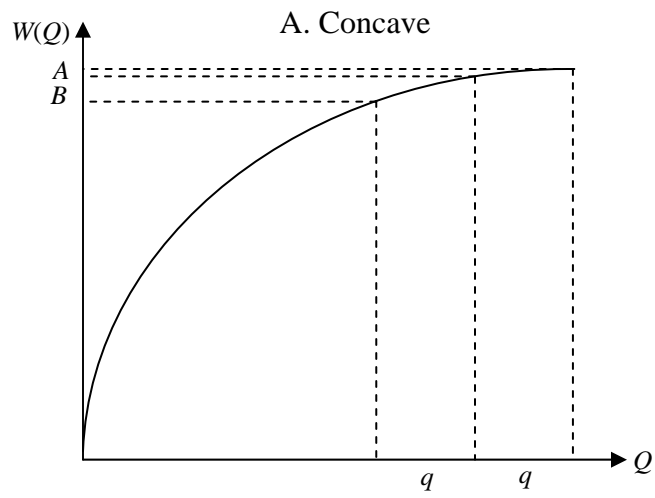
	$\hat{\alpha}$	$\hat{\beta}$	$\hat{\lambda}$	$N$
(a) All Rounds				
All Treatments	0.054 (0.066)	0.135*** (0.068)	0.098*** (0.008)	1,080
IMC Treatment	0.022 (0.080)	0.098 (0.068)	0.132*** (0.019)	360
CMC Treatment	0.035 (0.087)	0.549*** (0.169)	0.098*** (0.010)	360
DMC Treatment	0.223*** (0.073)	0.399* (0.211)	0.076*** (0.007)	360
(b) Last 30 Rounds				
All Treatments	0.068 (0.079)	0.133** (0.060)	0.130*** (0.015)	540
IMC Treatment	0.013 (0.074)	0.161*** (0.054)	0.197*** (0.041)	180
CMC Treatment	0.086 (0.095)	1.028*** (0.271)	0.100*** (0.010)	180
DMC Treatment	0.220** (0.110)	-0.411 (0.292)	0.106*** (0.014)	180

Notes: Maximum likelihood estimates of the parameters in equation (4).  $N$  is the number of seller-round observations. Standard errors reported in parentheses below coefficient estimates are heteroskedasticity-robust (following White 1980) and are clustered by seller. Coefficient significantly different from zero in a two-tailed test at the \*\*\* one-percent level, \*\* five-percent level, \* ten-percent level.

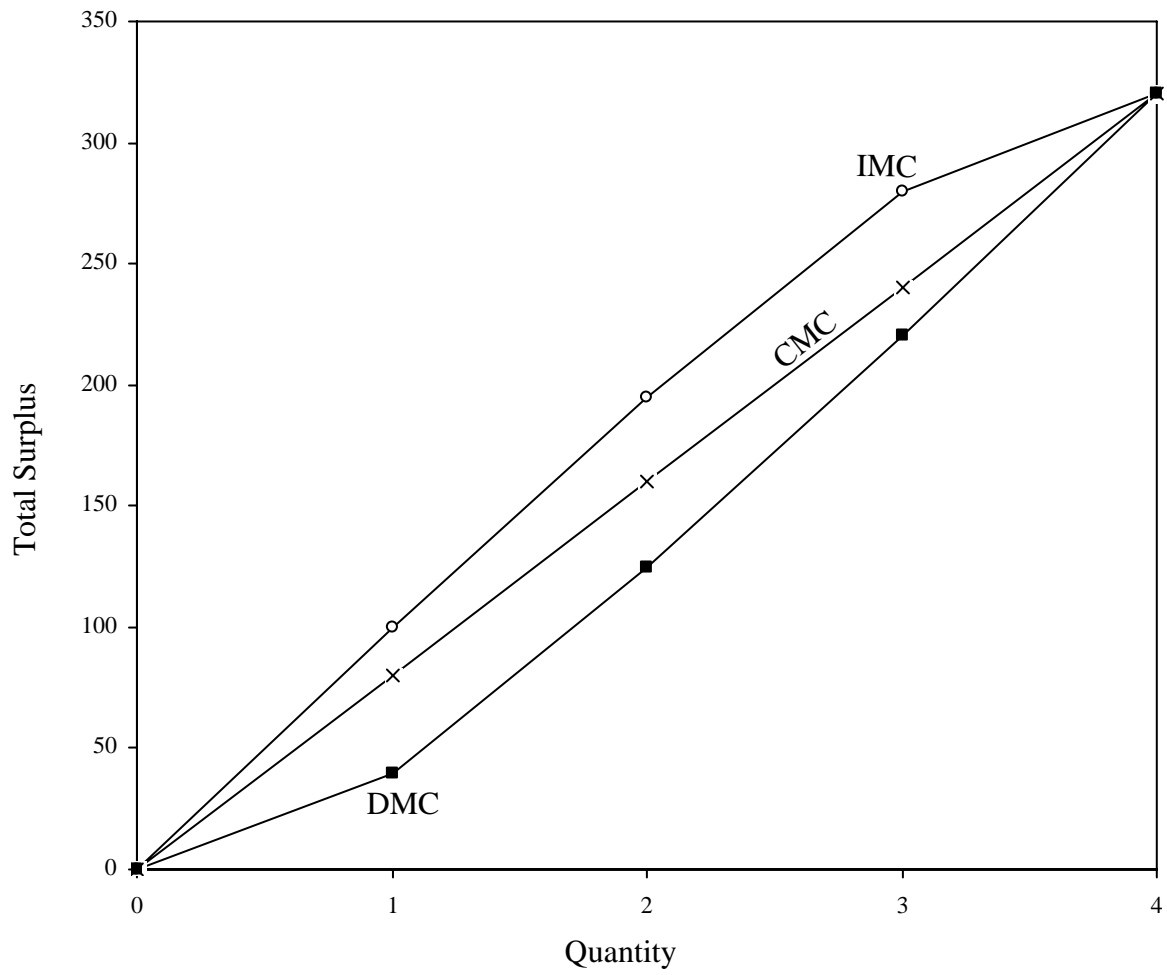
Table 5: Buyer-Bid Dynamics

	Interactions with Dummy for First 30 Rounds (a)	Interactions with Dummy for Last 30 Rounds (b)	(b) – (a)
Constant	0.290*** (0.101)	0.120*** (0.039)	-0.170* (0.094)
Bid Last Round	0.082*** (0.032)	0.063*** (0.018)	-0.019 (0.022)
Bid Last Round Played Same Treatment	0.367*** (0.055)	0.191*** (0.048)	-0.177*** (0.064)
Bid Last Round Played Same Treatment and Size Role	0.458*** (0.060)	0.710*** (0.045)	0.251*** (0.065)
Rejection Last Round	0.063*** (0.018)	0.028*** (0.011)	-0.035* (0.019)
Rejection Last Round Played Same Treatment	0.026 (0.023)	-0.001 (0.018)	-0.027 (0.026)
Rejection Last Round Played Same Treatment and Size Role	0.134*** (0.022)	0.087*** (0.012)	-0.047*** (0.026)

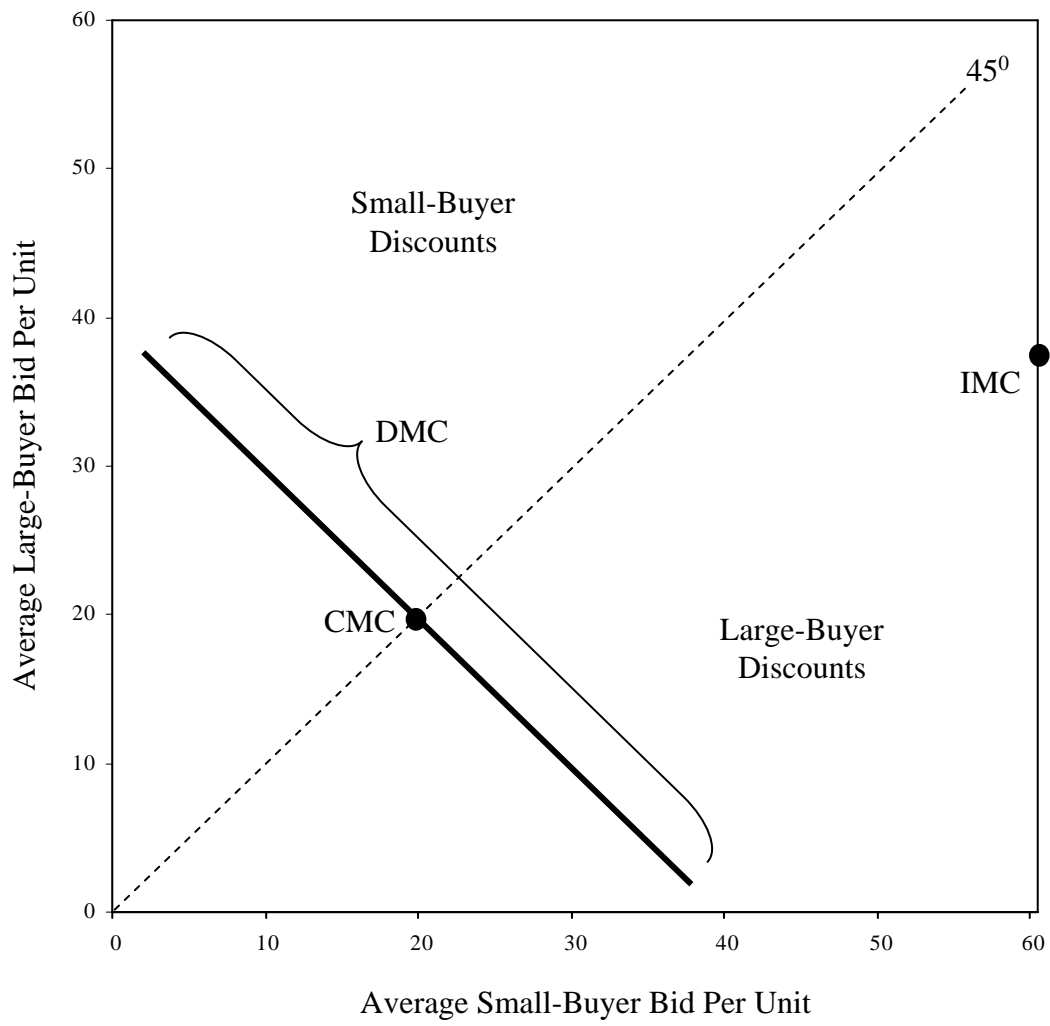
Notes: Results from a single random-effects regression with 2,916 observations (324 observations lost in formation of lagged variables) in which dependent variable is the natural logarithm of the buyer's bid. Overall  $R^2$  is 0.78. The three regressors involving lagged bids entered as natural logarithms; the three involving lagged seller rejections are dummy variables. Standard errors reported in parentheses below coefficient estimates are heteroskedasticity-robust (following White 1980) and are clustered by buyer. Coefficient significantly different from zero in a two-tailed test at the \*\*\*one-percent level, \*\*five-percent level, \*ten-percent level.



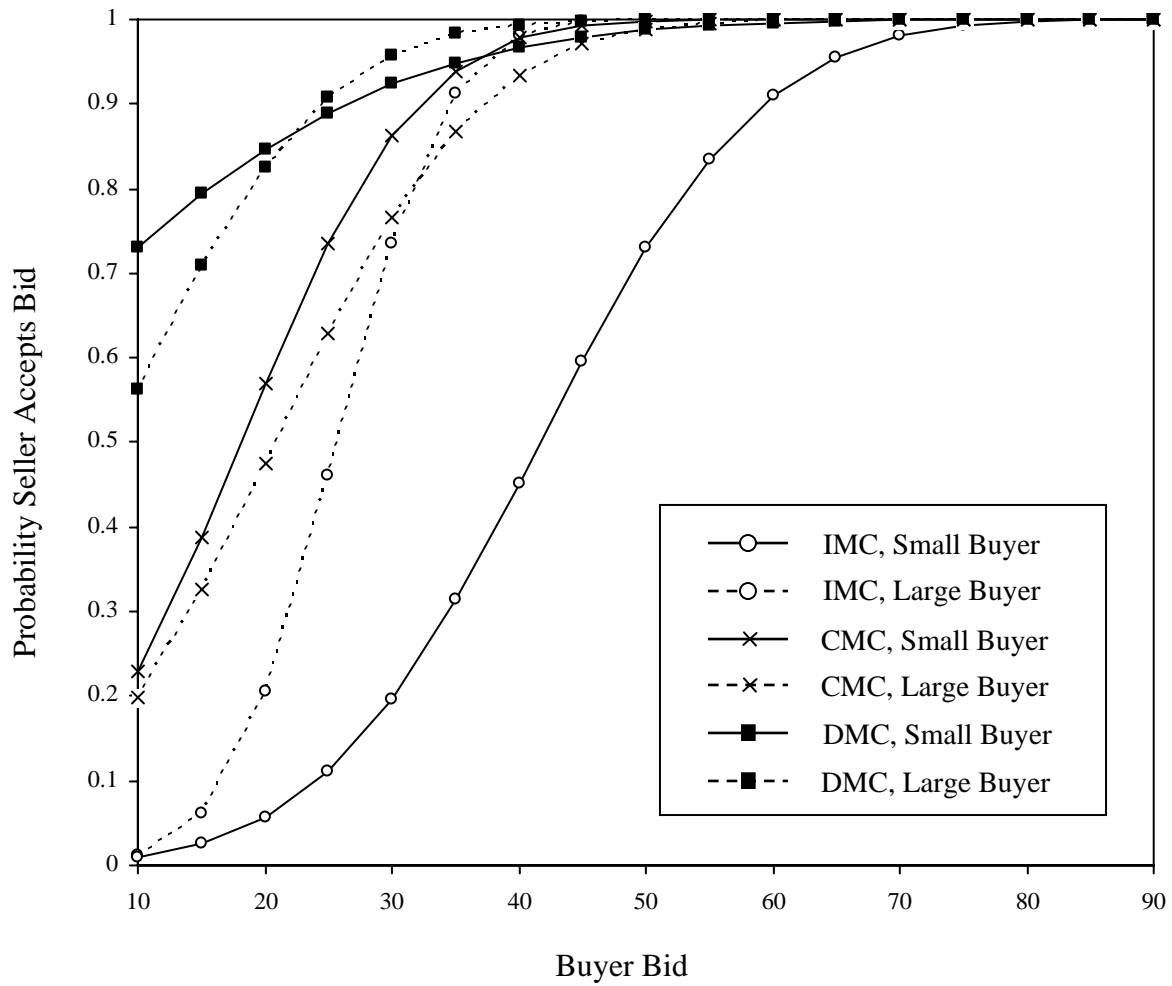
**Figure 1: Total Surplus Functions with Different Curvatures**



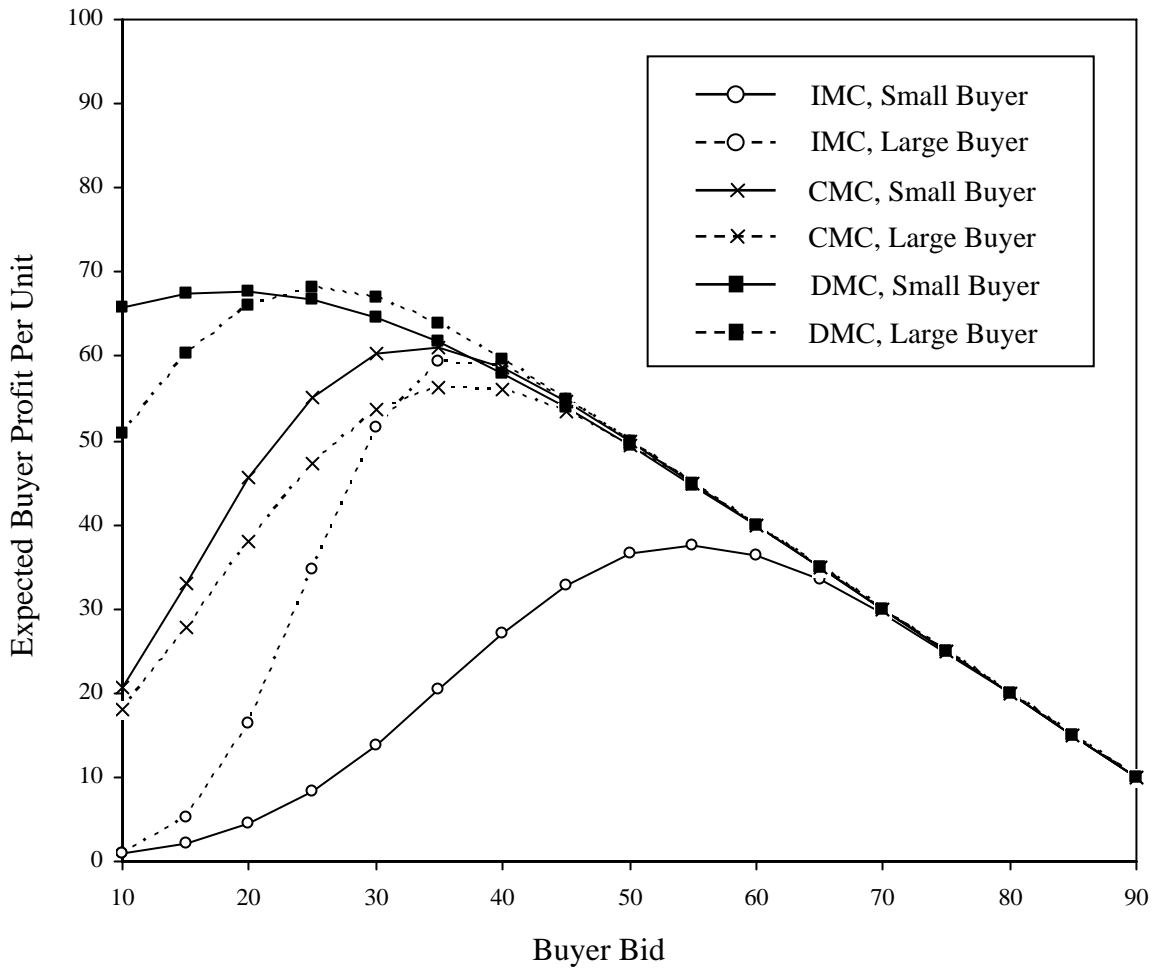
**Figure 2: Total Surplus Functions in Different Treatments**



**Figure 3: Equilibria for Experimental Parameters**



**Figure 4: Seller Acceptance Decision from Probit Estimates (Last 30 Rounds)**



**Figure 5: Optimal Buyer Bid Given Others' Experimental Behavior (Last 30 Rounds)**