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

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Abstract
Regulators' choices of market rules and permit allocations influence tradable emission permit programs. This paper uses laboratory experiments to study how transaction costs interact with permit allocations to determine the cost-effectiveness of emissions abatement. With positive transaction costs, in theory the initial distribution of permits can affect both abatement costs and equity. Consistent with theory, we find that with declining marginal transaction costs prices deviate less from the efficient level if the "misallocation" of the initial permit distribution is greater, and the deviation from efficient prices does not vary with the initial permit endowment when marginal transaction costs are constant.

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

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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]

Transaction costs can arise at various stages of trading. Prior to entering the permit market, the firm has to learn the market's rules, determine how to adjust its optimal production plan because of the environmental regulation, and decide whether or not it will trade permits. 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. Abundant anecdotal evidence exists regarding the importance of transaction costs in emission permit markets (e.g., Atkinson and Tietenberg 1991), but systematic empirical evidence is scarce (Kerr and Mare 1995; Gangadharan 2000). Many researchers have argued that the U.S. Environmental Protection Agency's early Emissions Trading Program to regulate air quality had very few inter-firm trades because of high transactions costs (Tietenberg 1990; Hahn and Hester 1989a and 1989b; Hahn 1989). One factor affecting these costs was the number of levels of bureaucracy involved in trade approval. For example, bubbles approved at the federal level (federal bubbles) were reviewed by the state, by the EPA regional offices and by EPA headquarters. Other trades, including those within state bubbles, were reviewed only by the states.[2] Trading data suggest that their more limited review led some state bubble programs to be more active than the federal programs that

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[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] Bubbles, which were one of the four strategies a source could employ to comply with the regulations, are derived from the concept of placing an imaginary bubble over a multi-source plant. The levels of emission control applied to different sources in a bubble could be adjusted to reduce abatement costs as long as the plant did not exceed the aggregate limit.

also required federal review and approval. The abundance of internal (within firm) trades in this market also suggests that firms preferred to trade with different branches within their organization, apparently to avoid search and bargaining transactions costs. Foster and Hahn (1995) document this for the Los Angeles region, where the trading data suggest that thinly traded pollutants were much more likely to be traded internally or as part of a multi-pollutant cluster or through an intermediary. In addition, very small size trades were uncommon and seemed to incur high transactions costs. Regulating the spatial distribution of emissions also led to higher costs in some markets. For example, in Los Angeles the market was segmented into 38 distinct zones, with many rules governing exchanges between them. This made markets very thin and probably increased transactions costs. Finally, the regulatory restrictions imposed on new and modified sources were also a major factor in limiting trading in this program. Although these sources were subject to more stringent emission control requirements than existing sources, they could not meet these requirements through external trading. Many of the existing sources, which often had lower marginal abatement costs, could have sold permits to new sources to their mutual benefit. However, these trades were not allowed.

The Wisconsin Fox River Water Permit Scheme, aimed at controlling the biological oxygen demand, is also criticized for having large transactions costs (Hahn and Hester 1989a; Hahn 1989). This program imposed several restrictions on eligibility for trades, and firms were required to justify the need for permits. This limited permit transfers to new polluters, plants that were expanding and treatment plants that could not meet the new environmental restrictions through their own abatement. Plants could not trade permits to simply reduce operating or abatement costs. Limits on the duration of permits also restricted trading. The maximum life of the traded right was five years, which is far less than the expected operating life of a facility. Traded rights were also required to be effective for at least one year. This precluded trading of rights for shorter periods to accommodate temporary changes in operating conditions. These restrictions led to high transactions costs and low trading volume.

In contrast to these permit trading programs, the lead permit market was very successful in meeting its environmental targets of lead phasedown from gasoline. This market is often cited as an early example of a well functioning permit market (e.g., Hahn and Hester 1989a), and it featured comparatively lower transactions costs. This regulatory program relied heavily on self-monitoring and reporting by refineries. Refineries only had to report information that was readily available to them and administrative costs for firms participating in lead trading were modest compared to the costs of other programs. Another reason for its success was that all the participants were refineries and they transacted in similar input and output markets. Even in this market, however, Kerr and Mare (1995) find that efficiency losses from transaction costs were about 10%.

In the Regional Clean Air Incentives Market (RECLAIM) in the Los Angeles basin, initiated to reduce NO_x and SO_x emissions, the participating firms are diverse and often do not interact in similar input and output markets. This increases the costs of searching for a trading partner. Rather than dividing the Los Angeles Basin into 38 trading zones, as in the EPA Emissions Trading Program, local regulators implemented only two distinct zones (Coastal and Inland) and overlapping permit expiration dates to avoid end-of-year price ‘‘squeezes.’’ Both of these design features were intended to reduce transactions costs.

Gangadharan (2000) shows that variables which proxy search- and information-type transactions costs appear to explain why a significant number of firms did not trade initially in this program. The effect of these transaction costs on market participation was most significant in the early years of the program, and these impacts declined as the market matured. This is consistent with the findings for the lead market (Kerr and Mare 1995).

These examples illustrate that the regulator can influence the magnitude and nature of transaction costs through the choice of trading rules and the details of the market design. Stavins (1995) showed that in theory, the impact of these transaction costs also 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 United States, endowments were 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.[3] More recently, alternative endowment schemes have 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 United States,[4] 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.[5] 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% of the cost-effective allocation to 60% 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

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[3] The extent to which countries could trade emission rights internationally was a major point of contention in 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.

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

[5] 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

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 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 the limited implementation of permit markets in the field limits empirical work based on field data. 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 United States (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 RECLAIM program discussed above (Carlson et al. 1993a, 1993b; Cason and Gangadharan 1998). Various researchers have used experiments to explore the impact of market power in permit markets (Soberg 2000; Muller et al. 2002; Godby 1999; Carlen 1999; 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.[6] 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'' commissions), or if traders' transactions costs decline as they acquire more experience in the market.[7] 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% of the cost-effective allocation or 60% 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% endowment treatment corresponds to the case in which endowments are not closely tied to past or projected emissions, while the 60% endowment treatment is closer to an historic output (i.e., grandfathering) or current output allocation scheme. In the 20% 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% sessions, the marginal values and control costs are different for each subject. The parameters chosen for the experiment do not reflect the conditions in a particular permit market, but they are consistent with the relevant economic theory and information about existing permit programs.[8] Our goal is to analyze the impact of the most common kinds of transactions costs and study how these costs interact with the initial permit endowment. Incorporating

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[6] 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.

[7] In the experimental treatment with decreasing transactions costs, the transactions costs are lower per-unit when the transaction volume is higher. It does not matter whether these economies arise due to a higher volume per se (such as through participants' learning by doing) or due to an increase in the average transaction size (which could, for example, reduce commissions that do not depend on the transaction size). But in the experiment each trade is for a single unit, so the former interpretation is more relevant.

[8] For example, we implement a permit demand and supply environment that simply corresponds to increasing marginal pollution abatement costs.

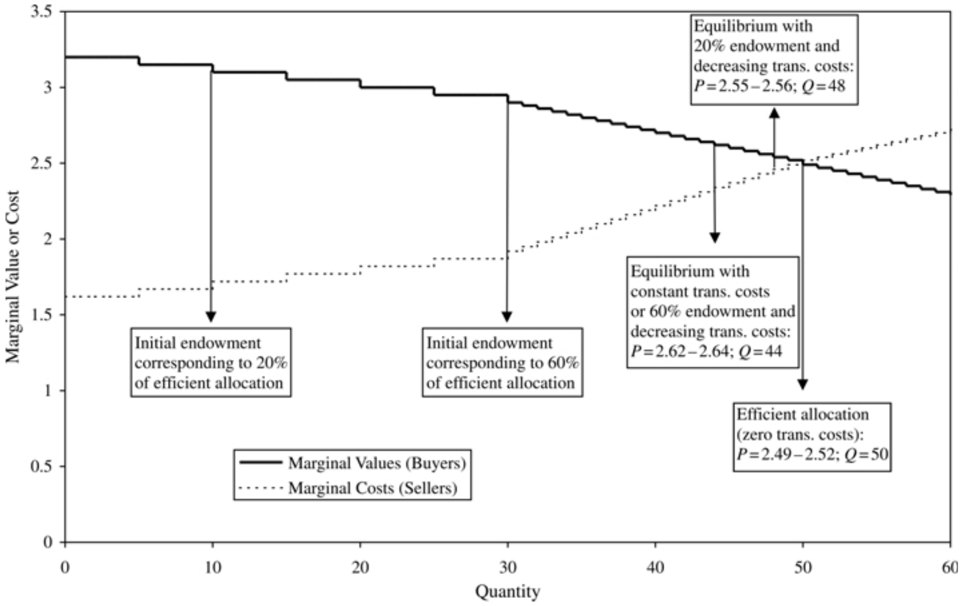

Figure 1. Induced marginal values and control costs for allowances.

specific costs estimated from markets in the field could have a quantitative impact on our results, but there is no reason to expect that the qualitative results would change.

All subjects are undergraduate students from Purdue University and the University of Melbourne. Subjects are randomly assigned as sellers and buyers. All sessions have five sellers and five buyers. Subjects trade in experimental dollars, which are later converted to local currency. The experimental dollars are multiplied by two in the United States and by three 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.[9] 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—available from the journal website at http://crri.rutgers.edu/jre/—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

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

Table 1. Experimental Design

Nature of Transaction Costs	Initial Endowment 20% of the Cost-Effective Allocation	 60% of the Cost-Effective Allocation
Zero (z)	Four sessions: one experienced M420z20 (14 periods) M901z20 (14 periods) P906z20 (14 periods) P913z20x (14 periods)	Four sessions: one experienced P420z60 (15 periods) M830z60 (15 periods) M905z60x (15 periods) P906z60 (11 periods)
Constant marginal transaction costs (c)	Five sessions: two experienced P413c20 (15 periods) M504c20 (17 periods) M522c20x (15 periods) P628c20 (15 periods) P713c20x (15 periods)	Five sessions: two experienced P427c60x (15 periods) M508c60 (15 periods) M516c60 (13 periods) P628c60 (15 periods) P712c60x (14 periods)
Decreasing marginal transaction costs (d)	Five sessions: two experienced P424d20x (15 periods) M505d20 (13 periods) M516d20 (15 periods) M518d20x (10 periods) P712d20 (15 periods)	Five sessions: two experienced P417d60 (11 periods) M511d60 (9 periods) M515d60 (15 periods) M523d60x (14 periods) P720d60x (12 periods)

Notes. 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.

sellers a summary of the transaction fees they incurred in the previous period. Each trading period lasts for 4 minutes in the inexperienced, 20% endowment sessions. For the sessions with 60% 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 nine 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:

$$\min_{r_i}[c_i(r_i) + p(u_i - r_i - q_{0i}) + T(t_i)] \quad \text{st}: r_i \geq 0, \tag{1}$$

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:

$$c_1'(r_1) + T'(t_1) = c_2'(r_2). \tag{2}$$

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}:

$$\frac{dr_1}{dq_{01}} = \frac{-T''(t_1)}{\left[T''(t_1) + c_1''(r_1) + c_2''(r_2)\right]}. \tag{3}$$

If $T''(t_1) = 0$, then $dr_1/dq_{01} = 0$. 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 $dr_1/dq_{01} > 0$.[10] 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.

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

3. Results

We organize the results presentation 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 measures of market performance generally support the model's predictions. We employ three alternative statistical procedures to reach this conclusion: non-parametric Mann-Whitney tests, classical analysis of variance, and panel regression models that use random session effects.

3.1. Transaction Prices

Hypothesis 1: Transactions costs raise prices compared to the zero transactions cost baseline.

Evidence: The first column of table 2 presents mean transaction prices for the final five periods in each of the 28 sessions. Prices in the eight baseline sessions with zero transaction costs (shown at the bottom of this table) converged to or slightly below the competitive equilibrium range $[249, 252]$. By contrast, mean prices are above the upper competitive equilibrium price of 252 francs in 19 of the 20 sessions with positive transaction costs (session M505d20 is the only exception). A conservative two-sample, one tailed non-parametric Mann-Whitney test (using one observation per session—the mean price over the final five 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, $n_1 = 4$, $n_2 = 5$, $p < 0.05$).[11]

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

Evidence: The top portion of table 2 presents the mean transaction prices in the decreasing transaction costs sessions. When the initial endowment is only 20% of the cost-effective allocation, mean prices range between 250 and 260. When the initial endowment is 60% of the cost-effective allocation, mean prices in all five sessions exceed 261. Figure 2 summarizes the mean transaction prices and quantities traded over the final five periods of each session. Table 2 and this figure indicate that these late period mean transaction prices in the decreasing, 20% endowment treatment (the diamonds) are all lower than the corresponding prices in the decreasing, 60% 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 ($U = 0, n_1 = n_2 = 5, P < 0.01$).

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

Table 2. Average Transaction Prices, Normalized Quantity Traded and Cost-Effectiveness for the 28 Individual Sessions

Session Name	Ave. Transaction Price (Final Five Periods)	Normalized Quantity (Final Five Periods)	Average Cost-Effectiveness (Final Five Periods)
Decreasing transaction costs, 20% endowment			
P424d20x	259.7	46.0	96.86
M505d20	250.5	49.2	99.56
M516d20	253.8	47.4	98.39
M518d20x	256.5	47.2	98.57
P712d20	254.9	47.0	98.73
Treatment Mean	255.1	47.4	98.42
Decreasing transaction costs, 60% endowment			
P417d60	263.5	44.4	97.33
M511d60	263.9	44.0	97.16
M515d60	261.3	44.2	97.30
M523d60x	264.1	43.8	97.04
P720d60x	264.3	43.8	96.88
Treatment Mean	263.4	44.0	97.14
Constant transaction costs, 20% endowment			
P413c20	260.2	45.0	97.78
M504c20	266.3	41.8	93.61
M522c20x	262.9	43.8	95.69
P628c20	264.8	42.4	94.83
P713c20x	265.6	42.0	93.18
Treatment Mean	263.9	43.0	95.02
Constant transaction costs, 60% endowment			
P427c60x	262.4	44.2	97.42
M508c60	262.0	44.4	97.44
M516c60	264.0	44.0	97.16
P628c60	265.0	43.2	96.32
P712c60x	263.1	44.2	97.45
Treatment Mean	263.3	44.0	97.16
Zero transaction costs, 20% endowment			
M420z20	251.1	50.8	99.02
M901z20	249.4	48.0	96.21
P906z20	249.6	48.6	98.14
P913z20x	248.8	49.4	99.65
Treatment Mean	249.7	49.2	98.26
Zero transaction costs, 60% endowment			
P420z60	251.0	50.0	99.82
M830z60	248.9	49.8	99.90
M905z60x	247.9	48.2	98.75
P906z60	249.0	50.0	99.58
Treatment Mean	249.2	49.5	99.51

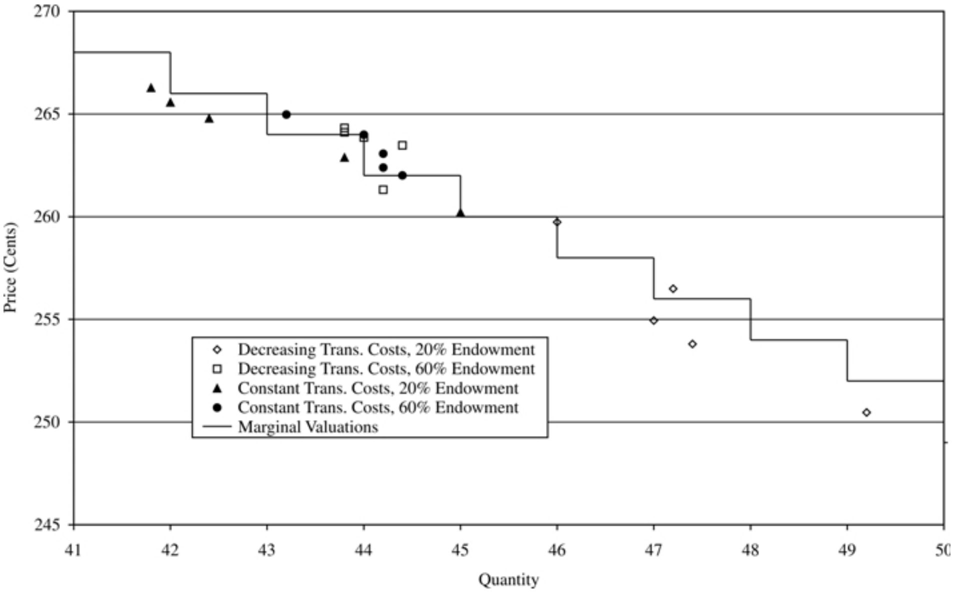

Figure 2. Mean transaction prices and quantities over final five periods of each session.

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

Evidence: The middle section of table 2 presents the mean transaction prices in the constant transaction costs sessions. When the initial endowment is only 20% of the cost-effective allocation, mean prices range between 260 and 267 in the second half of the sessions. The range of mean prices is similar but narrower when the initial endowment is 60% of the cost-effective allocation, varying between 262 and 265. Figure 2 indicates that the end-period mean transaction prices in the decreasing, 20% endowment treatment (the triangles) bracket the corresponding prices in the decreasing, 60% 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 $(U = 9, n_1 = n_2 = 5,\ ns)$.

For an alternative statistical test to evaluate Hypotheses 1–3, consider the analysis of variance presented in table 3. The top part of Panel A reports a cross-tabulation of the mean price for each endowment and transactions costs treatment, summarizing the treatment means already presented in table 2. Mean prices are clearly lower without transactions costs (Hypothesis 1), and there is a clear interaction effect between the endowment and transactions costs, consistent with Hypotheses 2 and 3. The ANOVA shows that this interaction is highly significant.

Table 4 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

Table 3. Summary of Market Performance Measures for Each Treatment (Final Five Periods)

Panel A: Average transaction price

(Zero Transaction Cost Competitive Equilibrium is 2.49–2.52)

	Constant Transaction Costs	Decreasing Transaction Costs	Zero Transaction Costs	Total
20% endowment	263.9	255.1	249.7	256.7
60% endowment	263.3	263.4	249.2	259.3
Total	263.6	259.2	249.5	258.0

Analysis of variance:

Source	Sum of Squares	Degrees of Freedom	Mean Square	*F* Statistic	*p*-value
Endowment	47.06	1	47.06	11.51	0.003
Transaction cost	915.70	2	457.85	111.97	< 0.001
Endowment × transaction cost	128.47	2	64.23	15.71	< 0.001
Model	1091.23	5	218.25	53.38	< 0.001
Error	89.96	22	4.09		
Total	1181.18	27			

Panel B: Normalized quantity

(Zero Transaction Cost Competitive Equilibrium is 50)

	Constant Transaction Costs	Decreasing Transaction Costs	Zero Transaction Costs	Total
20% endowment	43.0	47.4	49.2	46.3
60% endowment	44.0	44.0	49.5	45.6
Total	43.5	45.7	49.4	45.9

Analysis of variance:

Source	Sum of Squares	Degrees of Freedom	Mean Square	*F* Statistic	*p*-value
Endowment	3.86	1	3.86	4.11	0.055
Transaction cost	153.13	2	76.56	81.51	< 0.001
Endowment × transaction cost	26.37	2	13.19	14.04	< 0.001
Model	183.36	5	36.67	39.04	< 0.001
Error	20.66	22	0.94		
Total	204.03	27			

Panel C: Average cost-effectiveness

(Zero Transaction Cost Competitive Equilibrium is 100)

	Constant Transaction Costs	Decreasing Transaction Costs	Zero Transaction Costs	Total
20% endowment	95.02	98.42	98.26	97.16
60% endowment	97.16	97.14	99.51	97.82
Total	96.09	97.78	98.88	97.49

Analysis of variance:

Source	Sum of Squares	Degrees of Freedom	Mean Square	*F* Statistic	*p*-value
Endowment	3.11	1	3.11	2.63	0.12
Transaction cost	36.05	2	18.02	15.27	< 0.001
Endowment × transaction cost	15.60	2	7.80	6.61	0.006
Model	54.76	5	10.95	9.28	< 0.001
Error	25.96	22	1.18		
Total	80.72	27			

Table 4. 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

*Significant at the 95% significance level.

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 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% 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% endowment. Consistent with Hypothesis 2, a Wald test rejects the null hypothesis that the decreasing marginal transactions costs, 20% endowment dummy variable equals the decreasing marginal transaction cost, 60% endowment dummy variable $(\chi^2_{1\ \mathrm{d.f.}} = 6.00, p < 0.01)$.[12] And consistent with Hypothesis 3, a Wald test fails to reject the null hypothesis that the constant marginal transactions costs, 20% endowment

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[12] 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 $(\chi^2_{2\ \mathrm{d.f.}} = 6.39, p < 0.05)$.

dummy variable equals the constant marginal transaction cost, 60% endowment dummy variable ($\chi^2_{1\text{ d.f.}} = 0.004$, $p = 0.97$).[13]

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.[14] The middle column of table 2 reports the mean normalized transaction 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, normalized transaction quantity is greater and is closer to 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 2 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% of the cost-effective allocation rather than 60% 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 2 presents the mean normalized quantity traded in the final five periods of the constant transaction costs sessions. These mean quantities overlap

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[13] 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% endowment dummy variable.

[14] This comparison is normalized to account for the fact that actual transaction volumes are lower (by 20 units) when the initial endowment is 60% rather than 20% of the cost-effective allocation of allowances. We add 10 to the actual quantity traded in the 20% endowment sessions and 30 to the quantity traded in the 60% 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.

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 $(U = 6, n_1 = n_2 = 5,\ ns)$. Panel B of table 3 presents an analysis of variance that also supports Hypotheses 4 and 5.

Table 5 presents estimation results from a random effects model on the normalized transaction quantity in each period—analogous to the mean price model in table 4—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% endowment treatment is approximately three times greater than the estimate in the decreasing transaction costs 20% endowment treatment. This difference is highly significant $(\chi^2_{1\ \text{d.f.}} = 12.17, p < 0.01)$. Consistent with Hypothesis 5, the

Table 5. 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

*Significant at the 95% significance level.

coefficient estimates for the two constant transaction cost dummy variables (-7.58 vs -6.44) are not significantly different ($\chi^2_{1\ \mathrm{d.f.}} = 1.11, p = 0.29$).[15]

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.[16] The rightmost column of table 2 presents the cost-effectiveness 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.[17]

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

Evidence: The top portion of table 2 displays the decreasing marginal transaction costs sessions. In the final five periods, the cost-effectiveness in four of the 20% endowment sessions exceeds the highest cost-effectiveness across all five 60% endowment sessions. The lowest cost-effectiveness occurs in a 20% 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% 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% level, however.

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[15] 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 ($\chi^2_{2\ \mathrm{d.f.}} = 15.85, p < 0.01$); 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 ($\chi^2_{2\ \mathrm{d.f.}} = 1.24, p = 0.54$).

[16] 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.

[17] 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 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 study in future research.

Table 6. 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

*Significant at the 95% significance level.

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

Evidence: The middle of table 2 displays the constant marginal transaction costs sessions. In 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. Panel C of table 3 indicates a significant interaction between transaction costs and the endowment, consistent with Hypotheses 6 and 7.

Table 6 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.[18] 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

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[18] 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.

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% 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 $(\chi^2_{2\ \text{d.f.}} = 61.27, p < 0.01)$.

4. Conclusion

Well-functioning emission permit markets do not require extensive regulator involvement, as indicated by the successful experience in the U.S. SO_2 permit 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, and these decisions 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 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. Since a government-sponsored auction may have low transactions costs, it could be a cost-effective way to allocate the permits in order to minimize the inter-firm trading that follows the allocation. If instead the most significant transaction costs are transfers (e.g., brokerage fees), however, then such costs are not deadweight losses. In this case, an accurate initial endowment is less important.

The policy implications also depend on whether the transactions costs are more commonly decreasing or constant in transaction volume. Most permit markets in the field undoubtedly have both constant and decreasing marginal transaction costs. In the early stages of a new permit market, participants would incur high search, information, bargaining and decision costs, but these costs could decline as the market matures and participants gain experience (Kerr and Mare 1995; Gangadharan 2000). The constant reporting or brokerage costs, however, are likely to decline less over time. Hence in the long run, the constant marginal transactions costs may be more important than the decreasing marginal transactions costs. If this is the case, regulators should focus on reducing these costs by allocating more permits to those participants expected to have high abatement costs, thereby reducing the expected trading volume required to achieve a cost-effective distribution of pollution abatement. As discussed in the introduction, regulators can of course influence the overall level of transactions costs through the various rules they implement in permit markets. Our empirical results reiterate Stavins' theoretical point that when implementing tradable permit programs, regulators should carefully consider how market rules affect transactions costs.

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