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Which performs better under a trader setting, double auction or uniform price auction?

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Abstract

A marketable permit system (MPS) has been suggested as solutions to environmental problems. Whereas properties of MPSs in non-trader settings (each player becomes either a seller or a buyer) are well-documented, little is explored about how MPSs perform in trader settings (each player can be both a seller and a buyer). We instituted two auctions of trader settings in MPS experiments: double auction (DA) and uniform price auction (UPA), obtaining the following results: UPAs are more efficient and generate more stable prices than DAs; UPAs induce subjects to more truthfully reveal information about abatement costs for emissions; and a considerable proportion of trades in DAs consist of speculation. Thus, UPAs are likely to work better than DAs in trader settings.

Key words: Marketable permits; economic experiments; double auction; uniform price auction; trader settings.

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1 Introduction

There have been many debates about the effectiveness of a marketable permit system (MPS) for environmental problems. Economists have long sought to address the advantages and disadvantages of such a system (Goeree et al., 2010, Hahn, 1989, Hahn and Stavins, 2011, Tietenberg, 2006), and they appear to reach a consensus on the following advantages provided by MPSs: (i) efficiency or least cost property, (ii) incentive to innovate and (iii) information requirements for efficiency (Field and Field, 2006, Kolstad, 2010).[1] Previous studies have examined which trading rules and institutions work best in MPS controlled laboratory experiments.[2] The literature has demonstrated that there are two important factors for the experimental design: (i) the choice of auction mechanisms and (ii) trader or non-trader settings. The first factor is concerned with how the price determination mechanism is organized in the permit market. In this paper, we focus on the performance of double auctions (DAs) and uniform price auctions (UPAs).

The DA mechanism is known to perform well under general settings and has been extensively applied in economic experiments (see, e.g., Cason, 2010, Van Boeing and Wilcox, 1996). The DA is a real-time trading institution in which agents can submit bids to buy and offers to sell for permits; the agents can accept the best bid and offer made by other agents at any time during a trading period of several minutes.[3] Therefore, a DA gives flexibility for agents to trade. In contrast, a UPA is considered simpler than a DA because all of the permit trades are made with a uniform price.[4] First, a buyer is asked to submit "bids to buy" for each unit of additional permits, and a seller is asked to submit "offers to sell" for each unit of permits he has. Typically, subjects exclusively play the role of either a buyer or a seller. After all of the agents submit bids to buy and offers to sell, a central authority collects and ranks all of the bids to buy from high to low (i.e., a demand curve), and all of the offers to sell from low to high (i.e., a supply curve), and finally determines the intersection of the demand and supply curves. More precisely, this intersection occurs at the last unit in which the bid to buy exceeds the offer to sell, and the uniform price is the average between the two.

The difference for the second factor of trader or non-trader settings is whether each agent in

[1]More specifically, it is generally argued that (i) an MPS achieves efficiency in the sense that pollution reduction takes place in the lowest cost manner, and (ii) an MPS provides firms with stronger incentives to innovate abatement technology because such innovative firms are likely to gain more from trading permits, compared with less innovative firms. Most importantly, (iii) the aforementioned events can be supported even when the government does not know any information about the firms' abatement technologies. In an MPS, the government must determine the total number of permits to be distributed to an industry and the initial allocation for each firm. The firms are allowed to trade permits under the assumption that the trading rules for marketable permits function well. Therefore, the regulatory burden may be less than that for other types of pollution controls such as environmental tax.

[2]See Muller and Mestelman (1998) and Cason (2010) for an extensive literature review.

[3]See Davis and Holt (1992) for details about DAs.

[4]A UPA is also known as a call market. See Davis and Holt (1992) for further information.

a permit market can be both a seller and a buyer during trading periods or whether each agent can only be one or the other. If the agents can take on both roles, we call the environment a "trader setting," otherwise the environment is referred to as a "non-trader setting" (see Ledyard and Szakaly-Moore, 1994). Reflecting on the history of MPSs, a trader setting is closer to reality. However, there are many experimental works that employ non-trader settings because such settings simplify the experimental procedures and reduce the decision complexity of agents.

A majority of the previous works have used DAs for the experimental study of MPSs. In particular, Kilkenny (2000), Plott (1983) and Cason et al. (2003) use DAs under non-trader settings and report that the average efficiency observed in the experiments is approximately 98%. DAs under non-trader settings promise further simplicity of decision making processes for agents in experiments and relief from administrative burdens compared to DAs under trader settings. These MPS results of DAs under non-trader settings are consistent with the high efficiency achieved under DAs in general auction studies, such as those by Williams (1980) and Plott and Gray (1990).

Another group of studies including those by Godby et al. (1997), Ledyard and Szakaly-Moore (1994), Muller et al. (2002) and Cason and Gangadharan (2006) have used DAs under trader settings. These experiments demonstrate that observed efficiencies, which range between 60% and 98%, can exhibit higher variation and be lower on average than those obtained in DA experiments under non-trader settings. Furthermore, these works report that the observed prices of permits could be unstable. In summary, DAs under trader settings are more likely to generate lower efficiencies and less stable price dynamics than DAs under non-trader settings. Some economists conjecture that agents are given more opportunities for speculative trades for permits under trader settings, which may be the reason for the results, although no one has demonstrated the corresponding evidence for the existence of speculative trades (see, e.g., Ledyard and Szakaly-Moore, 1994).[5]

Although DA experiments are generally established to provide good performance with respect to efficiency, Cason and Plott (1996) and Cason and Gangadharan (2005) conducted an experiment with UPAs under non-trader settings as a possible alternative. These studies confirm that UPAs are efficient in an MPS, and induce true revelations of abatement cost schedules for pollution through observed bids to buy and offers to sell in the experiments. The studies also find that price dynamics are stable and more responsive to changes in the market structures during the experiment, which follow economic theory.

In summary, the literature on MPS mostly employs DAs and establishes that the institution achieves high efficiency for pollution reduction under non-trader settings. However, efficiencies and prices in DAs under trader settings could be lower and less stable than those under non-trader

[5]We will demonstrate evidence of speculative trades in DAs under trader settings. This is one of the novelties in this paper.

settings (Cason, 2010, Muller and Mestelman, 1998). For instance, Anderson and Sutinen (2005) clearly demonstrate an event of "bubbles" in the laboratory experiments of tradable fishing allowances with DAs under trader settings, and Muller and Mestelman (1998), Smith et al. (1982) and Cason et al. (1999) also state a necessity of exploring an alternative auction mechanism that can work better than DAs. However, no previous works show the existence of other auction mechanisms that could work better than DAs in a trader setting.[6] This comparison is critical in exploring the possible application of MPSs to the real world because players in the MPS participate as traders in reality and it is reported to have some possibility of speculative trades in DAs under trader settings, which may lead to deviation from equilibrium prices and efficiency losses (Cason et al., 1999).

Given the necessity of developing a better mechanism than DAs in a trader setting, we design and implement UPA experiments as a possible alternative. The motivation comes from our intuition that follows. First, many subjects in the DAs can repeatedly buy and sell permits in a single trading period just for arbitrage as a "trader," whereas the opportunity of resell and redemption is simply unavailable in the UPAs. This type of additional speculative activities available in DAs appears to generate noise in the market performance. Therefore, we hypothesize that a feature of real-time trading in DAs, particularly under a trader setting, may be a cause of different performances compared with the UPAs.

To directly compare the two auctions, UPA and DA experiments are carried out employing the same environment and controls except for the auction rules. Our study's novelty lies in the design of the UPA experiments under trader settings in which each subject is asked to simultaneously submit "bids to buy" for each additional unit he may purchase as well as "offers to sell" for each unit of permits he has in each trading period. More precisely, each subject is required to determine both "bids to buy" and "offers to sell," and to submit them to the central authority simultaneously. In this manner, the UPA can be considered a trader setting because each subject does not know in advance whether he will be a buyer or a seller, and the subject could be both, depending on the bidding and offering strategy as well as the announced uniform price. To the best of our knowledge, this study is the first to design and implement a UPA for marketable permits in a trader setting and to make a direct comparison with the performance of a DA on the same grounds.

[6]Smith et al. (1982) establish that DAs work slightly better than UPAs in the non-trader settings of various environments. Anderson and Sutinen (2006) implemented laboratory experiments of tradable fishing allowance markets employing UPA and DA. However, their UPA is a "continuous uniform double auction," which is fundamentally different from the UPA we use in our experiment. Our UPA is a sealed-bid uniform price auction, which is the same as the one adopted in Smith et al. (1982) and Cason and Plott (1996) except that we use trader settings. In addition, Anderson and Sutinen (2006) focus on the price discovery of fishing allowance markets, and thus use different experimental parameters for UPAs and DAs. The direct comparison between the two auctions cannot be made on the same ground, which is noted by the authors as well. In finance, Van Boening et al. (1993) compare the price dynamics under DA and UPA showing that UPA institution reduces price bubbles.

Our experiments yield the following novel results: (1) UPAs are more efficient than DAs in a trader setting, which is in sharp contrast with the established results in non-trader settings; (2) UPAs generate more stable price dynamics; (3) UPAs induces subjects to more truthfully reveal information about abatement costs for emissions; and (4) a considerable proportion of the total trades in DAs consist of speculative trades that decrease its performance. With these results, we conclude that UPAs are likely to work better than DAs in a trader setting. Our results appear to be contradictory with earlier experimental MPS studies that consistently apply DAs. However, many previous works have not considered UPAs for comparison, except Smith et al. (1982).

UPAs attract less attention in MPS studies of trader settings, although the UPAs are often employed for the real world trades such as in Tokyo Commodity Exchange. Our results shed light on effectiveness of UPAs for MPSs, noting that a primary objective of MPSs is to achieve efficiency for pollution reduction. On the other hand, based on our observations for DA experiments, we realize that subjects often trade permits without considering their underlying cost and value, which we call "speculative trades." We demonstrate that a considerable proportion of the total trades consist of such speculation that leads to efficiency losses and unstable price dynamics in DAs under trader settings, which has never been illustrated in any previous literature. This "speculative" result can be considered consistent with the arguments made by Shiller (1981, 2005) and Smith et al. (1988). That is, if individuals' trading behavior is more dependent on their expectation of the rate of return rather than the underlying value of assets or stocks, then the corresponding price and market dynamics can be very volatile.

2 Experimental design

2.1 Experimental procedure

The economic experiment was carried out in the computerized experimental laboratory of Yokohama National University and International University of Japan using Z-tree programs (see Fischbacher, 2007, for further information on Z-tree programs). The experiment comprised 12 sessions each involving eight subjects for a total of 96 subjects. Furthermore, each session comprised 10 decision-making periods. The subjects were volunteer undergraduate and graduate students in various fields other than economics; they participated in only one session and were paid an average of \$30 based on cumulative earnings. One session took approximately 1.5 hour, and each session consists of two parts; In the first part, practice rounds were implemented for the subjects to ensure their understanding of the experiments. In the second part, actual rounds took place. The subjects' earnings were the sum of their earnings from the actual rounds.

The subjects participated in 10 experimental periods, which were unknown to them.[7] At the beginning of each session, eight subjects were asked to read instructions and listen to an oral presentation made by an experimenter. For instructions and the oral presentation, we consistently used neutral terminologies in describing the experimental procedures, such as the rules of trading. For instance, emission permits were referred to as "coupons," and marginal abatement costs were simply "production costs," following the wordings used in Cason and Gangadharan (2006).

[Table 1 about here.]

[Figure 1 about here.]

[Figure 2 about here.]

Each subject was assigned to one type of marginal abatement costs (MACs) for 10 units of pollution and initial permit endowments where there are four types of MACs, denoted as $\{T1, T2, T3, T4\}$, and each MAC type has the corresponding initial endowments (See table 1 and figure 1). Once each subject is allocated to one type of MACs, it does not change throughout the session. Two subjects were allocated to each type. Therefore, 32 permits were distributed to the subjects as a fixed supply in the permit market, and the corresponding demand for permits was derived from the avoided abatement costs. Given this cost structures, the aggregate supply (total permits supplied) and aggregate demand for pollution (derived from avoided marginal abatement costs) are displayed in figure 2(a) where the equilibrium price ranges between 88 and 91. The corresponding aggregate supply and demand for permits are shown in figure 2(b). Figure 2(b) also shows that there must be at least 12 trades for social efficiency.

2.2 Treatments

Two treatments were prepared: (i) DA and (ii) UPA. We conducted six sessions for each treatment with the cost structures introduced in table 1. Regarding DAs, we strictly followed the basic design and procedure used by Ledyard and Szakaly-Moore (1994) and Cason and Gangadharan (2006) where trader settings were employed throughout their experiments. However, we did not incorporate several additional factors considered in these studies, such as market power, imperfect enforcement, uncertainty and banking. Because our focus is on the most fundamental properties of efficiency, price dynamics, and cost revelation under the most basic DA, and on the comparison with the UPA.

The basic design and procedure used to implement UPAs in this study followed those used by Cason and Plott (1996) except for the trader settings. Recall that this study employs trader

[7] This feature is adopted to avoid "end effects," following Cason and Gangadharan (2006).

settings, whereas Cason and Plott (1996) used non-trader settings. Each participant in the UPAs under trader settings was asked to submit a bid to buy, with which he would be willing to purchase each additional unit of permits and an offer to sell, with which he would be willing to sell each unit of permits he holds. In other words, they are asked to submit both bids to buy and offers to sell simultaneously in a single experimental period, and each subject could be a buyer or a seller, depending on the uniform price announced by the central authority. With the uniform price, each subject traded permits, and a final payoff for the period was automatically calculated in the computer display. When a subject has some permits, he does not need to incur the cost for the units of production covered by the permits, otherwise he would incur.

[Table 2 about here.]

Table 2 provides an illustrating example of the terminal display of the computer for each subject that corresponds to the case of a T1 firm. As shown in table 2, when a subject is assigned to a T1 firm, the induced cost schedule for abatement and two permits of the initial endowment are given to that subject, which should be consistent with the information provided in table 1. The subject is asked to consider how he makes bids to buy for additional units of permits and offers to sell for the permits he holds. As mentioned previously, because our experiment employs a trader setting, we ask each participant to submit both of bids to buy and offers to sell simultaneously; therefore, this subject of a T1 firm is required to submit eight distinct bids to buy for each of the additional permits that would cover the eighth to first units of production costs, as well as two distinct offers to sell each of the two permits that currently covers the tenth and ninth units of production costs. Every subject was required to perform the same procedure. For instance, another subject of type T4 was asked to submit four distinct bids to buy and six distinct offers to sell (See T4 type schedule of cost and initial endowments in table 1).

The participants did not know the abatement cost schedules and initial endowments of the other players, nor did they know whether they become a buyer or a seller. Again note that whether a subject becomes a buyer or a seller in each period depends on how he/she makes bids to buy, offers to sell and the uniform price in our UPA experiments. The experimenter collected all of the information regarding 48 bids to buy and 32 offers to sell submitted by eight participants for each period in a session, and calculated a uniform price by ranking bids to buy from high to low and offers to sell from low to high by identifying the intersection of the demand and supply. More specifically, the uniform price is the average of the bid to buy and the offer to sell at the last unit of trades in which the former exceeds the latter.

Table 2 illustrates how the payoff for each subject was calculated in a period for the case where a uniform price was announced as 89. In this case, this subject purchased three additional permits to cover the production costs for eighth, seventh and sixth units because the bids to buy for those units (111, 98, 92) exceed the uniform price of 89 and he purchased three permits. Finally, this subject's payoff was determined by the summation of the total production costs, the net payment for permit trades, and fixed revenue.[8] This subject has incurred the production costs from the first to fifth units, and successfully avoided incurring the costs for sixth, seventh,..., tenth units of production because they were covered by holding five units of permits from trading.

The permits traded in a single period do not carry over to the next period under the DA and UPA treatments, following previous studies. In other words, although a subject purchased two additional permits and received some payoff in a given period, everything returned to the initial situation of endowment and payoff before trading in the following period. Thus, a subject was asked to experience the same type of decision environment repeatedly.

3 Experimental result: DAs vs. UPAs

In this section, we present the experimental results by comparing the data obtained from two treatments of DAs and UPAs under trader settings. Our focus in this comparison is on (i) the efficiency achieved, (ii) the price dynamics and (iii) the value and cost revelation in the two treatments, and then we seek to determine which DAs or UPAs work better in the same environment.

3.1 Efficiency

In this subsection, we compare the efficiency achieved from the DA and UPA treatments on the same grounds. Figure 3(a) presents the average efficiency achieved over the six sessions in each period per treatment. Visual observation of figure 3(a) suggests that the average efficiencies achieved over the periods in the UPAs are higher than those achieved in DAs, and our efficiency results for the DAs are consistent with previous studies that also employ a trader setting (see, e.g., Ledyard and Szakaly-Moore, 1994).[9]

[Figure 3 about here.]

Whereas DAs are well-known to have a high efficient property, particularly in a non-trader setting where each subject is assigned as either a buyer or a seller, Ledyard and Szakaly-Moore (1994) provide a well-established result for DAs under a trader setting that exhibit a similar trend with our results in terms of efficiency. More specifically, Ledyard and Szakaly-Moore (1994) find that the average efficiency achieved in DA sessions under a trader setting is between 60% and 80%, which is similar to the range obtained here.

[8]Fixed revenue was included in the payoff calculation for adjustment purposes.

[9]Note that there has been no research that employs UPAs under trader settings for marketable permit experiments.

Next, we observe each individual session's data more closely and provide a statistical test to evaluate the difference between DAs and UPAs with respect to efficiency. Figure 3(b) presents all sessions' observations of efficiency over 10 periods. Six sessions were conducted for both DA and UPA treatments, implying six observations per treatment in each period. This figure provides another confirmation that UPAs tend to achieve higher efficiency than DAs. Furthermore, two boxplots in figure 3(c) are drawn by pooling the efficiency observations per group over periods; these two boxplots appear to be statistically different with UPAs being more efficient than those DAs.

To statistically check whether the observations on the two treatments differ, we run a two-sample Kolmogorov-Smirnov test by pooling observations of efficiency per group across periods for each treatment, i.e., DAs vs. UPAs and $N = 120$. The null hypothesis is that the probability distribution of observations on efficiency obtained in DAs is the same as that obtained in UPAs. The result indicates that the null hypothesis is rejected at even 1% significance level; thus, we confirm that UPAs tend to be more efficient than DAs. To robustify this result, we also run a random effects model by exploiting the panel structure of our data taking cross sectional unit as a session and time as an experimental period. Consistent with the result of the Kolmogorov-Smirnov test, the column (1) of efficiency in table 3 shows that efficiency is higher in UPAs than DAs with 1% statistical significance (See the coefficient on UPA dummy variable in table 3).

[Table 3 about here.]

In summary, we obtained a series of visual observations and statistical results that indicate that UPAs tend to be more efficient than DAs under trader settings. This result can be attributed to many factors. First, many subjects in the DA treatment repeatedly buy and sell a coupon in a single period just for arbitrage as a "trader," whereas the opportunity of resell and redemption is simply unavailable in the UPA treatment. This type of additional speculative activities available in DAs appears to generate noise in the market performance. Although we will address this issue in further detail in the next section and the conclusion, a feature of real-time trading in DAs, particularly under a trader setting, may be a cause of the difference in efficiency between DAs and UPAs.

3.2 Price dynamics and volume of trades

We now discuss the observed price dynamics per treatment and focus on how the observed trading prices per treatment are close to the theoretical equilibrium price across periods. Figure 4(a) presents the plot of the observed trading prices per treatment in each period.[10] The result

[10] An observed trading price for DAs in each period is the average over the prices of all the trades made during three minutes of trading in that experimental period.

suggests that the DA prices are likely to be more widespread, whereas the UPA prices are more concentrated in the range between 80 and 90 (see 95% confidence intervals (CIs) for DA and UPA averages prices in figure 4(b)). Reflecting on what we observed in figure 4(a), the average UPA prices in each period are lower than the corresponding DA prices, as shown in figure 4(b). Recall that our experimental setup yields the theoretical equilibrium prices of $88-92$. If the DA and UPA trading rules are effective, the observed prices in the experiments should be sufficiently close to the theoretical value. In other words, the trading mechanism could be considered more desirable if it gives rise to more stable trading price dynamics around the theoretical equilibrium level.

[Figure 4 about here.]

With this in mind, we further seek to characterize the observed prices over the periods for each treatment. Figure 4(c) presents the boxplots drawn by pooling the observed prices over the periods for each treatment. The results also suggest that the distributions of observed prices under the DA and UPA treatments appear to be different. More specifically, the DA distribution exhibits a higher average price and a wider variation than the UPA distribution. To confirm these observed differences, we run the two-sample Kolmogorov-Smirnov test with the null hypothesis that the probability distributions of prices under the two treatments are identical where the unit of observations is a price of all trades made in each session over periods (The sample size is $N = 3967$).

The result indicates that the null hypothesis is rejected at even the 1% significance level, implying that the probability distribution of observed prices for DAs differs from that of observed prices for UPAs. We can confirm this result from a random effects model in the column (2) of table 3 illustrating that a coefficient on UPA dummy is negative with 1% statistical significance. To further establish the difference, we also run a squared rank test of variances by taking a unit of observation as the uniform price for UPAs and the average price for DAs per session in each period. The null hypothesis is that the variance of the observed DA trading prices are higher than that of the observed UPA trading prices (see Conover, 1999, for the squared rank test of variances). This result suggests that the null hypothesis is not rejected at any level of significance; thus, DAs are likely to observe a higher variance. In summary, we conclude that price dynamics under UPAs are different from, and more stable around, the theoretical equilibrium price than under DAs, based on Kolmogorv hypothesis testing for the probability distribution and a squared rank test of variances.

Next, we investigate the volume of trades that occurred in a period per treatment. Summary statistics of the volume of trades in a period are shown in table 4 by pooling the observed data per treatment. Following our intuitions, the volume of trades in DAs is larger than in UPAs. Furthermore, DAs exhibit considerably higher variation than UPAs with no overlap in the range (See the minimum and maximum volume of trades for DAs and UPAs in table 4).

[Table 4 about here.]

As mentioned previously, there must at least 12 trades to achieve economic efficiency. Considering this fact, the volume of trades is slightly low in UPAs, with an average of 9.65. However, the standard deviation is quite small (1.117); therefore, the observed volume of trades is concentrated around 10 in UPAs. In contrast, the DA results display a minimum of 28 trades and a maximum of 111 trades, implying that the number of trades can differ considerably depending on how the trades evolve within a period. The average number of trades in DAs is 46.3, and the standard deviation is 14.53. Thus, the volume of trades fluctuates more in DAs than in UPAs.

Finally, figure 4(d) presents the observed volume of trades for each session per treatment over all periods. The volume of trades in DAs is considerably more widespread than in UPAs. These trends are quite consistent with the summary statistics in table 4. In general, the volume of trades in UPAs is confined to a range between 7 and 12, which generates a high economic efficiency. However, DAs can involve an excessive number of trades, in some cases exceeding 50, and we have identified that such excessive trades are driven by speculative trades. Such speculative trades in DAs may greatly reduce the efficiency achieved in those periods. In other words, many trades could be irrelevant for efficiency if they are are "corrected" by later trades even in DAs. Unfortunately, however, too many trades that occur in DAs appear to lead to displacement of the surplus. This factor is one of the most significant pieces of evidence in our experiment that UPAs are preferable to DAs and could be consistent with Van Boening et al. (1993) with respect to speculative trades or bubbles. As mentioned previously, we will address the speculative trades in the discussion and conclusion sections.

3.3 Cost and value revelation

In this subsection, we report how bids to buy and offers to sell closely follow the true costs and values induced in the experiments. In general, trading prices tend to diverge from equilibrium prices when the market mechanisms work in such way that people misrepresent or do not follow their true valuation for assets and commodities. Consequently, it is less likely to obtain efficient (or Pareto optimal) results. Therefore, we attempt to identify which mechanism in DAs or UPAs induces a more truthful revelation of costs and values for emissions through bids to buy and offers to sell.

[Figure 5 about here.]

[Figure 6 about here.]

[Figure 7 about here.]

Figures 5, 6 and 7 illustrate how much bids to buy and offers to sell observed in each auction mechanism reflect the true value of MACs for emissions. First, we focus on the UPA data, which is shown in figure 5. Subfigures 5(a) and 5(b) show bids to buy and offers to sell versus the values of MACs, respectively. The distinction between the two subfigures can be clearly observed. Bids to buy tend to be lower than the 45 degree line, whereas offers to sell tend to be above this line.

This feature in the observed data can be attributed to the fact that bids to buy (offers to sell) must be lower (higher) than or equal to the value of the MAC to avoid an unnecessary loss from a trade. If the subjects are rational and understand the mechanism of UPAs at the beginning of the experiments, there should not be any bid to buy above the 45 degree line nor any offer to sell below that line. However, the observed data suggests that there are some irrational behaviors, because the subjects may misunderstand, or make mistakes. In fact, other research employing UPAs has also observed some degree of irrationality as well. In our UPA experiments, approximately 10 percent of bids to buy and 8 percent of offers to sell are considered irrational.

[Table 5 about here.]

To confirm the general trends observed in the UPAs, we run the ordinary least squares (OLS) and median regressions for each of the bids to buy and offers to sell. Table 5 presents the regression results of bids to buy and offers to sell for UPAs (See the different columns for UPAs in table 5 for bids to buy and offers to sell). Demand and value are said to be revealed more truthfully when the regression is closer to the 45 degree line, implying the estimated slope and intercept in the regressions should be around 1 and 0, respectively. Consistent with figures 5(a) and 5(b), the regression results indicate that both bids to buy and offers to sell are positively correlated with the true values of the MACs, regardless of the regression types (See the corresponding columns of table 5). The "bids to buy" OLS and median regressions for UPAs indicate that the intercept and estimated slope are statistically significant, strictly positive, and can be considered sufficiently close to the 45 degree line as shown in the "bids to buy" and "UPA" columns of table 5.[11] The "offers to sell" regressions shown in the "offers to sell" and "UPA" columns of table 5 are also considered to be close to the 45 degree line because the intercept is not statistically significant and the slope estimate is statistically significant, with estimates of 1.130 and 1.023 for the OLS and median regressions, respectively. Thus, the subjects in the UPA experiments truthfully revealed their MACs (or values) through bids to buy and offers to sell.

Next, we analyze the DAs in a similar manner. Figures 6(a) and 6(b) present the scatter plots of the observed revelations over the true cost and values through bids to buy and offers to sell. These two figures reveal that both the observed bids to buy and offers to sell do not appear to be correlated with the true value or MACs, thus differing from the UPA results shown in figure 5. Regressions are run to statistically confirm this visual observation of the DA results.

[11] Here note that the practical magnitude of this estimated intercept for bids to buy regressions is not large and could be considered negligible.

The "DA" columns of table 5 present the OLS and median regression results for the bids to buy and offers to sell under DAs. The estimated intercept and slope are very different from zero and unity, respectively. In fact, the slope estimates include negative, zero, or small positive values for the OLS and median regressions (See the slope estimates in the "DA" columns of table 5 for bids to buy and offers to sell). Thus, observed trading behaviors in the experiments in DAs deviate from true revelation of values, as the "bids to buy" and "offers to sell" regressions estimated using the data obtained in DAs are far from the 45 degree line.

Finally, we look at the aggregate data of the pooling of observed bids to buy and offers to sell per treatment and run the OLS and median regressions with the aggregate data. Figure 7 presents the scatter plot of the aggregate data, where subfigures 7(a) and 7(b) correspond to UPAs and DAs, respectively. These two figures confirm the general tendency that bids to buy and offers to sell in UPAs are more positively correlated with the values of the MACs than those in DAs. The "aggregate" columns of table 5 present the regression results for UPAs and DAs, respectively. These regression results confirm the visual observation for UPAs and DAs, that is, bids to buy and offers to sell in UPAs more closely follow the 45 degree line than those in DAs because the "aggregate UPA" column of table 5 displays an estimated slope of 1.144 for OLS and of 1.034 for median regression with statistical significance, whereas "aggregate DA" column in table 5 displays an estimated slope of 0.007 for OLS and of 0.000 for median regression. These regression results are generally in line with visual observation in figures 7(a) and 7(b).

4 Discussion on speculative trades

Overall, our results suggest that UPAs perform better than DAs in terms of all aspects of the experimental market data, given the schedules of MACs for the eight firms employed in this experiment. However, this does not mean that UPAs are better than DAs in every environment. Therefore, in this section, we explore some possible explanations for our results considering the fact that our experiments were conducted under trader settings. Observing that considerably more trades occur in DAs than in UPAs and that trades were made with unstable prices in DAs, two possible arguments emerge to characterize our results:

1. The existence of speculative trades in DA under trader settings, and
2. the schedule of MACs for an MPS in an experimental setup.

4.1 The existence of speculative trades in DAs under trader settings

A critical observation we made in the process of implementing the experiments is that the subjects conducted speculative trades in DAs. This issue has never been addressed with empirical evidence. In particular, we realize that the subjects' trading behaviors appeared not to be based on the MACs in DA experiments as illustrated in figures 6(a), 6(b) and 7(b). Rather, some subjects appeared to only care about price movements during a trading period in DAs when they frequently sold and bought permits. Under trader settings, DAs provide subjects with opportunities to buy and sell the same unit of permits within a trading period and to potentially engage in speculative trades, whereas under trader settings, UPAs do not provide subjects with such opportunities.

To confirm the existence of some types of speculative trades, we closely analyzed the individual "bids to buy," "offers to sell" and "the corresponding trading data" obtained in the experiment. More specifically, we ensured each subject's record of all trades made over a trading period of 3 minutes for 10 experimental periods. Our intent here is to identify possible speculative trades among all the records and to clarify the proportion of speculation relative to the total trade volume in DAs. To this end, we prepare some possible definitions of "speculative trades" that can occur in DAs under trader settings for MPS. Each possible definition is given as follows:

Definition 4.1 (Pure speculation) *A permit trade is "pure speculation" if either of the following cases holds:*

- *A subject purchases a permit at a price which is higher than the MAC that will be covered by the purchased permit. Then, the subject sells the permit at a higher price than the purchase price.*
- *A subject sells a permit at a price that is less expensive than the MAC that was covered by the permit sold in the market. Again, the subject then purchases the permit at a cheaper price than the price at which he initially sold the permit.*

Pure speculation consists of both buying and selling of the same unit of permits by a single player such that the player does not appear to consider the underlying MAC. Rather, the subject seeks to obtain more rent out of pure speculation without considering the underlying MAC.

Definition 4.2 (Speculation) *A permit trade is "speculation" if either of the following cases holds:*

- *A subject purchases a permit but then the subject sells the same permit at a higher price.*
- *A subject sells a permit but then the subject purchases the same permit at a lower price.*

Speculation also consists of both buying and selling the same unit of permits by a single player. The difference between pure speculation and speculation is that in speculation, the player may care about the associated MAC of an initial permit trade, but then, his second action of trading for the same unit of permits is oriented toward obtaining more rents such that the player does not appear to care about the MAC.

Definition 4.3 (Quasi-speculation) *We call a trading behavior "quasi-speculation" if either of the following behaviors is observed in a single permit trade:*

- *A subject purchases a permit at a higher price than the MAC that will be covered by that permit.*
- *A subject sells a permit at a lower price than the MAC that must be incurred by selling the unit of permits.*

Quasi-speculation consists of either buying or selling a permit by a single player. This type of quasi-speculation can occur due to irrationality and speculation. In contrast to the previous two definitions of pure speculation and speculation, quasi-speculation represents behavior of either buyers or sellers that involves a single permit trade.

[Figure 8 about here.]

Given these three possible definitions of speculative trades, we classified the number of trades that have occurred in each session and each period. Figure 8(a) displays the average numbers of trades categorized by pure speculation, speculation and quasi-speculation relative to the average total trade volume over six sessions in each period. These results reveal that speculative trades account for considerable proportion of total trades, although the number of pure speculation trades accounts for only a small proportion. However, speculation and quasi-speculation are substantial when considered simultaneously.[12]

To further clarify the proportion of speculative trades, we converted the volume of trades into percentage terms for each category, as shown in figure 8(b). Pure speculation, speculation and quasi-speculation account for approximately 5%, 16% and 40% of the total permit trades, respectively. This result confirms that a considerable proportion of the total trades consist of some types of speculative trades, and these speculative trades definitely affects both the dynamics of the permit prices observed in our DA experiments and the overall performance of the DAs.

To establish an efficiency gain in MPS, those with relatively high MACs should buy additional permits from those with relatively low MACs. However, the above result in DAs suggests that some considerable proportion of trades were made in such a way that MACs may not have been

[12]We have to note that some portions of bids to buy and offers to sell observed in UPA experiments are irrational, illustrated in figures 5(a) and 5(b). If subjects are rational, they should not give any bid to buy which is higher than the corresponding MAC, implying that bids to buy should not be above 45 degree line of figure 5(a). In the same way, rational subjects should not give any offer to sell which is lower than the corresponding MAC, implying that offers to sell should not be below 45 degree line of figure 5(b). Recall that approximately 10 percent of bids to buy and 8 percent of offers to sell are considered irrational in our UPA experiments. The proportion of irrational bids and offers may be slightly higher in this study than previous studies of UPA experiments. It is due to the fact that this study employs trader settings, whereas others use non-trader settings.

considered. Therefore, the existence of the speculative trades based on our three definitions is one of the main factors that contribute to the instability of permit prices and the low efficiencies observed in the DAs.

4.2 The schedule of MACs in an experimental setup

Another possible reason for unstable prices and low efficiencies in DAs under trader settings might be the schedule of MACs in MPS experiments. In other words, how MACs are organized at individual and aggregate levels may be crucial in DAs under trader settings. Our results indicate that DAs under trader settings achieve an efficiency of approximately 80%. This result is very similar to that of Ledyard and Szakaly-Moore (1994), whereas Godby et al. (1997) and Muller et al. (2002) find an efficiency of more than 90%. The question now becomes "why do the observed efficiencies differ?"

[Figure 9 about here.]

Godby et al. (1997) and Muller et al. (2002) share the same features of MACs for their MPS experiments and consider the MPS environment that possesses the following features:

1. Heterogeneity of MAC schedules across firms is very high such that the range of MACs do not overlap considerably at least as a group. Therefore, each subject may be able to easily identify whether to be a buyer or a seller.

2. Some special experimental factors exist to advise subjects to trade permits, such as provision of advice by computer wizards.

These two features encourage the subjects to easily identify whether they possess a relatively high or a relatively low MAC schedule in an experimental session. For instance, Godby et al. (1997) employ four types of MAC schedules, and two of which (types A and C in that paper) are clearly lower than the other two types (types B and D) (See figure 9(b)). More specifically, the range of MACs for types A and C do not overlap with the range for types B and D. For example, subjects with type A should be able to understand whether they should be buyers or sellers through experimental experiences and learning because they can identify that their MACs are relatively lower than the others. Furthermore, Godby et al. (1997) focus on the effect of introducing a feature of shares when emission discharge is uncertain. Therefore, burdens on the decision making of the subjects are heavy in the experiment. Therefore, the authors also included some special experimental designs of computer wizards to provide advice to the subjects regarding how to trade in such a complex decision environment. This also contributes to the high efficiency obtained by the authors.

Another work by Muller et al. (2002) also obtains a high efficiency in DAs under a trader setting. Similar to Godby et al. (1997), these authors also consider highly heterogeneous MAC schedules across firms (Figure 9(c)). A group with the types A, B, C, D and E are much higher in MACs than a group of types F, G, H, I and J, and the range of MACs for the former group does not overlap with that for the latter group. This design for MACs is understandable, because the authors' focus is on effects of monopoly and monopsony on performances of MPSs. Thus, their MAC schedules are intentionally considered idiosyncratic as a group, where a majority of firms emit only two units of pollution, and one of the firms is designated as a monopoly or monopsony. Our conjecture here is that the subjects in the experiment easily identified whether they should be buyers or sellers through the experimental experiences and learning because of the highly heterogeneous environment of MACs in a group-wise manner.

In contrast, our study and that of Ledyard and Szakaly-Moore (1994) share the opposite features from the above works. That is, each firm's MAC schedule is relatively homogeneous in that the range of MACs across all types overlaps (figures 9(a) and 9(d)). Therefore, the subjects may not be able to identify whether to be buyers or sellers in DAs under a trader setting, in contrast with the subjects in the experiments of Godby et al. (1997) and Muller et al. (2002). In our case, the subjects may not be able to view being a buyer or a seller as a "correct" position even with experimental experiences. Each subject is more likely to be induced into a situation where a speculative trade is encouraged and yields a larger gain than the gain that can be obtained from MAC-based trading. Again, this type of occurrences is possible because other subjects also possess relatively similar MACs.

Put differently, in our experiment, it is more likely that many subjects have homogeneous valuations for the permits. In such a case, they are tempted to conduct more trades for permits because they cannot identify their "correct" position and are exposed to opportunities to earn more by repeatedly buying and selling the unit of permits. Such speculative trades of permits yield unstable prices and excessive trade volume. This result is consistent with the arguments made by Shiller (1981, 2005) implying that price dynamics and market performances in MPSs become more volatile and unstable when people trade the permits based on speculation rather than the underlying value. In summary, we surmise that if subjects' MAC schedules are relatively homogeneous, some types of speculative trades can frequently occur in DAs under trader settings. This would be one of the main reasons for our DA results.

5 Conclusion

We analyzed the fundamental performances of the marketable permits system (MPS) by comparing two auction mechanisms of double auction (DA) and uniform price auction (UPA) under trader settings. Although numerous works have examined the MPS in controlled laboratory experiments, none have compared the two mechanisms under trader settings on the same grounds. Several works have noted that UPAs might be a good alternative to DAs that enable high efficiency and stable price dynamics (see, e.g., Muller and Mestelman, 1998). However, none of the previous studies have supported this conjecture with evidence. Therefore, our research sought to fill this gap.

Our experimental results provided the following novel results: (1) UPAs are more efficient than DAs in a trader setting, which is in sharp contrast to the established result in non-trader settings; (2) UPAs generate more stable price dynamics; (3) UPAs induce subjects to more truthfully reveal information about abatement costs for emissions through bids to buy and offers to sell; (4) a considerable proportion of the total trades in DAs consist of speculative trades that decrease the performance. With these results, we conclude that UPAs are likely to work better than DAs in a trader setting. Our results appear to be inconsistent with the literature because many experimental MPS studies have consistently used only DAs for their analysis of markets. An exception is the study of Smith et al. (1982) that compares UPAs with DAs under non-trader settings, and finds excellent performance for both types of auctions, concluding that DAs are slightly better than UPAs under non-trader settings. Our results confirm that UPAs are more effective than DAs under trader settings.

We intended to address the reason behind our results. Participants in DAs under trader settings are given many opportunities to resell and redeem permits. More specifically, DAs are considered to provide more opportunities for speculative trades. This types of speculative trades may be independent of the efficiency aspects of the MPS. However, we are concerned that when a considerable proportion of bids to buy and offers to sell submitted in the market do not necessarily reflect the underlying marginal abatement costs (MACs), the existence of such speculative trades will not improve or even worsen the market performance with respect to efficiency and price dynamics.

In this experiment, we employed the MAC schedules parametrized by Cason and Gangadharan (2006). We realize the differences and similarities between our setting and other previous works with respect to MAC schedules (see figure 9). Ledyard and Szakaly-Moore (1994), who obtain a similar result to ours in terms of efficiency, employ the relatively homogeneous and qualitatively similar MAC schedules to our MAC schedules. In contrast, Godby et al. (1997) and Muller et al. (2002) employed different types of MAC schedules that are highly heterogeneous across firms at least in a group-wise manner. Therefore, we surmise the manner in which MACs are organized across firms is a crucial factor, which we have addressed extensively in the discussion section.

These observations lead us to one hypothesis. That is, when the MAC schedules are homogeneous, subjects tend to have similar valuations for the permits. In such a case, the subjects may be more induced to conduct speculative trades for permits in DAs under a trader setting. Because they are exposed to more opportunities to earn more by repeatedly buying and selling a unit. We have also observed that such speculative trades of permits yield unstable prices and excessive trade volume, leading to efficiency losses. This result is consistent with the arguments made by Shiller (1981, 2005).

This is the first to design and implement UPAs for marketable permits in a trader setting, and the first to make a direct comparison with the performance of DAs under a trader setting on the same grounds. Our results clearly suggest some positive aspects of UPAs as an alternative to DAs for the real-world application of MPSs, such as in Tokyo Commodity Exchange. This study also raises a new open question that the market performance of DAs under trader settings may be highly dependent upon how MACs are organized. Future studies should address these unanswered questions related to DAs, while considering the potential use of UPAs given the results confirmed here. Although this research is still limited in the sense that our results are established in a simple environment of trader settings, this study can be extended to several different environments for comparing the performance of UPAs and DAs. We hope that this work becomes an important step toward further examination of successful auction mechanisms for MPSs.

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Appendix: Experimental instructions "for online publication"

In this section, a sample of experimental instructions used in our experiment is introduced. These instructions are a translated version of the original, which is written in Japanese. The difference between instructions for double auction (DA) and uniform price auction (UPA) is only derived from "trading rules for coupons," "some exercises," and "procedures." Therefore, the corresponding parts of explanations are separately prepared for DAs and UPAs, and the common portions are only introduced in the instructions for DAs.

Experimental instruction for double auctions (DAs)

Introduction

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions, you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in "experimental yen." These experimental yen will be converted to "real yen" at the end of the experiment with an exchange rate of experimental yen = 0.8 real yen. We will conduct a number of periods and your experimental earning in each period is determined as follows:

$$\begin{aligned} &\text{Your earning} = \text{Fixed revenue} - \text{Total production costs} \\ &+ \text{Sale proceeds from selling coupons} - \text{Amount spent when buying coupons.} \end{aligned}$$

Your total experimental earnings are the sum of your earnings over all periods. You will receive more cash by earning more experimental money. We will now explain each item that will be part of your experimental earnings.

Fixed revenue

The same amount of fixed revenue is automatically given to you in each period; the amount does not depend on any action you take.

Total production costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs may or may not be different from the costs of other participants. Your production costs are shown on the left side of your computer screen (the numbers for this example are different from the actual numbers used in the experiment, and you will not actually learn your values until the experiment begins). Everyone can produce up to 10 units, and the cost of each unit is written separately. For instance, your first unit produced would cost 25, your second unit would cost 35, and so on. If, for example, you produced three units, your **total** costs would be

$$25 + 35 + 47 = 107.$$

Here, you must recognize that the costs are the **additional** costs associated with each **additional** unit produced.

Coupons

You have a chance to trade "coupons" in each period following the compliance rule:

$$\text{Your production amount} + \text{the number of coupons you have} = 10.$$

This rule means that you can avoid production and save your production costs by holding coupons. Everyone starts with some number of coupons in every period and anyone can adjust their own holding of coupons by buying and selling them in a market that will operate over the computer network. If you sell the coupons, your cash increases by the sale amount, and if you buy coupons, your cash decreases by the sale amount. We will explain the rules for buying and selling coupons later on in the instructions.

Why might you want to buy a coupon? Remember that coupons allow you to avoid production. If you currently hold two coupons, for example, and if you had the example of production costs shown in table 6(a), then the production costs of ninth and 10th units are saved, and the last unit that you must produce is the eighth unit (so that your production of $8 + 2$ coupons $= 10$). The production cost of the eighth unit is 141. Thus, if you can buy a coupon for less than 141, it might be a good idea because it would allow you to save the production cost of 141. More specifically, if you buy a coupon for 120, you save the production cost of 141 and thus make a profit of $21(= 141 - 120)$ because of the lower costs that you incur. In this case, you will produce seven units and hold three coupons. ***Note that the same logic applies when you buy an additional coupon to save the production cost for each of seventh, sixth, ..., first units.***

Why might you want to sell a coupon? Continuing the illustration based on the previous example, suppose that you currently hold six coupons with the corresponding production costs shown in table 6(b). The production costs from fifth to 10th units are saved and the last unit that you must produce is the fourth unit (so that your production of $4 + 6$ coupons $= 10$). The production cost of fifth unit is 75. If you can sell a coupon of the fifth unit at a higher price than 75, it might be a good idea because these sales revenue exceeds the production cost for the fifth unit. For example, if you sell a coupon for the fifth unit at a price of 120, even if you incur the additional fifth unit production cost of 75, you would still make a profit of $45(= 120 - 75)$ on the sale. In that case, you would produce five units and hold five coupons. ***Note that the same logic applies when you sell an additional coupon for each of sixth, ..., 10th units.***

Trading rules for coupons

In each period, you are given an opportunity to buy and sell coupons over a trading duration of 3 minutes. At any time during the trading stage, everyone is free to make a bid to buy a coupon at a price he chooses (**a bid to buy or buy bid**); similarly, everyone is free to make an offer to sell a coupon at a price he chooses (**an offer to sell or sell offer**). Furthermore, at any time over the trading duration, everyone is free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best bid price specified by someone wishing to buy. Of course, there are some limitations: to sell a unit or make a sell offer, you need to have a coupon to sell, and to buy a unit or make a bid to buy, you need to have a sufficient amount of cash to pay. Throughout the trading duration, you will enter bid and offer prices or accept bid and offer prices to execute transactions using your computer. The time left in the trading duration is shown on the upper right of the trading screen.

Trading a coupon

In the trading duration of 3 minutes, coupon transactions will be made "one by one." If a pair of buyer and seller agree to trade a coupon at some price within the rules explained below, the transaction is immediately effective at that price.

How to buy a coupon There are two ways to buy a coupon.

1. Submit a "buy bid"—Participants interested in buying a coupon can submit a "buy bid" using the "price" box on the lower side of the screen, and then clicking on the "buy bid" button in the lower right. This bid price is immediately displayed on all traders' computers on the upper right of the screen, labeled "buy bid." Once this bid price has been submitted, it is binding in the sense that anyone wishing to sell accepts this price, and such an acceptance results in an immediate trade at that price. Then, the trade for that unit of coupons finishes at that moment.

   If nobody accepts the "buy bid," then everyone can submit a new buy bid, which must be higher than the current highest bid. Because sellers always prefer higher prices. If you try to bid a lower price than the best bid currently available, your computer will give you an error message.

2. Accept a "sell offer"—The other way to buy a coupon is to accept the best sell offer (that is, the lowest "sell offer" price) by simply clicking the "buy bid" button on the right bottom of their computer screen. This results in an immediate trade at that price, and the trade for that unit of coupons finishes at that moment.

How to sell a coupon There are two ways to sell a coupon.

1. Submit a "sell offer"—Participants interested in selling a coupon can submit a "sell offer" using the "price" box on the lower side of the screen, and then clicking on the "sell offer" button below that box. This sell offer is immediately displayed on all traders' computers on the right part of the screen, labeled "sell offer." Once this offer price has been submitted, it is binding in the sense that anyone wishing to buy can accept this price offer. Such an acceptance results in an immediate trade at that price and the trade for that unit of coupons finish at that moment.

   If nobody accepts that sell offer, then a new sell offer can be submitted by anyone wishing to sell, which must be lower than the current lowest sell offer. Because buyers always prefer lower prices. If you try to offer a higher price than the best offer price currently available, your computer will give you an error message.

2. Accept a “buy bid”—The other way to sell a coupon is to accept the best “buy bid” (that is, the highest buy bid) by simply clicking the “offer sell” button on the middle right side of their computer screen. This results in an immediate trade at that price and the trade for that unit of coupons finishes at that moment.

When a trade for a particular unit of coupons is agreed following the above rule, the trade of that unit is closed. Then a new trade opportunity for another unit of coupons starts from the beginning. The same trading procedure repeats until the trading duration of 3 minutes is over. You can be both a seller and buyer throughout the trading duration.

Some exercises

Use the following exercises to ensure your understanding. Suppose that you produce up to 10 units based on the production costs shown in table 7.[13] Answer the following questions.

(Q1) When you sell a coupon at a price of 100 during the trading period of 3 minutes, then your experimental earning in that period is calculated as follows:

$$\text{Experimental earning} = \text{Fixed revenue} - \underbrace{(v_1 + v_2 + v_3 + v_4 + v_5 + v_6)}_{\text{Total production costs}} + \underbrace{(100)}_{\text{Sales from selling coupons}}.$$

(Q2) When you buy a coupon at a price of 78, then your experimental earning is calculated as follows:

$$\text{Experimental earning} = \text{Fixed revenue} - \underbrace{(v_1 + v_2 + v_3 + v_4)}_{\text{Total production costs}} - \underbrace{(78)}_{\text{Amount spent for buying coupons}}.$$

(Q3) When you buy two coupons at prices of 87 and 70, respectively, and sell one coupon at the price of 80 during the trading period of 3 minutes, then your experimental earning is calculated as follows:

$$\text{Experimental earning} = \text{Fixed revenue} - \underbrace{(v_1 + v_2 + v_3 + v_4)}_{\text{Total production costs}} + \underbrace{(80)}_{\text{Sales from selling coupons}} - \underbrace{(87 + 70)}_{\text{Amount spent for buying coupons}}.$$

(Q4) When you buy two coupons at prices of 87 and 70, respectively, and sell four coupons at the prices of $\{80, 100, 90, 80\}$, respectively, during the trading period of 3 minutes, then your

[13] In the presentation, the concrete numbers for $v_1, \ldots, v_{10}$ and for bids to buy and offers to sell are provided to practice the following questions. A set of numbers is different for each subject.

experimental earning is calculated as follows:

$$\text{Experimental earning} = \text{Fixed revenue} - \underbrace{(v_1 + v_2 + v_3 + v_4 + v_5 + v_6 + v_7)}_{\text{Total production costs}}$$
$$+ \underbrace{(80 + 100 + 90 + 80)}_{\text{Sales from selling coupons}} - \underbrace{(87 + 70)}_{\text{Amount spent for buying coupons}}.$$

If you feel comfortable with these questions, you are now ready!

Procedures

Step 1: Your production costs for 10 units, fixed revenue, and the initial number of coupons will be announced to you. This information does not change over the experiment and may or may not be the same as other participants.

Step 2: You are asked to determine the offers to sell and bids to buy as well as whether or not you accept the best buy bids and sell offers throughout the trading duration of 3 minutes.

Step 3: After the trading stage, you must check how many coupons you hold and your experimental earning on the sheet in that experimental period.

Step 4: Move to the next period and the same procedure will be repeated until the experimenter announces the end of the experiment.

Step 5: Finally, the total experimental earnings will be calculated, and the experimenters will apply an exchange rate to identify the real cash payment to you.

It is very important that you clearly understand these instructions.
Please raise your hand if you have any questions.
Please do not talk with other participants during the experiment. If there are no questions, we start the practice and real rounds.

[Table 6 about here.]

[Table 7 about here.]

Experimental instruction for UPAs

Trading rules for coupons in UPAs

The authority requires that in each period you must submit a **bid** price at which you would buy each additional unit of coupons and an **offer** price at which you would sell each additional unit of coupons you have. In other words, if you have x coupons, then you have to submit x distinct offers to sell at which you would sell each coupon you hold now, and you also have to submit $10 - x$ distinct bids to buy at which you would buy for each additional coupon you might obtain.

For instance, suppose that you are given two coupons based on the example shown in table 6(a). In that case, you must produce eight units, and the production costs of ninth and 10th units are saved since you own two coupons. However, you now have a chance to trade, and are required to submit two distinct offers to sell at which you would sell for each coupon of ninth and 10th units you hold now, and you also must submit eight distinct bids to buy at which you would buy each additional coupon you may obtain. Therefore, the general rule for submitting offers to sell and bids to buy is written as follows:

$$\text{The number of offers to sell} + \text{The number of bids to buy} = 10.$$

The price at which all of coupons are traded will be determined as follows: Imagine there are eight participants each of which produces up to 10 units. Then, depending on the initial number of coupons, each participant must submits offers to sell for each unit of coupons he has as well as bids to buy for each additional coupon he will obtain, following the aforementioned rules. After the offers and bids from all participants are collected on the computer network, the authority ranks all of the bids to buy from highest to lowest. Next, the authority ranks all of the offers to sell from lowest to highest. For example, imagine that 26 coupons are distributed among eight participants and each submits offers to sell and bids to buy accordingly. Then the authority will receive 26 distinct offers to sell and 54 distinct bids to buy (in fact, 54$(= 80 - 26)$ bids to buy will be submitted to the authority). Finally, the authority will create a ranking for these offers and bids. as shown in table 8.

[Table 8 about here.]

Here, units of coupons are traded in order from left to right as long as the bids to buy exceed or equal the matching offers to sell. In the example from table 8, the highest 19 bids to buy and the lowest 19 offers to sell are accepted as trades. The uniform market price, which is paid by all buyers and is received by all sellers, is determined as the average of the bid to buy and offer to sell of the last unit traded. In this example, the last unit traded is the 19th coupon and it has a bid to buy of 111 and an offer to sell of 99. Therefore, the uniform market price is 105 $(= (111 + 99)/2)$ and all units traded in this market are bought and sold at this price. After this uniform price is announced by the authority, your experimental earning in that period is determined by:

$$\begin{aligned}\text{Your earning} &= \text{Fixed revenue} - \text{Total production costs} \\ &\quad + \text{Sale proceeds from selling coupons} - \text{Amount spent when buying coupons.}\end{aligned}$$

Some exercises for UPAs

Use the following exercises to ensure your understanding. Suppose that you produce up to 10 units based on the production costs shown in table 7. Furthermore, assume that you have five coupons and submitted your offers to sell and bids to buy, which are also shown in table 7.[14] Answer the following questions.

(**Q**1) When the authority announces a uniform price of 150, how are the coupons traded in your transaction?

(**Q**2) When the uniform price is 67, how are the coupons traded in your transaction?

(**Q**3) When the uniform price is 95, how are the coupons traded in your transaction?

(**Q**4) When the uniform price is 150, then your experimental earning is calculated as follows:

$$\text{Experimental earning} = \text{Fixed revenue} - \underbrace{(v_1 + v_2 + v_3 + v_4 + v_5 + v_6 + v_7)}_{\text{Total production costs}} + \underbrace{(150 + 150)}_{\text{Sales from selling coupons}}.$$

Then, calculate your experimental earning when the price is 170.

(**Q**5) When the uniform price is 67, then your experimental earning is calculated as follows:

$$\text{Experimental earning} = \text{Fixed revenue} - \underbrace{(v_1 + v_2)}_{\text{Total production costs}} - \underbrace{(67 + 67 + 67)}_{\text{Amount spent for buying coupons}}.$$

Then, calculate your experimental earning when the price is 86.

(**Q**6) Finally, calculate your experimental earning when the price is 95.

Procedures

Step 1: Your production costs for 10 units, your fixed revenue, and the number of coupons will be announced to you. This information does not change over the experiment and may or may not be the same as other participants.

Step 2: You determine the offers to sell and bids to buy and record them in an excel sheet on your computer screen. The, submit them to the authority over the computer network.

Step 3: The authority announces a uniform price and you must check how many units of the coupons in your transaction are traded in the excel sheet. Then, the computer will automatically calculate the resulting experimental earning for each period.

[14] In the presentation for UPA experiments, the concrete numbers for $v_1, \ldots, v_{10}$, bids to buy and offers to sell are provided to practice the following questions. A set of numbers is different for each subject.

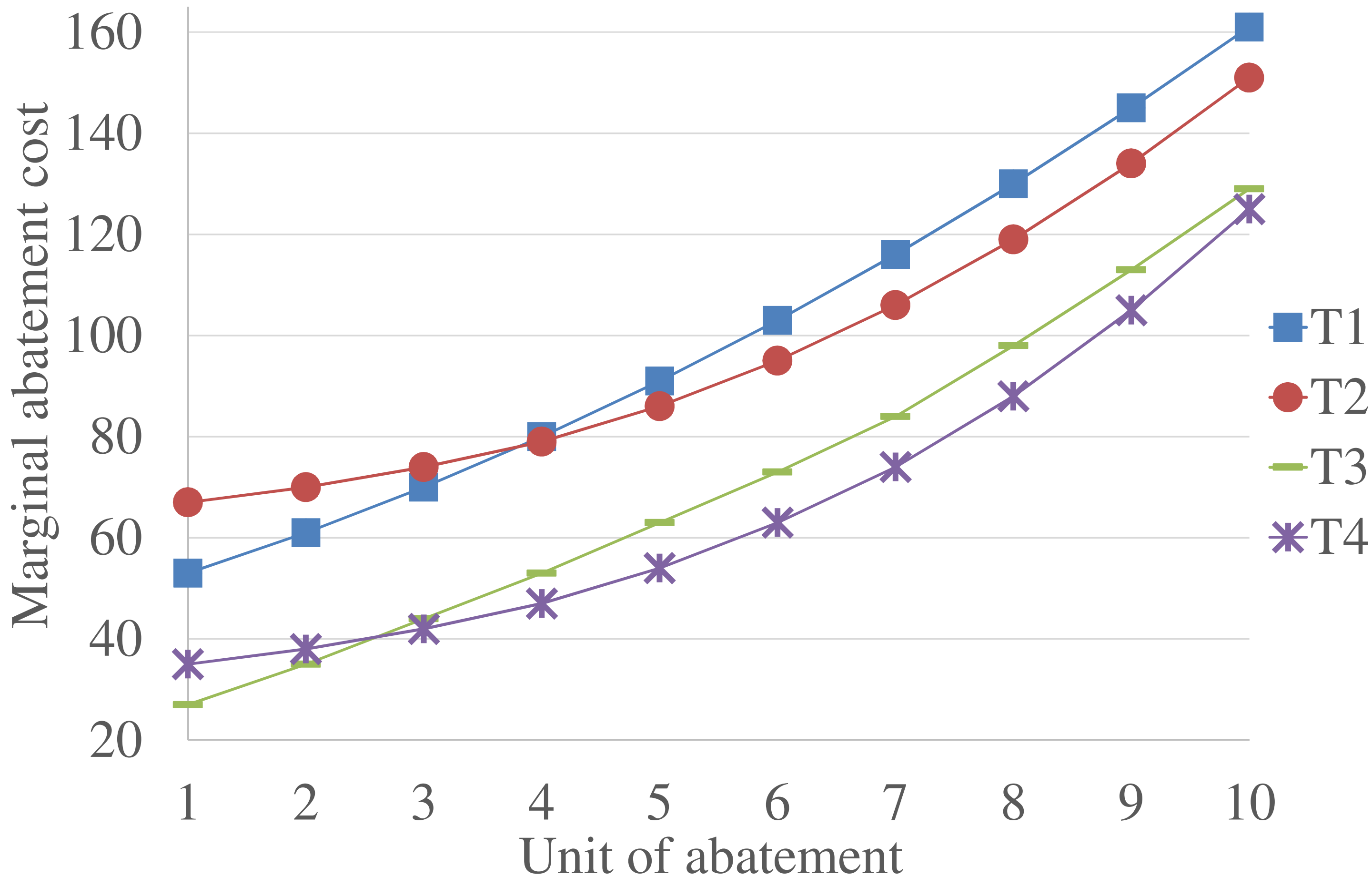
Step 4: Record your experimental earning in the record sheet, and Steps 2-4 will be repeated until the experimenter announces the end of the experiment.

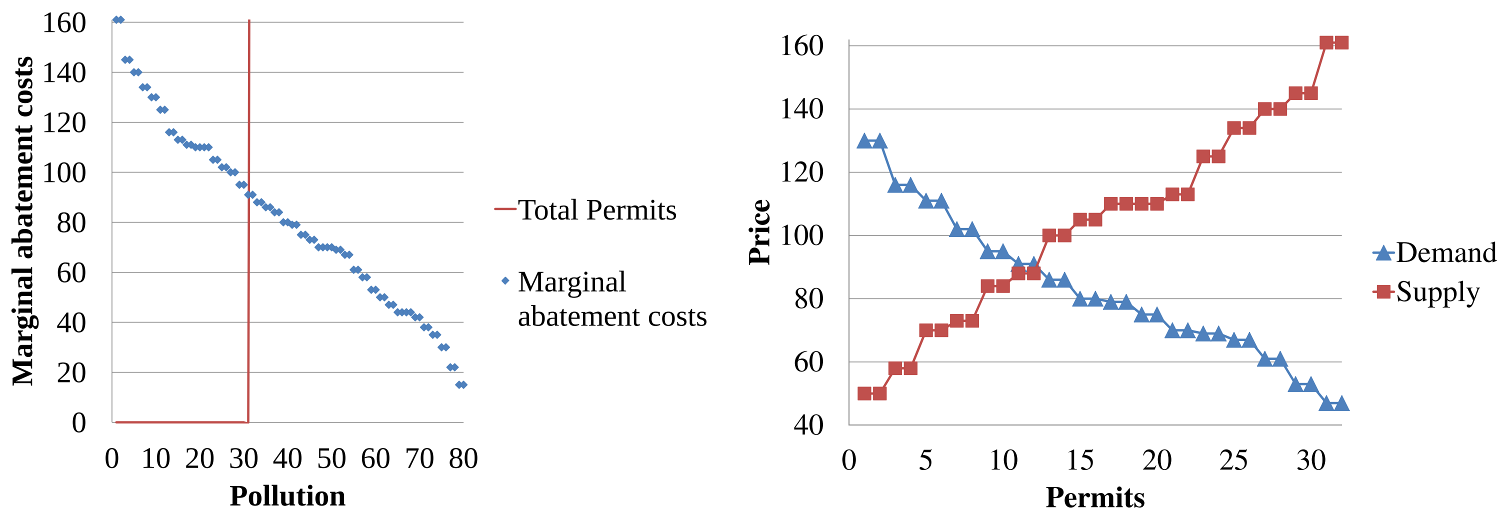
Step 5: Finally, the total experimental earnings will be calculated, and the experimenters will apply the exchange rate to identify the real cash payment to you.

It is very important that you clearly understand these instructions.
Please raise your hand if you have any questions.
Please do not talk with other participants during the experiment. If there are no questions, we start the practice and real rounds.

List of Figures

Figure 1: Marginal abatement cost schedules of all types in this work and Cason and Gangadharan (2006)

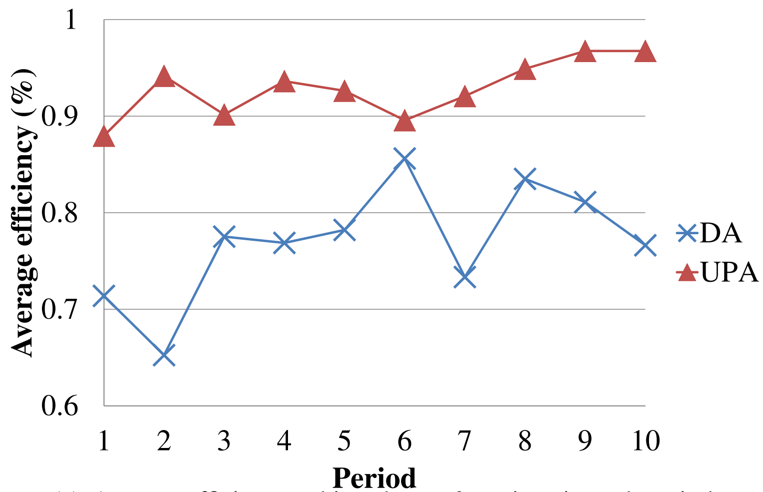




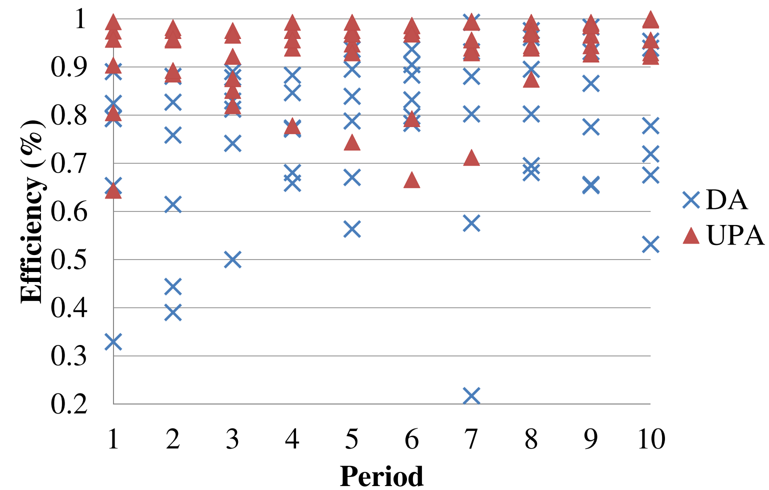
(a) Aggregate demand and supply for pollution

(b) Aggregate demand and supply for pollution permits in the market

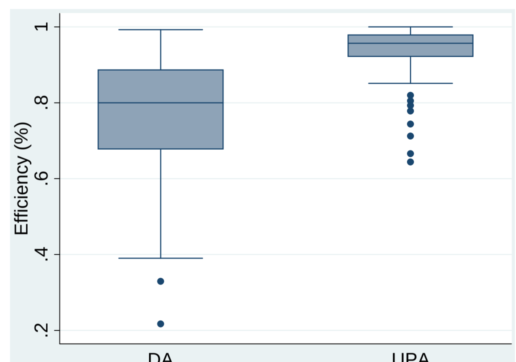
Figure 2: Demand and supply of permits



(a) Average efficiency achieved over 6 sessions in each period

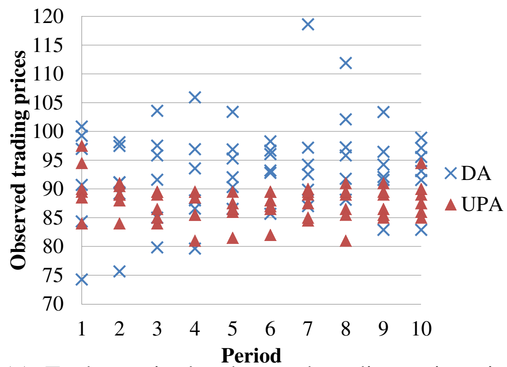


(b) Each session's data of efficiency in each period

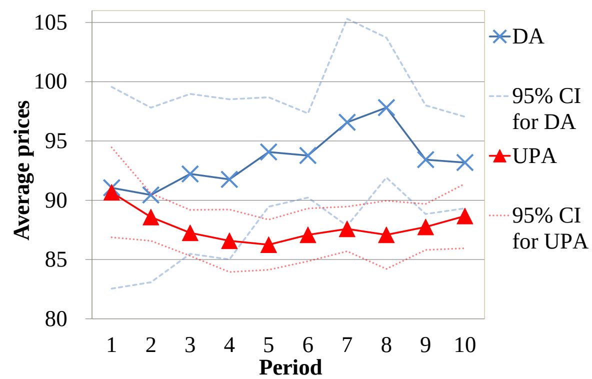


(c) Boxplots of efficiency data pooling the observations per group over periods for each treatment

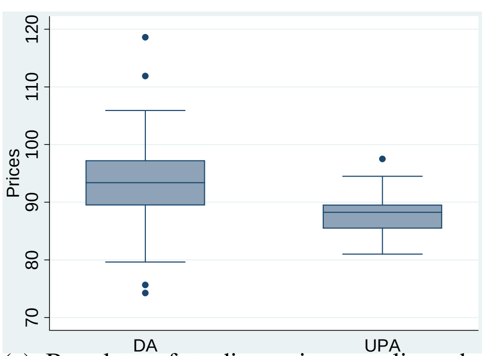
Figure 3: Efficiencies: DAs vs. UPAs



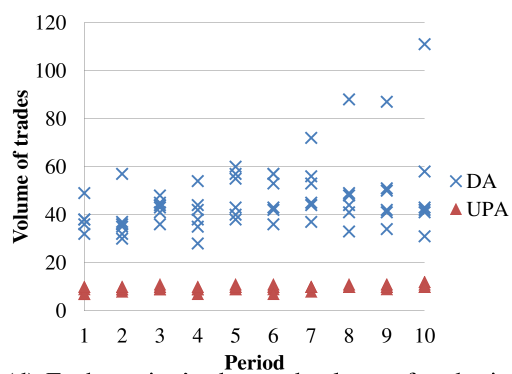
(a) Each session's observed trading prices in each period



(b) Average prices in each period per treatment

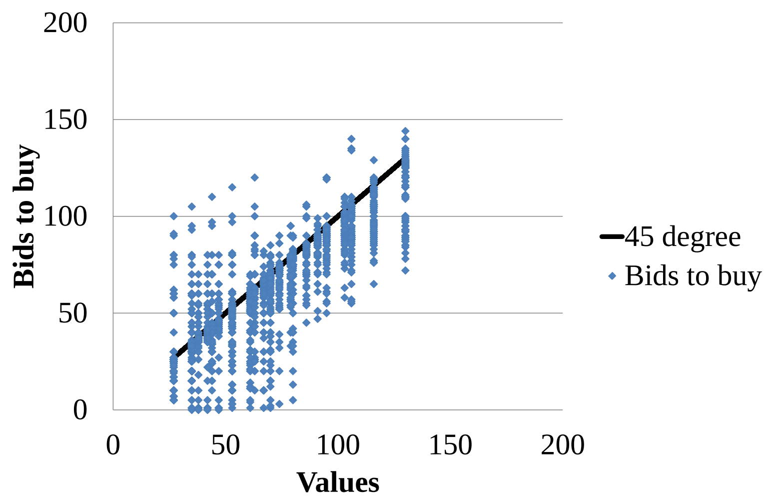


(c) Boxplots of trading prices pooling observed data over periods per treatment

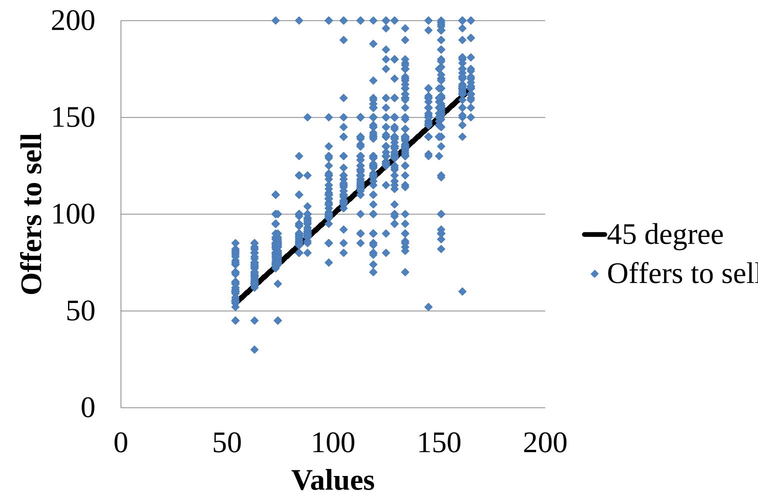


(d) Each session's observed volume of trades in each period

Figure 4: Prices and trade volume: DAs vs. UPAs

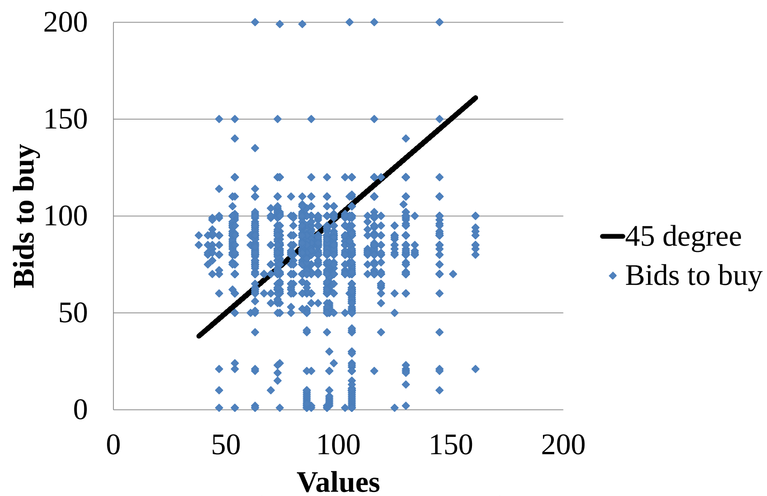


(a) Bids to buy over values in UPAs

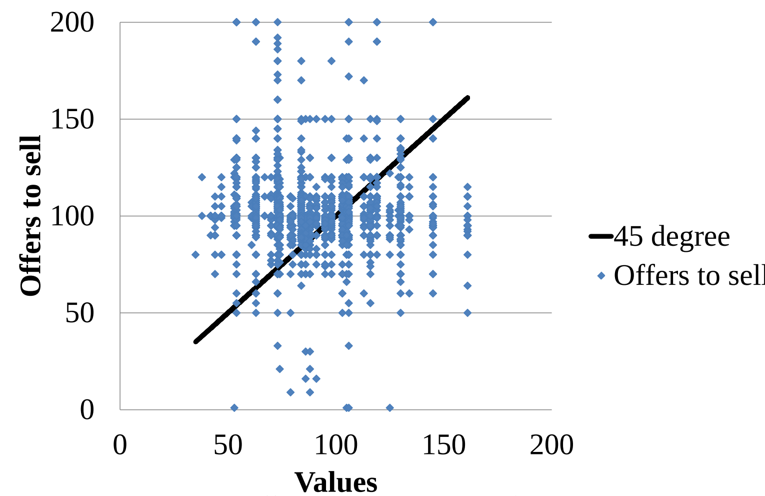


(b) Offers to sell over values in UPAs

Figure 5: Bids to buy and offers to sell over values (MACs) in UPAs

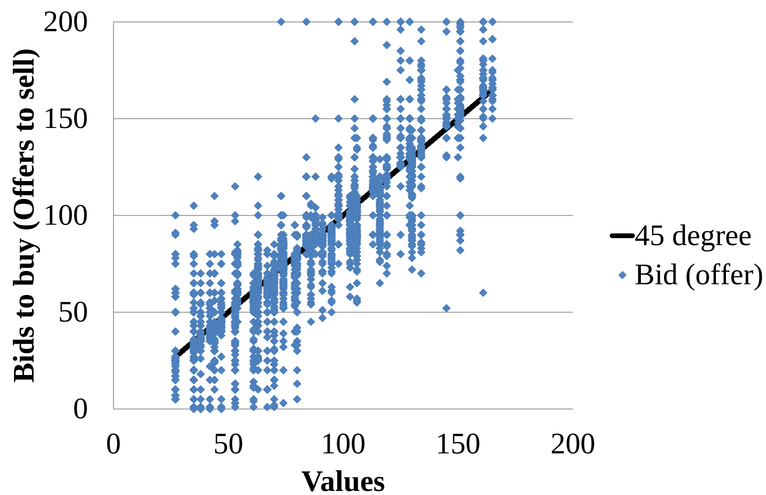


(a) Bids to buy over values in DAs

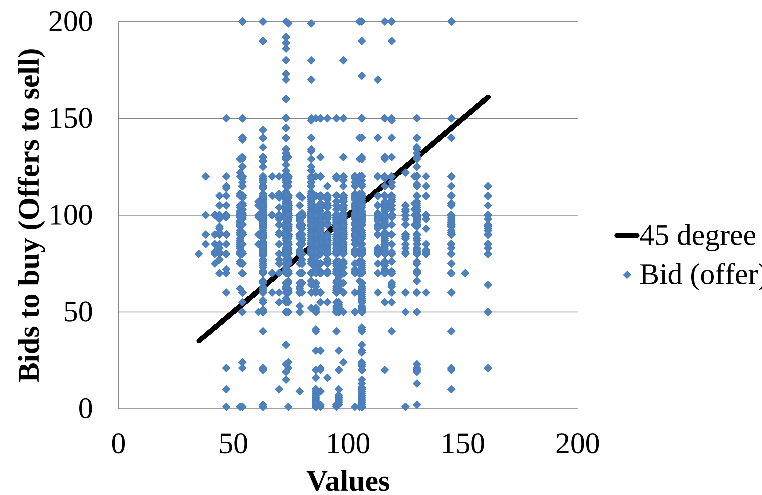


(b) Offers to sell over values in DAs

Figure 6: Bids to buy and offers to sell over values (MACs) in DAs

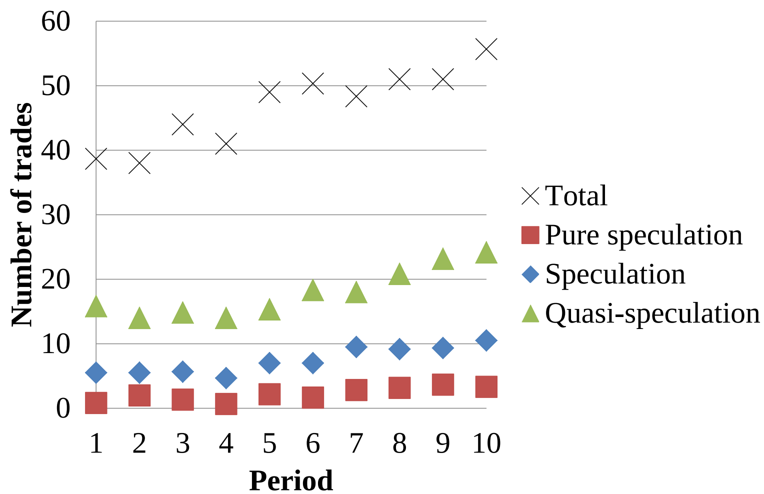


(a) Pooled data of aggregating bids to buy and offers to sell over values in UPAs

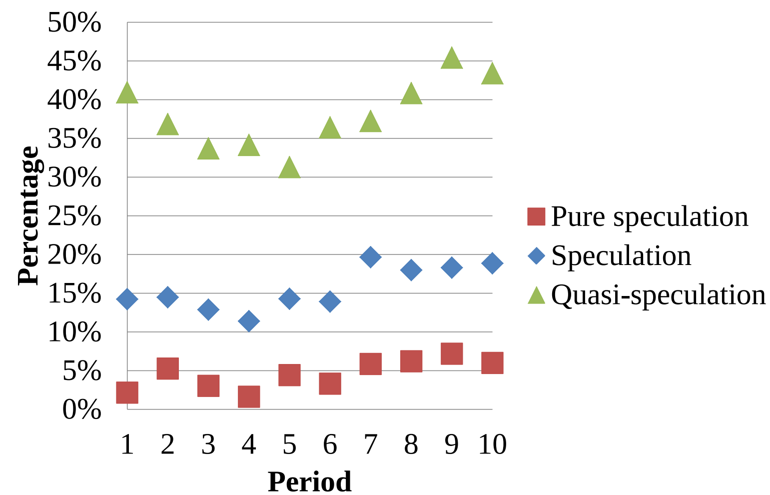


(b) Pooled data of aggregating bids to buy and offers to sell over values in DAs

Figure 7: Aggregate bids to buy and offers to sell over values (MACs) for both UPAs and DAs

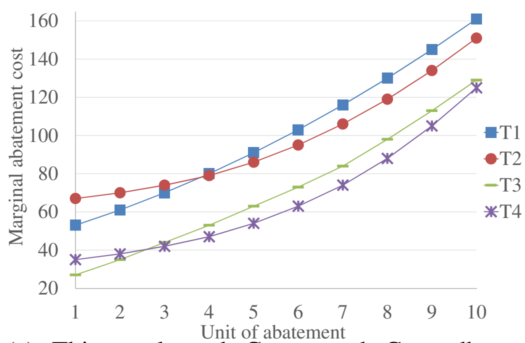


(a) Average number of trades

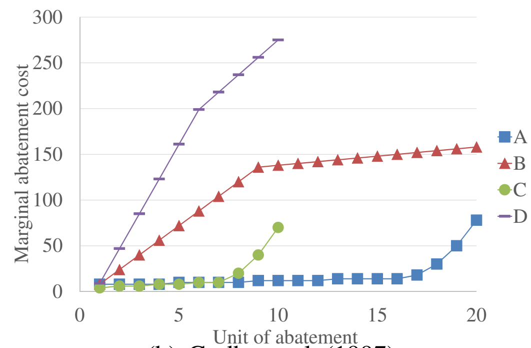


(b) Percentage of trades

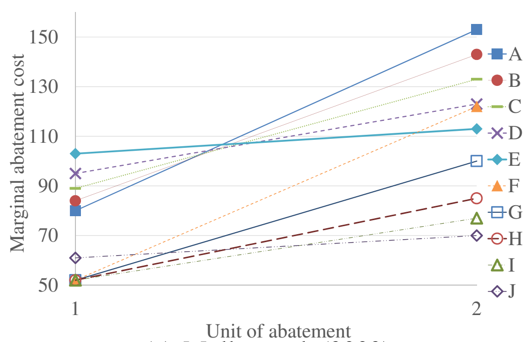
Figure 8: Pure speculation, speculation and quasi-speculation relative to the total volume of trades over six sessions in each period



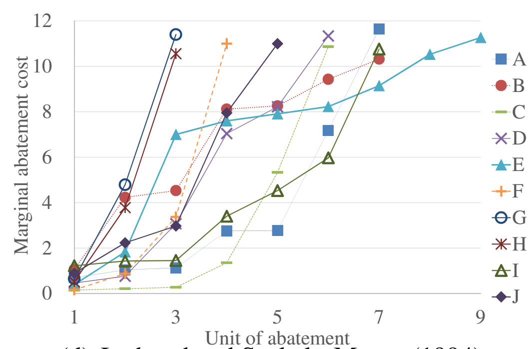
(a) This work and Cason and Gangadharan (2006)



(b) Godby et al. (1997)



(c) Muller et al. (2002)



(d) Ledyard and Szakaly-Moore (1994)

Figure 9: Marginal abatement cost schedules for all types in each work for MPS studies

List of Tables

Unit of abatement	T1 (firms 1-2)	T2 (firms 3-4)	T3 (firms 5-6)	T4 (firms 7-8)
1	53	67	27	35
2	61	70	35	38
3	70	74	44	42
4	80	79	53	47
5	91	86	63	**54**
6	103	95	**73**	**63**
7	116	106	**84**	**74**
8	130	**119**	**98**	**88**
9	**145**	**134**	**113**	**105**
10	**161**	**151**	**129**	**125**
Permit endowment	2	3	5	6

Table 1: Assigned marginal abatement costs and permit endowments where the bold numbers indicate the marginal abatement costs saved by the initial permit endowments for each type of firms

Initial coupons =	2

Unit	1	2	3	4	5	6	7	8	*9*	*10*
Cost	53	61	70	80	91	103	116	130	145	161
Bids to buy	35	55	63	72	84	92	98	111		
Offers to sell									150	155

# of coupons you traded =	3
Fixed Revenue =	1000
Total production cost =	−355
Sale from selling =	0
Amount spent for buying =	−267

Your market transaction	
a uniform price =	*89*
# of coupons purchased =	*3*
# of coupons sold =	*0*

After coupons are traded

Production Cost	53	61	70	80	91	0	0	0	0	0

Experimental earning =	***378***
Total earning =	***674***

Table 2: An example of the subjects' computer terminal display

Table 3: Random effects model to test the effect of UPA treatment on efficiency and price

	(1) Efficiency	(2) Price
UPA dummy	0.160^{***}	-5.683^{***}
	(0.0356)	(1.597)
Constant	0.769^{***}	93.43^{***}
	(0.0252)	(1.129)
Observations	120	120
Wald χ^2	20.10	12.66
	[0.000]	[0.000]

Standard errors in parentheses

p-value for Wald χ^2 in square brackets

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Variable	**Mean**	**Std. Dev.**	**Min.**	**Max.**
DA	46.3	14.534	28	111
UPA	9.65	1.117	7	12

Table 4: Statistics for the volume of trades in a period per treatment ($N = 60$)

	Bids to buy				Offers to sell				Aggregate			
	UPA		DA		UPA		DA		UPA		DA	
	OLS	Median	OLS	Median	OLS	Median	OLS	Median	OLS	Median	OLS	Median
Value	0.883**	0.937**	−0.109*	0.000	1.13**	1.023**	0.121**	0.000	1.144**	1.034**	0.007	0.000
	(0.009)	(0.005)	(0.051)	(0.016)	(0.030)	(0.007)	(0.078)	(0.000)	(0.019)	(0.003)	(0.051)	(0.0228)
Intercept	1.537*	0.625*	91.535**	82.000**	−1.851	0.568	94.640**	100.000**	−11.291**	−3.310**	94.405**	95.000**
	(0.774)	(0.083)	(5.380)	(1.515)	(2.322)	(0.884)	(6.473)	(0.000)	(1.235)	(0.241)	(4.438)	(2.160)
Observations	2880	2880	1739	1739	1920	1920	2228	2228	4800	4800	3967	3967
R^2	0.75	0.63	0.03	0.000	0.322	0.599	0.004	0.000	0.549	0.649	0.000	0.000

Note that ** and * indicate the 1% and 5% significance levels, respectively, and numbers in parentheses are standard deviations. For median regressions, R^2 is "pseudo" R^2.

Table 5: OLS and median regressions of "bids to buy," "offers to sell," and the "aggregate" for UPAs and DAs

Table 6: Production costs for (a) 2 coupons and (b) 6 coupons, respectively

(a) A case of 2 coupons

Unit	1	2	3	4	5	6	7	8	**9**	**10**
Cost	25	35	47	61	75	91	111	141	173	211

(b) A case of 6 coupons

Unit	1	2	3	4	**5**	**6**	**7**	**8**	**9**	**10**
Cost	25	35	47	61	75	91	111	141	173	211

The bold face of the number in the "unit" column represents the production units whose costs are saved by holding coupons.

Table 7: Production costs

Unit	1	2	3	4	5	**6**	**7**	**8**	**9**	**10**
Cost	v_1	v_2	v_3	v_4	v_5	v_6	v_7	v_8	v_9	v_{10}

Table 8: Ranking of offers to sell and bids to buy

Coupons	Bids to buy	Offers to sell
1	200	30
2	198	35
3	195	39
4	185	40
5	174	42
6	172	49
7	170	50
8	170	51
9	168	51
10	165	53
11	163	57
12	147	64
13	145	65
14	144	70
15	139	71
16	138	74
17	120	85
18	114	85
19	111	99
20	98	100
21	96	101
22	85	111
23	83	120
24	79	123
25	77	142
26	66	155