Transactions Costs in Tradable Permit Markets: An Experimental Study of Pollution Market Designs[*]

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Abstract

Many countries have adopted or are considering incentive approaches to environmental regulation, such as tradable permit schemes to control pollution. This paper uses laboratory experiments to study an important design feature of tradable permit programs: how the transaction costs incurred by participants interact with the initial permit endowment mechanism to influence the cost-effectiveness of overall emissions abatement. In a competitive market without transaction costs the initial distribution of permits affects equity but has no impact on the cost-effectiveness of final abatement responsibility. In the presence of transaction costs, however, even in a competitive market the initial distribution of permits can affect both abatement costs and equity. We study treatments in which marginal transaction costs are zero, constant and declining, all using the continuous double auction institution. Our results show that consistent with theory, when marginal transaction costs are declining prices deviate less from the competitive equilibrium if the "misallocation" of the initial permit distribution is greater. The deviation from the zero transaction cost competitive equilibrium does not vary with the initial permit endowment when marginal transaction costs are constant.

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1. Introduction

Many countries have adopted or are considering incentive approaches to environmental regulation, such as tradable permit schemes to control pollution. Tradable emissions permits (or "allowances") are one of the regulatory instruments that use market incentives to achieve environmental standards at lower costs. Owners of permits are allowed to emit pollutants up to a specified level. Participants can trade permits with each other, so polluters whose abatement costs are relatively high have an incentive to buy permits, while polluters whose abatement costs are relatively low have an incentive to sell permits. Permit buyers therefore tend to pollute more than permit sellers, yet overall environmental standards are met because the regulator issues only enough permits to achieve the standard in aggregate. Trading permits between polluters minimizes the cost of complying with the standard because a well-functioning permit market with low transaction costs equalizes the marginal cost of emissions abatement across firms.

Environmental regulators must make numerous design choices when implementing new permit markets, and many of these design choices affect the transaction costs incurred by market participants. Regulators must also decide how to endow firms or consumers with permits. This paper uses laboratory experiments to study how transaction costs interact with the initial permit endowment to influence the cost-effectiveness of the overall emissions abatement. With zero transaction costs, the initial endowment affects only equity, and not the cost-effectiveness of the final competitive allocation of permits following trading. In the presence of transaction costs, however, cost-effectiveness can be significantly compromised depending on which endowment mechanism is used.[1]

Abundant anecdotal evidence exists regarding the presence of transaction costs in emission permit markets (e.g., Atkinson and Tietenberg, 1991), but systematic empirical evidence is scarce (Kerr and Mare, 1995, and Gangadharan, 2000). Transaction costs can arise at various stages of trading. Prior to entering the market, the firm has to learn the rules of the market, work out its optimal production plan and decide whether or not it will trade. Once it obtains information about the market and decides to trade, the firm searches for trading partners and initiates negotiations. Hence the potential sources of transaction costs incurred by firms in tradable permit markets include search, information, bargaining and decision costs. Another source of transaction costs is the settlement costs of finalizing a trade. The seller must deliver the permit as agreed in the contract, and transaction costs might be incurred to enforce the contract.

Stavins (1995) showed that in theory, the impact of transaction costs depends on the initial endowment of permits. Political concern over permit trading has often focused on the initial endowment mechanism, with powerful industry groups lobbying for one endowment or the other (Cramton and Kerr, 1999). Historically, initial endowments have been negotiated and "grandfathered" based on past emissions or outputs. In the SO_2 trading program created by the Clean Air Act Amendments of 1990 in the U.S., endowments are based on the electricity generating capacity of the affected units. International emission endowments were negotiated in the 1997 Kyoto Protocol to reduce worldwide greenhouse gas emissions, based on percentage reductions relative to 1990 emission levels.[2] More recently, alternative endowment schemes have

[1] In the long run with endogenous entry and exit, Kling and Zhao (2000) show that the endowment mechanism can affect total abatement costs even without transaction costs. The present paper considers only short run cost-effectiveness, and how different types of transaction costs affect this overall abatement efficiency.
[2] The extent to which countries could trade emission rights internationally was a major point of contention is the failed 2000 Protocol implementation talks in The Hague. The United States, Canada, Japan and Australia argued for free international trading with low transaction costs, while the European Union argued for significant international restrictions.

been proposed. For example, an "updating" endowment method based on changes in output has been proposed in some States for the NO_x trading system in the Ozone Transport Commission in the Northeastern U.S.,[3] and an initial endowment to households (rather than firms) has been proposed for carbon trading in Australia. In this proposed Australian system households would then be free to sell these allowances to emitters or retain them.[4] Clearly, an output-based endowment is closer to a cost-efficient final allocation than is a household-based endowment, and it is important to understand the effect of the initial endowment accuracy on total realized abatement costs in the presence of permit market transaction costs.

This paper uses laboratory double auction markets to examine the impact of transaction costs in emission permit markets and to study the impact of transaction costs on market outcomes when initial permit endowments differ. We examine treatments in which marginal transactions costs are zero, constant or declining. In these treatments the initial endowment is changed from 20 percent of the cost-effective allocation to 60 percent of the cost-effective allocation. Our results indicate how permits could be endowed to reduce the impact of transaction costs, depending on the properties of the transaction costs function.

We find that positive transaction costs cause prices to deviate from the zero transactions costs baseline. Consistent with the theoretical results in Stavins (1995) (summarized below in Section 2.2), when marginal transactions costs are decreasing, the prices and quantity traded deviate less from the zero transactions costs equilibrium if the initial endowment is further away from the cost-effective allocation. This is because the *marginal* impact of the transaction costs is lower in this decreasing transactions costs treatment when the initial endowment is highly

[3] http://www.sso.org/otc. See Fischer (2000) for an analysis of output-based endowments.

[4] National Emissions Trading, Australian Greenhouse Office, Discussion paper 2, page 48. This discussion paper is available online at the Australian Greenhouse Office Internet Site at http://www.greenhouse.gov.au/ emissionstrading.

suboptimal and therefore requires a significant transaction volume to reallocate permits. Also consistent with Stavins' model, when marginal transaction costs are constant the initial endowment of permits does not influence transaction prices or quantity traded.

2. Experimental Design and Model Predictions

This paper follows in the tradition of laboratory research on permit market designs, which has been very active because empirical work based on field data is constrained by the limited implementation of permit markets in the field. Most experimental work has focused on specific features of emissions trading. For example, many recent experiments have evaluated features of the trading institutions implemented or planned for specific emissions trading programs, such as experiments run to testbed and evaluate the SO_2 market in the U.S. (e.g., Franciosi et al., 1993, and Cason and Plott, 1996). Muller and Mestelman (1994) present experiments which compare the trading rules for the U.S. SO_2 market with rules proposed for trading NO_x allowances in Southern Ontario, and find improved efficiency in the proposed Canadian trading institutions. Experiments were also conducted to testbed and study the design in the Regional Clean Air Incentive Market (RECLAIM), a tradable permit program implemented in Los Angeles to reduce the emissions of sulfur and nitrogen oxides (Carlson et al., 1993a, 1993b, and Cason and Gangadharan, 1998). Various researchers have used experiments to explore the impact of market power in permit markets (Soberg, 2000, Muller et al., 2001, Godby, 1999, Carlen, 1999 and Ledyard and Szakaly-Moore, 1994) and the effect of uncertainty in the market on trading prices, volume and the firms ability to realize cost savings (Ben-David et al., 2000)

To focus on the market features of interest—here the interaction of different forms on transaction costs with different initial permit endowments—this paper deliberately abstracts from many additional market characteristics that exist in the field. For example, we do not include an opportunity for traders to “bank” permits for future use (as studied by Cronshaw and Brown-Kruse, 1999), nor do we study the implications of irreversibility in the choice of production process (as studied by Ben-David et al., 1999). We focus on the implications of transaction costs in a relatively simple market environment in order to draw clear inferences from the laboratory data. Although this limits the parallelism between the laboratory and the field, we believe that the laboratory is most useful for studying simple, special cases. Data from the field are more appropriate for evaluating the overall performance of specific emissions trading systems.

2.1 Environment and Treatment Variables

We conduct 28 sessions, in each of which ten subjects trade in a computerized double auction, using the University of Arizona Economic Science Laboratory Double Auction (ESLDA) software. We chose the double auction trading institution because it has very small endogenous transaction costs, which allows us to control transaction costs as an exogenous treatment variable, using “fees” that sellers must pay to execute transactions.[5] We focus on the impact of two treatment variables: transaction costs and the initial permit endowment. We study treatments in which these marginal transaction costs are zero, constant and declining. The sessions with zero transactions costs are conducted to serve as a baseline case. Constant marginal transaction costs can be thought of as the cost of reporting a trade to the regulatory authority or fixed permit brokerage commissions, which remain the same (per unit) regardless of the quantity traded. Declining transaction costs might occur, for example, if brokers offer quantity discounts, if commissions do not depend directly on the units traded (such as fixed “per trade”

[5]Jamison and Plott (1997) study the behavior of double auction markets in which a cost is imposed in the form of a tax on bids and asks but not on transactions. Their study indicates that this type of tax on the provision of public bid and ask price information has a surprisingly small impact on market outcomes.

commissions), or if traders' transactions costs decline as they acquire more experience in the market. Sellers in this laboratory market pay the transaction costs as is common in many financial and housing markets. In some markets in the field both buyers and sellers (or only buyers) pay transaction fees, but in equilibrium the fees' overall impact on the market is the same regardless of who pays. This equivalence is analogous to the familiar liability side equivalence for tax incidence (e.g., Musgrave, 1959). In the constant marginal transaction costs sessions, sellers incur a transaction fee of 30 cents for every unit they trade. In the decreasing costs sessions, sellers incur a 40-cent transaction fee for the first unit they trade and then the fee decreases by 4 cents for every additional unit sold.

The other treatment variable we consider is the initial endowment of permits. The initial endowment of permits is set to either 20 percent of the cost-effective allocation or 60 percent of the cost-effective allocation. Figure 1 presents the induced values and costs used in all sessions. The differing endowment treatments correspond to shifting the vertical axis between the Q=10 and Q=30 positions, as indicated in the figure. The 20 percent endowment treatment corresponds to the case in which endowments are not closely tied to past or projected emissions, while the 60 percent endowment treatment is closer to an historic output (i.e., grandfathering) or current output allocation scheme. In the 20 percent sessions, the subjects have the same induced marginal values and control costs for the first 4 units and then the abatement cost curves become steeper near the marginal units. In the 60 percent sessions, the marginal values and control costs are different for each subject.

All subjects are undergraduate students from Purdue University and the University of Melbourne. Subjects are randomly assigned as sellers and buyers. All sessions have 5 sellers and 5 buyers. Subjects trade in experimental dollars, which are later converted to local currency. The experimental dollars are multiplied by 2 in the U.S. and by 3 in Australia, and then an amount is added or subtracted to arrive at the final earnings paid to subjects. This non-salient component of subject earnings varies according to the specific treatment studied.[6] This payment procedure ensures that the marginal incentives to trade are the same across treatments; the different amounts of non-salient payoffs are used only to adjust the absolute amount of payoffs to subjects due to changes in permit endowments or transaction costs. Most subjects earned between U.S. $25 and $40, and sessions lasted between 90 and 120 minutes.

Instructions on how to calculate transaction fees are distributed to both sellers and buyers. These instructions—reproduced in the Appendix—are read aloud after subjects complete the basic computerized instructions on how to trade in the market. At the end of each trading period, the experimenter distributed to the sellers a summary of the transaction fees they incurred in the previous period. Each trading period lasts for 4 minutes in the inexperienced, 20 percent endowment sessions. For the sessions with 60 percent endowment and for all sessions with experienced subjects, the trading period lasts for 3 minutes. Table 1 summarizes the experimental design. The table indicates that all sessions ran for at least 9 periods, and most ran for 13 to 15 periods. Some sessions concluded early due to lab time constraints or network difficulties.

2.2 Theoretical Model

The testable hypotheses in this paper are derived in Stavins (1995). Here we summarize the essential components of the model. The cost minimizing problem for firm *i* in a competitive pollution permit market with transaction costs is described by the following equation:

[6] For example, in the decreasing transaction costs sessions with 20 percent endowment, subjects have a nonsalient payoff of –65, whereas in the decreasing transaction costs, 60 percent endowment sessions, subjects have a nonsalient payoff of +25. So effectively in the 20 percent endowment sessions, we are taking away some of the large inframarginal trading surplus which traders do not earn in the 60 percent endowment sessions.

$$\min_{r_i} \left[c_i(r_i) + p(u_i - r_i - q_{0i}) + T(t_i) \right] \text{ st: } r_i \geq 0$$

where r_i denotes emission reductions, u_i is unconstrained emissions, q_{0i} is the initial permit allocation, t_i denotes the quantity of permits traded (so $t_i = |u_i - r_i - q_{0i}|$), p is the price of permits, $c_i(r_i)$ is the pollution abatement cost function and $T(t_i)$ is the transaction cost function.

In equilibrium all firms minimize costs and the permit price p adjusts to clear the market, so that the sum of marginal control costs and marginal transactions costs is equal across firms. In a two-firm model, with firm 1 being a seller and firm 2 being a buyer, the equilibrium condition would be the following:

$$c_1'(r_1) + T'(t_1) = c_2'(r_2) .$$

As long as marginal transaction costs are positive ($T'(t_1) > 0$), the transaction costs drive a wedge between the buyer's and the seller's marginal emission control costs ($c_1'(r_1)$ and $c_2'(r_2)$ respectively). The equilibrium therefore does not minimize overall control costs. Since the seller's marginal control costs are lower than the buyer's control costs, the trading volume and the emission reductions r_1 of the seller are lower than in the zero transactions cost baseline.

We want to examine the effect of changes in the initial endowment on the equilibrium outcomes in the presence of transaction costs. This effect is obtained by differentiating both sides of the above equilibrium condition with respect to r_1, r_2 and q_{01}:

$$\frac{dr_1}{dq_{01}} = \frac{-T''(t_1)}{\left[T''(t_1) + c_1''(r_1) + c_2''(r_2) \right]}$$

If $T''(t_1) = 0$, then $\frac{dr_1}{dq_{01}} = 0$. This implies that when marginal transaction costs are constant, the initial endowment of permits has no effect on the equilibrium. Hence with constant transaction costs, the result is similar to the case when transaction costs are zero. On the other hand, if marginal transaction costs are decreasing then the initial allocation affects the equilibrium outcome. A change in the initial allocation away from the cost-effective allocation will lead to outcomes that are nearer to the zero transactions cost competitive equilibrium, i.e., if $T''(t_1) < 0$, then $\frac{dr_1}{dq_{01}} > 0$.[7] As mentioned above, declining marginal transaction costs might occur if brokers offer quantity discounts, if transaction costs are mostly "per trade" rather than "per unit," or if firms acquire more information about the market and hence experience lower information and search costs. Since transaction costs decline with each additional unit traded, firms can benefit from scale economies when trading additional units. An inaccurate initial endowment requires firms to engage in more trade so that a move from a relatively cost-effective initial endowment to a less cost-effective initial endowment leads to a higher transaction volume and hence lower marginal transaction costs. That is, the marginal wedge between buyers' and sellers' control costs is smaller if the inaccurate endowment encourages high transaction volume and marginal transaction costs are decreasing.

3. Results

We organize the presentation of the results using the formal hypotheses derived from the Stavins (1995) model of transaction costs. We present market prices, transaction quantities and the cost-effectiveness of the final abatement responsibility following trading. All of these related

[7] The second-order conditions ensure that the denominator of the above expression is positive.

measures of market performance generally support the model's predictions.

3.1 Transaction Prices

Hypothesis 1: Transactions costs cause prices to deviate from the zero transactions cost baseline.

Evidence: Figures 2 through 6 present mean transaction prices for the 28 sessions. Most of the eight baseline sessions with zero transaction costs shown in Figure 2 converged to the competitive equilibrium range [249, 252], with the exception of sessions M901z20 and P906z20. By contrast, Figures 3 through 6 indicate that in the later periods mean prices rise above the upper competitive equilibrium price of 252 francs in 19 of the 20 sessions with positive transaction costs (session M505d20 is the exception). A conservative two-sample, one tailed non-parametric Mann-Whitney test (using one observation per session—the mean price over the final 5 periods) rejects the null hypothesis of no mean price impact of both types of transaction costs in favor of Hypothesis 1, for all possible pairwise treatment comparisons between zero and non-zero transaction cost sessions (U=0 or 1, n_1=4, n_2=5, p<0.05).[8]

Hypothesis 2: With decreasing marginal transaction costs, transaction prices deviate less from the zero transaction costs competitive equilibrium if the initial endowment of allowances is further away from the cost-effective allocation.

Evidence: Figures 3 and 4 present the mean transaction prices in the decreasing transaction costs sessions. When the initial endowment is only 20 percent of the cost-effective allocation (Figure 3), mean prices range between 250 and 260 after the first few periods. When the initial endowment is 60 percent of the cost-effective allocation (Figure 4), mean prices in all five sessions eventually exceed 260. Figure 7 summarizes the mean transaction prices and quantities traded over the final five periods of each session. This figure indicates that these late period mean transaction prices in the decreasing, 20 percent endowment treatment (the diamonds) are all lower than the corresponding prices in the decreasing, 60 percent endowment treatment (the squares). Therefore, a two-sample Mann-Whitney test rejects the null hypothesis that mean prices do not depend on the initial endowment with decreasing transaction costs, in favor of Hypothesis 2 (U=0, n_1=n_2=5, p<0.01).

Hypothesis 3: With constant marginal transaction costs, the initial endowment of allowances has no impact on transaction prices.

Evidence: Figures 5 and 6 present the mean transaction prices in the constant transaction costs sessions. When the initial endowment is only 20 percent of the cost-effective allocation (Figure 5), mean prices range between 258 and 267 in the second half of the sessions. The range of mean prices is similar but narrower when the initial endowment is 60 percent of the cost-effective allocation (Figure 6), varying between 261 and 265 throughout most of the sessions. Figure 7 indicates that the end-period mean transaction prices in the decreasing, 20 percent endowment treatment (the triangles) bracket the corresponding prices in the decreasing, 60 percent endowment treatment (the circles). The data therefore support Hypothesis 3: a two-sample Mann-Whitney test fails to reject the null hypothesis that the mean prices are equal for the two initial endowment treatments when transaction costs are constant (U=9, n_1=n_2=5, *ns*).

Table 2 presents some parametric tests of Hypotheses 1-3 when controlling for other factors such as subject experience, session location, and time trends. It reports a random effects model of the mean price observed in each period as a function of these factors and the four treatment dummies. We also interact the treatment dummies with the time trend variable to allow convergence rates to vary across the main treatments (note that 1/period approaches zero as period increases). The omitted dummies are for inexperienced subjects at Purdue University in the zero transaction costs sessions. The generalized least square estimates presented are corrected

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[8] U denotes the Mann-Whitney test statistic, and n_1 and n_2 are the sample sizes.

for autocorrelation, and the 28 individual sessions are the random effect.

The estimates indicate that experiment location and subject experience do not have a significant influence on mean prices, and the only significant price trend is in the constant transaction cost, 20 percent endowment treatment. Consistent with Hypothesis 1, the dummy variables indicate that mean prices are significantly higher in all treatment sessions compared to the zero transaction costs baseline, with the exception of the decreasing costs sessions with 20 percent endowment. Consistent with Hypothesis 2, a Wald test rejects the null hypothesis that the decreasing marginal transactions costs, 20 percent endowment dummy variable equals the decreasing marginal transaction cost, 60 percent endowment dummy variable ($\chi^2_{1\text{ d.f.}} = 6.00$, $p<0.01$).[9] And consistent with Hypothesis 3, a Wald test fails to reject the null hypothesis that the constant marginal transactions costs, 20 percent endowment dummy variable equals the constant marginal transaction cost, 60 percent endowment dummy variable ($\chi^2_{1\text{ d.f.}} = 0.004$, $p=0.97$).[10]

3.2 Trading Volume and Final Allowance Distributions

Based on the support for Hypothesis 1 (transaction costs raise prices), it is not surprising that the data support the analogous prediction for transaction quantity: Normalized quantity traded is lower in the sessions with positive transaction costs, compared to the baseline sessions with zero transactions costs.[11] The first column of Table 3 reports the mean normalized transaction

[9] A two-restriction test that both the decreasing transaction cost dummy variables and time trend treatment interaction terms are equal also rejects the null hypothesis of no treatment effect in favor of Hypothesis 2 ($\chi^2_{2\text{ d.f.}} = 6.39$, $p<0.05$).

[10] A two-restriction test that both the constant transaction cost dummy variables and time trend treatment interaction terms are equal does reject the null hypothesis of no treatment effect, contrary to Hypothesis 3 ($\chi^2_{2\text{ d.f.}} = 14.36$, $p<0.01$). This significant difference arises due to the negative and significant 1/period interaction with the constant transaction cost, 20 percent endowment dummy variable.

[11] This comparison is normalized to account for the fact that actual transaction volumes are lower (by 20 units) when the initial endowment is 60 percent rather than 20 percent of the cost-effective allocation of allowances. We add 10 to the actual quantity traded in the 20 percent endowment sessions and 30 to the quantity traded in the 60 percent endowment sessions, so as to make the transaction quantity totals comparable (as in Figure 1). After the first few inexperienced periods, subjects always had plenty of time to execute all the trades that they desired.

quantity over the final five periods in each session. The mean transaction quantity in all eight zero transaction cost sessions exceeds the mean transaction quantity in 19 of the 20 sessions with positive transactions costs. One-tailed Mann-Whitney tests reject the null hypothesis that the quantity traded is not lower in the positive transactions costs sessions compared to the zero transactions costs sessions (U=0, 1 or 2 depending on the pairwise comparison, for all cases n_1=4, n_2=5, p<0.05). In the remainder of this subsection, we test the other transaction quantity implications of the theoretical model.

Hypothesis 4: With decreasing marginal transaction costs, transaction quantity deviates less from the zero transaction costs competitive equilibrium if the initial endowment of allowances is further away from the cost-effective allocation.

Evidence: The top third of Table 3 indicates that when transaction costs are decreasing, transaction quantity is always greater—and thus closer to the zero transactions cost benchmark—when the initial endowment is only 20 percent of the cost-effective allocation than when the initial endowment is 60 percent of the cost-effective allocation. The data therefore reject the null hypothesis of no impact of the initial endowment in favor of Hypothesis 4 based on a two-sample Mann-Whitney test (U=0, n_1=n_2=5, p<0.01).

Hypothesis 5: With constant marginal transaction costs, the initial endowment of allowances has no impact on transaction quantity.

Evidence: The middle third of Table 3 presents the mean normalized quantity traded in the final five periods of the constant transaction costs sessions. These mean quantities overlap in the two endowment treatments with constant transaction costs, and consistent with Hypothesis 5 the Mann-Whitney test fails to reject the null hypothesis that mean transaction quantities are unaffected by the initial permit endowment (U=6, n_1=n_2=5, *ns*).

Table 4 presents estimation results from a random effects model on the normalized transaction quantity in each period—analogous to the mean price model in Table 2—to provide a more powerful but parametric test of Hypotheses 4 and 5. The estimates for the treatment dummies show that the quantity traded is significantly lower in all four cases than in the baseline case of zero transaction costs. The negative and significant coefficient on the time trend (1/period) indicates that quantity traded is also lower in the initial periods. This is common in double auction markets, as subjects usually take some time to understand the market and the trading structure. As with the mean price model, neither experience nor session location significantly affect quantity traded. Consistent with Hypothesis 4, the coefficient estimate on the dummy variable for the decreasing transaction costs 60 percent endowment treatment is approximately three times greater than the estimate in the decreasing transaction costs 20 percent endowment treatment. This difference is highly significant ($\chi^2_{1\text{ d.f.}} = 12.17$, $p<0.01$). Consistent with Hypothesis 5, the coefficient estimates for the two constant transaction cost dummy variables (–7.58 versus –6.44) are not significantly different ($\chi^2_{1\text{ d.f.}} = 1.11$, $p=0.29$).[12]

3.3 Cost-Effectiveness of Abatement

Trade in this market reallocates how much each firm is responsible for emissions abatement, and we define the cost-effectiveness of this reallocation as the total gains from trade (resulting from reduced emission control costs) as a percentage of the maximum possible gains from trade.[13] The two rightmost columns of Table 3 present the cost-effectiveness for each

[12] Similarly, a two-restriction test that both the decreasing transaction cost dummy variables and time trend treatment interaction terms are equal rejects null hypothesis of no treatment effect, consistent with Hypothesis 4 ($\chi^2_{2\text{ d.f.}} = 15.85$, $p<0.01$); and a two-restriction test that both the constant transaction cost dummy variables and time trend treatment interaction terms are equal does not reject the null hypothesis of no treatment effect, consistent with Hypothesis 5 ($\chi^2_{2\text{ d.f.}} = 1.24$, $p=0.54$).

[13] We do not include realized transaction costs in this cost-effectiveness comparison. As we discuss in the conclusion, the proper way to treat transaction costs in the calculation of the overall cost-effectiveness of the permit trading system depends on their interpretation.

session, both for all periods and for the final five periods of each session. Cost-effectiveness is high in this setting, but this result is due to the specific marginal emission control costs (resulting in the induced allowance demand and supply shown in Figure 1) implemented in the experiment. The gains from trade for the inframarginal units are quite high, so the inefficiencies arising from failures to trade marginal units or extramarginal substitution are comparatively small. What is important for our hypotheses is the relative cost-effectiveness in the various treatments, not the overall levels.[14]

Hypothesis 6: With decreasing marginal transaction costs, final cost-effectiveness is higher if the initial endowment of allowances is further away from the cost-effective allocation.

Evidence: The top half of Table 3 displays the decreasing marginal transaction costs sessions. In the final five periods, the cost-effectiveness in four of the 20 percent endowment sessions exceeds the highest cost-effectiveness across all five 60 percent endowment sessions. The lowest cost-effectiveness occurs in a 20 percent endowment session (P424d20x), however, which leads to an insignificant Mann-Whitney *U* statistic of 5 (n_1=n_2=5). This nonparametric test therefore fails to reject at the 5 percent significance level the null hypothesis of no endowment treatment effect for the decreasing transaction cost sessions in favor of Hypothesis 6. It does reject this null hypothesis in the direction predicted by Hypothesis 6 at the marginally significant 10 percent level, however.

Hypothesis 7: With constant marginal transaction costs, the initial endowment of allowances has no impact on final cost-effectiveness.

Evidence: The middle of Table 3 displays the constant marginal transaction costs sessions. In the

[14] Besides the cost-effectiveness of the final abatement responsibility, it is necessary to know the avoided environmental damages in order to assess the overall efficiency of the permit market. By comparing only the cost-effectiveness across treatments we have implicitly assumed that such avoided damages are equal across treatments. This is not unreasonable for a uniformly mixed pollutant since overall emissions are fixed across treatments by the

final five periods, the cost-effectiveness is usually higher when the initial endowment is closer to the cost-effective allocation, but the highest observed cost-effectiveness in this treatment is in a low endowment session (P413c20). Consequently, the Mann-Whitney *U* statistic is 5. This is not significant for the n_1=n_2=5 sample size, based on a two-sided test because the direction is not predicted. The data are therefore consistent with Hypothesis 7.

Finally, consider Table 5, which presents an alternative parametric comparison of the cost-effectiveness in the various treatments using a random effects tobit model. We use a tobit specification to account for the restriction that cost misallocation is bound below by zero.[15] Consistent with previous laboratory double auction experiments, cost misallocation falls over time (i.e., trading efficiency rises over time), as indicated by the positive and highly significant coefficient on the 1/period term. Contrary to Hypothesis 6 (but consistent with the nonparametric test results above), cost misallocation levels in the two decreasing costs treatments are not significantly different ($\chi^2_{1\text{ d.f.}} = 0.40$, p=0.53). The time interaction with the decreasing transaction cost, 60 percent endowment dummy is negative and significant, however, which indicates that cost misallocation is lower in the initial periods in this treatment compared to the zero transaction cost (omitted baseline) treatment. A Wald test rejects the null hypothesis that both the dummy and the interaction terms are equal in the decreasing transaction costs treatment ($\chi^2_{2\text{ d.f.}}$ = 28.66, p<0.01). Similar results hold in the constant transaction costs comparison of Hypothesis 7. The treatment dummies alone are not significantly different ($\chi^2_{1\text{ d.f.}} = 0.01$, p=0.94), but the data reject the hypothesis that both the dummy and the interaction terms are equal in the constant transaction costs treatment ($\chi^2_{2\text{ d.f.}} = 61.27$, p<0.01).

emissions cap. All laboratory experiments on emissions trading that we are aware of also do not explicitly include environmental damages, but this might be an interesting feature to include in future research.

4. Conclusion

Well-functioning emission permit markets do not require extensive regulator involvement, as indicated by the experience in the U.S. sulfur dioxide allowance market. The regulator must, however, make important design decisions—such as how the trading instrument is defined, the necessary reporting requirements, and whether to sponsor centralized trading mechanisms. All of these decisions impact transaction costs. As the Stavins (1995) model highlights, the regulator also makes initial permit endowment decisions, which can affect the cost-effectiveness of the final equilibrium allocations in the presence of transaction costs. Without transaction costs, the initial endowment does not affect final allocations, which is perhaps why economists have paid less attention to the typically more political issue of the initial permit endowment.

The results of this experiment generally support the implications of Stavins' model of transaction costs for permit markets. Transaction costs drive a wedge between buyers' and sellers' marginal costs of emission control, so they cause prices and final allocations to deviate from the zero transaction cost competitive equilibrium. The deviations are equally great with constant marginal transaction costs, irrespective of the accuracy of the initial endowment of permits. With decreasing marginal transaction costs, by contrast, the deviations from the zero transaction costs competitive equilibrium are lower when the initial endowment is further away from the cost-effective allocation. This is because the more inaccurate endowment requires a higher transaction volume to approach the cost-effective allocation, which leads to lower marginal transaction costs when marginal transaction costs are decreasing. That is, the marginal

[15] We use cost misallocation = 1 – cost-effectiveness because the lower bound restriction of zero is fixed in LIMDEP's maximum likelihood tobit estimation procedure with random effects.

wedge between buyers' and sellers' emission control costs is lower if marginal transaction costs decrease to a lower level.

The policy implications of these results depend on whether the transaction costs in permit markets are mostly real resource costs or are simply transfers to other agents in the economy (such as to brokers). If the most significant transaction costs are real (e.g., compliance, reporting, information acquisition) costs, then the transactions costs represent a deadweight loss that should be included in the overall cost of the trading program. To minimize such costs, the regulator should focus on achieving relatively accurate initial endowment. Grandfathering or (especially) auctions can help make the initial endowment more accurate. If instead the most significant transaction costs are transfers (e.g., brokerage fees), then such costs are not deadweight losses. In this case, an accurate initial endowment is less important. The experiment supports the Stavins model, indicating that more cost-effective final allocations could be achieved in the presence of decreasing marginal transaction costs if initial endowments are less accurate. More research that investigates the source and magnitude of transaction costs in emission permit markets would be useful to draw specific policy recommendations.

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Appendix
Exact Typescript of Additional Instructions following Computerized Instructions (for Decreasing Marginal Transaction Cost Treatment)

Additional Instructions

In today's experiment sellers will pay a *transaction fee* for every unit that they sell. Your computer will not compute these transaction fees, so instead you will keep track of them on a piece of paper. Each seller will keep track of his or her earnings on the attached Personal Earnings Sheet, and the amount paid will be as indicated by these written figures—not the amount shown on the computer. Buyers do not pay any transaction fees, so they can rely on the computer to calculate their earnings.

The *transaction fee* paid will depend on the number of units sold. The first unit incurs a transaction fee of 40 experimental cents, and each additional unit sold incurs a transaction fee that is 4 cents less than the previous unit's fee. The following table summarizes the additional fees paid for each unit sold, as well as the total fees paid for all units sold in each period.

Unit Sold in This Period	Additional Transaction Fee Paid When Selling That Unit	Total Transaction Fees Paid for All Units Sold This Period
1st	$0.40	$0.40
2nd	$0.36	$0.76
3rd	$0.32	$1.08
4th	$0.28	$1.36
5th	$0.24	$1.60
6th	$0.20	$1.80
7th	$0.16	$1.96
8th	$0.12	$2.08
9th	$0.08	$2.16
10th	$0.04	$2.20

When deciding what prices to offer and accept, keep in mind that the transaction fee is an additional cost that increases your total costs beyond the costs displayed on your computer trading screen. Your total costs for a unit are your computer-displayed costs for that unit PLUS the transaction fee that you must pay to sell that unit, so you should try to have sufficient computer-displayed profits on each unit to cover your transaction fees on that unit.

Each period the experimenter will distribute to each seller a printout of the previous period's transaction fees. Sellers should enter the total fees in column (2) of their Personal Earnings Sheet. Sellers should enter the total trade earnings from their computer in column (1) of their Earnings Sheet. The difference of the gross (computer) earnings in column (1) and the transaction fees in column (2) is the net earnings, which should be written in column (3). The sellers will be paid the total of their net earnings summed across all periods of the experiment. We recommend keeping track of the cumulative earnings (the total earnings in all previous periods) in column (4).

Please note that all earnings during the experiment are expressed in *Experimental Dollars*. These earnings will be converted to real dollars at the end of the experiment, which you will receive in cash. First everyone's experimental dollars will by multiplied by __. Then you will have an amount either added to or subtracted from this total to arrive at the final figure that you will be paid. Your amount to be added or subtracted is written on the sheet attached to these instructions. These amounts are *private information* that you should not reveal to other participants, and the amounts might differ across participants. Be aware that the more experimental dollars you earn, the more cash you take home at the end of the experiment.

Personal Earnings Sheet Seller Number _____

Period Number	Gross Earnings from Computer (col. 1)	Total Transaction Fees (col. 2)	**Net** Earnings (col. 3=col. 1 - col. 2)	Cumulative Earnings (col. 4)
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				
14				
15				

Multiply total by ___ = ___________

Add or Subtract = ___________

Grand Total in real $ = ___________

Table 1: Experimental Design

Nature of Transaction Costs	Initial Endowment	
	20 percent of the cost-effective allocation	60 percent of the cost-effective allocation
Zero (z)	4 sessions: one experienced M420z20 (14 periods) M901z20 (14 periods) P906z20 (14 periods) P913z20x (14 periods)	4 sessions: one experienced P420z60 (15 periods) M830z60 (15 periods) M905z60x (15 periods) P906z60 (11 periods)
Constant Marginal Transaction Costs (c)	5 sessions: two experienced P413c20 (15 periods) M504c20 (17 periods) M522c20x (15 periods) P628c20 (15 periods) P713c20x (15 periods)	5 sessions: two experienced P427c60x (15 periods) M508c60 (15 periods) M516c60 (13 periods) P628c60 (15 periods) P712c60x (14 periods)
Decreasing Marginal Transaction Costs (d)	5 sessions: two experienced P424d20x (15 periods) M505d20 (13 periods) M516d20 (15 periods) M518d20x (10 periods) P712d20 (15 periods)	5 sessions: two experienced P417d60 (11 periods) M511d60 (9 periods) M515d60 (15 periods) M523d60x (14 periods) P720d60x (12 periods)

Note: A P in the session name denotes Purdue University and M denotes Melbourne University. An x in the session name denotes subjects who were experienced in a previous session in this experiment. The z, c and d codes refer to the transaction costs treatment shown in the left column.

Table 2: Generalized Least Squares Estimates from Random Effects Model for Mean Price

Dependent Variable: Mean price each period		
Number of Observations: 362		
R-squared: 0.234		
F (11, 350): 9.74		
Significance level: 0.00000		
Variable	**Coefficient**	**Standard Error**
Dummy for Decreasing Transaction Costs, 20% Endowment	4.26	2.89
Dummy for Decreasing Transaction Costs, 60% Endowment	12.27*	2.97
Dummy for Constant Transaction Costs, 20% Endowment	13.86*	2.82
Dummy for Constant Transaction Costs, 60% Endowment	13.74*	2.86
(Dummy for Decreasing Transaction Costs, 20% Endowment) * (1/period)	2.97	6.50
(Dummy for Decreasing Transaction Costs, 60% Endowment) * (1/period)	10.25	6.54
(Dummy for Constant Transaction Costs, 20% Endowment) * (1/period)	-23.98*	6.46
(Dummy for Constant Transaction Costs, 60% Endowment) * (1/period)	2.96	6.48
Location Dummy (=1 if site is Melbourne)	0.12	1.93
Experience Dummy (=1 if subjects are experienced)	1.61	2.01
Time trend (1/period)	-0.57	4.02
Rho (autocorrelation coefficient)	0.764*	0.030
Constant	249.69*	2.13

* indicates significant at the 95 percent significance level.

Table 3: Average Normalized Quantity Traded and Cost-Effectiveness for the 28 Individual Sessions

Session Name	Normalized Quantity (Final 5 Periods)	Average Cost-Effectiveness (All Periods)	Average Cost-Effectiveness (Final 5 Periods)
Decreasing Transaction Costs, 20% Endowment			
P424d20x	46.0	94.99	96.86
M505d20	49.2	97.06	99.56
M516d20	47.4	96.64	98.39
M518d20x	47.2	98.21	98.57
P712d20	47.0	97.09	98.73
Treatment Mean	47.4	96.80	98.42
Decreasing Transaction Costs, 60% Endowment			
P417d60	44.4	96.33	97.33
M511d60	44.0	95.39	97.16
M515d60	44.2	97.19	97.30
M523d60x	43.8	96.96	97.04
P720d60x	43.8	96.82	96.88
Treatment Mean	44.0	96.54	97.14
Constant Transaction Costs, 20% Endowment			
P413c20	45.0	94.80	97.78
M504c20	41.8	93.91	93.61
M522c20x	43.8	94.78	95.69
P628c20	42.4	88.43	94.83
P713c20x	42.0	88.56	93.18
Treatment Mean	43.0	92.10	95.02
Constant Transaction Costs, 60% Endowment			
P427c60x	44.2	97.28	97.42
M508c60	44.4	96.65	97.44
M516c60	44.0	96.13	97.16
P628c60	43.2	95.47	96.32
P712c60x	44.2	97.26	97.45
Treatment Mean	44.0	96.56	97.16
Zero Transaction Costs, 20% Endowment			
M420z20	50.8	98.09	99.02
M901z20	48.0	96.02	96.21
P906z20	48.6	89.16	98.14
P913z20x	49.4	99.26	99.65
Treatment Mean	49.2	95.63	98.26
Zero Transaction Costs, 60% Endowment			
P420z60	50.0	99.67	99.82
M830z60	49.8	98.55	99.90
M905z60x	48.2	99.19	98.75
P906z60	50.0	98.83	99.58
Treatment Mean	49.5	99.06	99.51

Table 4: Generalized Least Squares Estimates from Random Effects Model for Quantity Traded

Dependent Variable: Quantity traded each period		
Number of Observations: 362		
R-squared: 0.363		
F (11, 350): 18.14		
Significance level: 0.00000		
Variable	**Coefficient**	**Standard Error**
Dummy for Decreasing Transaction Costs, 20% Endowment	-1.83*	1.01
Dummy for Decreasing Transaction Costs, 60% Endowment	-5.79*	1.03
Dummy for Constant Transaction Costs, 20% Endowment	-7.58*	0.98
Dummy for Constant Transaction Costs, 60% Endowment	-6.44*	1.00
(Dummy for Decreasing Transaction Costs, 20% Endowment) * (1/period)	-2.83	8.21
(Dummy for Decreasing Transaction Costs, 60% Endowment) * (1/period)	4.15	8.22
(Dummy for Constant Transaction Costs, 20% Endowment) * (1/period)	15.10	8.19
(Dummy for Constant Transaction Costs, 60% Endowment) * (1/period)	11.35	8.20
Location Dummy (=1 if site is Melbourne)	0.46	0.52
Experience Dummy (=1 if subjects are experienced)	-0.77	0.54
Time Variable for initial outcomes (1/period)	-14.98*	5.09
Rho (autocorrelation coefficient)	0.568*	0.042
Constant	51.00*	0.70

* indicates significant at the 95 percent significance level.

Table 5: Maximum Likelihood Estimates of Random Effects Tobit Model for Cost Misallocation

Dependent Variable: Cost Misallocation Levels		
Number of Observations: 390		
Log Likelihood Function: 678.13		
Restricted Log Likelihood: 652.97		
Chi-Squared (1): 50.33		
Significance level: 0.00000		
Variable	**Coefficient**	**Standard Error**
Dummy for Decreasing Transaction Costs, 20% Endowment	0.011	0.031
Dummy for Decreasing Transaction Costs, 60% Endowment	0.040	0.042
Dummy for Constant Transaction Costs, 20% Endowment	0.044*	0.019
Dummy for Constant Transaction Costs, 60% Endowment	0.033	0.151
(Dummy for Decreasing Transaction Costs, 20% Endowment) * (1/period)	0.006	0.020
(Dummy for Decreasing Transaction Costs, 60% Endowment) * (1/period)	-0.107*	0.022
(Dummy for Constant Transaction Costs, 20% Endowment) * (1/period)	0.075*	0.013
(Dummy for Constant Transaction Costs, 60% Endowment) * (1/period)	-0.085	0.058
Location Dummy (=1 if site is Melbourne)	-0.012	0.016
Experience Dummy (=1 if subjects are experienced)	-0.009	0.015
Time Variable for initial outcomes (1/period)	0.135*	0.012
Constant	-0.002	0.017

* indicates significant at the 95 percent significance level.