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Emission Trading with Shares and Coupons
A Laboratory Experiment

R. Andrew Muller
Stuart Mestelman

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McMaster University
Hamilton, Ontario
Canada L8S 4M4

Abstract

Increasing attention is being paid to emission trading programs for the control of air and water pollution. The United States EPA has implemented a tradable emission allowance program for sulphur oxides. The EPA auction has been investigated in the laboratory by Cronshaw and Brown Kruse and by Franciosi, Isaac, Pingry and Reynolds. A somewhat different proposal has been made for controlling nitrous oxides in southern Ontario. Trade would occur in coupons (emission permits) and shares (entitlements to coupons). This paper reports a laboratory investigation of the Canadian proposal in which the experimental design developed by Cronshaw and Brown Kruse was modified to reflect the proposed Canadian institution. The results indicate dispersed but relatively stable prices, higher efficiency than obtained in related experiments modelling the EPA plan, and little arbitrage between share and coupon prices. The results could be due to differences in the market institutions or the training of subjects.

Emission Trading with Shares and Coupons: A Laboratory Experiment[*]

I. Introduction

Increasing attention is being devoted to emission trading programs for the control of air and water pollution. These trading programs offer the possibilities of lower cost pollution control, reduced conflicts between economic growth and pollution control, and increased political acceptability for pollution control. Many important questions, such as the nature of the permits being traded, the extent of a mandatory market in permits, and the possibility of banking permits must be considered in designing a practical emissions trading program. Experimental economics can provide important insights into the design of trading systems. In this paper we report a laboratory experiment intended to "testbed" certain aspects of an emissions trading market proposed for the control of nitrous oxides (NOx) and volatile organic compounds (VOCs) in southern Ontario and Quebec. These aspects are a relatively unstructured trading environment, simultaneous trading in emissions permits (coupons) and time streams of permits (shares), and banking of permits.

We adopt an experimental design developed by Cronshaw and Brown Kruse (1992) at the University of Colorado and replicated in modified form by Franciosi, Isaac, Pingry and Reynolds (1993b) at the University of Arizona. Both of these experiments were designed to reflect aspects of the market in sulphur oxide emissions that has been created under the 1990 amendments to the U.S. Clean Air Act. We replace the market institution used in the Colorado and Arizona

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experiments by an institution resembling that proposed for southern Ontario. We obtain higher cost savings than observed in the Colorado and Arizona experiments, but the source of this improved performance has not been completely identified. We conclude that experiments of this type provide valuable information for the design of emission trading programs

A. Tradable Emission Permits: Theory and Practice

Tradable emission permit programs provide a decentralized method of translating a target for overall emissions of a pollutant into abatement plans for individual sources of the pollutant. In a typical application, a regulatory body specifies an overall "cap" on aggregate discharges of a particular pollutant. Emission permits convey the right to discharge the pollutant to individual firms. Each permit authorizes the discharge of one unit of the pollutant. No discharges are allowed without a permit; violators are subject to substantial penalties. Each accounting period, firms must surrender permits equal in number to the quantity of the pollutant they have discharged that period. Each period, the regulatory body distributes a quantity of permits equal to that period's cap. Firms are allowed to trade permits among themselves or, possibly, with third parties. Firms with low marginal abatement costs have an incentive to reduce their discharges in order to sell their permits to firms with higher marginal abatement cost. The overall target is thus achieved at a reduced cost.

The concept of tradable emission permits was popularized by Dales (1968) in the context of water pollution. Montgomery (1972) provided a rigorous theoretical treatment. Particularly thorough treatments of design issues have been provided by Tietenberg (1980, 1985, 1993) and by Hahn and co-authors (Hahn, 1988, 1989; Hahn and Noll, 1982, 1990; Hahn and Hester, 1988). This literature has identified a number of potential advantages of emission trading programs compared to command-and-control allocation of emission targets and environmental taxation.

These include cost efficiency, dynamic efficiency[1], decentralized decision making, and (possibly) increased political acceptability.[2]

During the 1980s, approximations to tradable permit schemes were implemented in the United States (Tietenberg, 1993; Hahn, 1989; Barakat and Chamberlin, 1991; Cropper and Oates, 1992; Canada, 1992). The most successful U.S. program, involving the lead content in gasoline, facilitated the complete phase-out of lead in automotive fuels. There has been considerable interest in trading credits for reduction of air emissions beyond mandated levels. Although intra-firm trading has been effective for reducing costs, there has been less trading of emission reduction credits among firms less than expected. The failure of active trading to develop in some of the applications has been variously ascribed to administrative complications in obtaining approval for trades, excessive restrictions on trading, and concern that unused permits may be expropriated (Hahn and Noll, 1990; Cropper and Oates, 1992, 690). These experiences show that the success of an emission permit program can depend heavily on the details of its design.

The U.S. Clean Air Act Amendments of 1990[3] provide for the most ambitious program to date. These amendments required the development of a tradable emission allowance (permit) plan

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[1] Dynamic efficiency may be defined as the degree to which an system can accommodate change and generate desirable new technology and products. A tradable emission permits program accommodates growth, even in non-attainment areas, by allowing new firms to bid permits away from incumbent firms. Moreover, the program generates a clear price signal to encourage firms to seek out new, more efficient control technology. The term "dynamic efficiency" seems useful in capturing this "dynamic" argument, which is made by Hahn (1988, 42) among others.

[2] Emission trading programs may be seen as fairer, and therefore more politically acceptable, than other forms of environmental regulation. First, they allow abatement to be concentrated in low abatement cost firms without giving high abatement cost firms a free ride. Second, they avoid the appearance of charging for both polluting and cleaning up. Third, they can avoid the appearance of a revenue grab by distributing permits to existing firms without charge or by adopting the revenue neutral auction advocated by Hahn (1988).

[3] U.S. Clean Air Act Amendments of 1990 (Public Law 101-549) Title IV (Acid Rain Provisions)

that will reduce sulphur dioxide emissions by ten million tons per year, relative to 1980 levels, by the year 2001 (U.S. EPA, 1991). The plan deals with a number of the perceived shortcomings of earlier experience. In particular, the problem of hoarding is addressed by a mandatory auction. Allowances will be allocated to existing sources but 2.8% of the permits allocated to each firm will be reserved by the EPA and offered for sale on behalf of the firms in a revenue neutral auction. Firms may voluntarily offer additional permits. Specific rules are given for the operation of the auction: it is to be a sealed bid, discriminative price auction in which the highest bids for permits will be matched with the lowest offers[4] and the successful bidders pay the entire price they bid. Sellers of reserved shares receive the average price paid for reserve shares. Sellers of voluntarily offered shares receive the actual bid price per share. The first auction was held in March 1993. 50,010 allowances for the 1995 enforcement year were exchanged in the spot market for an average price of $156 per ton. 100,000 allowances for the enforcement year 2000 were sold in an advance auction for an average price of $136 (U.S. EPA, 1993). In addition to the EPA auction, a less regulated private market has already begun to develop. Both direct trading among companies and brokered trading has been reported.

In a series of three substantial studies, an American consultant (NERA) has recommended a somewhat different proposal for trading in emissions of nitrous oxide (NOx) in the Windsor-Quebec corridor of southern Ontario and Quebec (Nichols and Harrison, 1990a, 1990b; Nichols, 1992). Table 1 compares the NERA and EPA proposals. The NERA proposal would create two tradable assets: coupons and shares. Each **coupon** would entitle the holder to discharge one tonne of NOx. Coupons would be valid indefinitely, i.e. banking would be allowed. The government would announce and enforce an overall cap on the total number of coupons issued each period. This cap would decline according to an announced schedule. Coupons would be distributed to users in proportion to their holding of **shares**. If, for example, 100 shares were issued, then each share would entitle its holder to 1 percent of the coupons issued in a given period. Shares and coupons would be freely traded. Few details are given concerning the market

[4] Reserved permits are entered with a zero offer price.

institutions under which trading would occur. It seems that unstructured, privately negotiated trades in coupons and shares are expected to develop. Seasonal and intra-regional restrictions on trading were considered, but rejected in the interests of simplicity. The initial allocation of shares is not specified but NERA insists that the allocation should have nothing to do with the current or future actions of firms. For example, if a firm shuts down, it should not lose its share of coupons.

B. The Role of Laboratory Experiments

The market design proposed by NERA differs significantly from the EPA auction market. Since large sums of money are at stake in plans of this nature, one would like to evaluate the proposed design on a rational basis. Nevertheless, policy analysts have only a limited body of knowledge to guide them. This knowledge comes from three sources: economic theory, field experiments, and laboratory evidence. Economic theory usually requires strong assumptions to obtain unambiguous results. Practical policy makers may hesitate to apply these results to the more complex environment in which they work. Field experiments would be ideal, but are difficult to implement because of the long time frame involved, because the costs both of pollution and pollution control may be very substantial, and because of political difficulties caused by unequal treatment of individuals. We argue that laboratory evidence can fill some of the gap between economic theory and field trials.

A relatively new sub-discipline of economics, experimental economics attempts to test economic theories and institutions in a simplified environment fully under the control of an investigator. In a typical experiment, subjects (sellers and buyers) exchange a fictitious commodity (a "token") which has value only because it can be purchased from or redeemed by the experimenter according to a given schedule of values.[5] Sellers earn laboratory profits by selling tokens at a price greater than the cost of acquiring them from the experimenter. Buyers earn

[5] Most experiments are conducted with university students. Davis and Holt (1993, 17) note a frequently expressed concern that students may be unrepresentative of decision makers that would actually be found in the field. They cite some evidence suggesting that the behaviour of sophisticated decision makers "has typically not differed from that exhibited by more standard (and far less costly) subject pools". Nevertheless, when resources permit, sophisticated subject pools provide valuable controls on the experimental findings.

laboratory profits by purchasing tokens at a price less than the price for which they can redeem them from the experimenter. At the end of the experiment, laboratory profits are converted to real dollars at a pre-announced exchange rate and the subjects are paid in cash. The experimenter controls the rules under which trading occurs (the market "institution") and studies the effect of different institutions on the convergence of the market to equilibrium and the properties of the equilibrium, such as stability, efficiency and distribution of gains.

Informal laboratory experimentation dates back at least to 1738 and formal reports of laboratory experimentation have been appearing since 1938 (Roth, 1988, 974). Nevertheless, attention to experimental methods and results greatly accelerated during the 1980s. Useful reviews of the experimental literature may be found in Roth (1988) and Plott (1989). This literature suggests that experimental techniques may be particularly useful in three ways: in screening and testing economic theories, in discovering new facts requiring explanation, and in designing and demonstrating new approaches to problems of public policy. The present research concerns public policy. Specifically, we wish to test the main features of a proposed market design at a small scale before embarking on a regulatory program that could imply costs of hundreds of millions of dollars. Plott (1993) refers to this as "testbedding" the proposed institution.

Several experiments have been run to testbed the U.S. EPA emission allowance program. Most of these have been run at the Universities of Colorado and Arizona under contract to the Oak Ridge National Laboratory. These experiments focused first on the properties of revenue neutral auctions (as opposed to auctions in which revenues were not redistributed to firms), and later on the effect of banking and the interaction between the mandated government auction and the less regulated private market in allowances (Hale and Bjornstad, 1991; Franciosi, Isaac, Pingry and Reynolds, 1993a). These have focused on the effect of a mandatory auction on market outcomes.

Cronshaw and Brown Kruse (1992), at the University of Colorado, designed an experiment to capture most of the features of the mandatory allowance market under the 1990 Amendments to the Clean Air Act Amendments, including mandatory transmission of a fraction of permits to the market, a discriminative call auction, banking of permits, and the availability of permits at a high, fixed price. Subjects were able to achieve about two-thirds of the gains theoretically available from banking alone, and a further 39% to 78% of the potential gains when trading was allowed. At the University of Arizona, Franciosi, Isaac, Pingry, and Reynolds (1993b) designed a similar experiment which allowed both a mandatory auction and a continuous private secondary market. They found that efficiency is improved by trading but that prices in the secondary market may not coincide with those in the auction. They also found some evidence that banking of permits may allow speculative "bubbles", as indicated by a tendency of the price of permits to collapse at the end of a session.

This paper reports an experiment designed to testbed aspects of the NERA proposal. To do so, we adopt Cronshaw's and Brown Kruse's experimental design, modifying it to reflect the essential features of the NERA proposal. We wish to discover, first, whether the proposed market mechanism leads to relatively stable prices and coupon use and, second, whether the proposed design performs better or worse than the EPA tradable emission allowance program.

II. Experimental Design

The experimental design is summarized and compared to the Colorado and Arizona designs in Table 2. The laboratory market consisted of ten subjects interacting over 12 periods. Subjects were told they owned a firm producing a fictitious commodity. Sales revenue from the commodity would be constant in each of the periods of the experiment. Subjects could increase their earnings by reducing their production costs. Production costs could be lowered by using a special input called "knocks". Since the total amount of knocks available each period was limited, subjects were required to surrender a ration coupon for each unit of knocks used. Subjects were provided with a schedule showing how production costs would change as they used more coupons. Five distinct production cost schedules were used, each assigned to two subjects. Table 3 reports these schedules, which may be interpreted as marginal abatement costs.

At the beginning of each period subjects received a coupon dividend which depended on the number of shares they held. Each subject received an initial allocation of three shares, physically represented by individual slips of paper. The coupons, represented by slips of paper differing in size and colour from the shares, were distributed at the beginning of each period. Subjects were informed that the coupon dividend would be two coupons per share in each of the first four periods and one coupon per share in each of the remaining periods. Subjects were also told how they could increase profits by banking coupons or by trading coupons or shares.

Each period was divided into a trading subperiod and an accounting subperiod. During the trading subperiod, subjects could purchase or sell coupons or shares. Negotiation occurred in the centre of the laboratory. No restrictions were placed on the nature of negotiations. When a contract was agreed upon, the buyer and seller completed an "Agreement of Purchase and Sale". This form was completed in triplicate and confirmed by the monitor. Copies were kept by the monitor, the buyer, and the seller, and the transaction was completed by the seller transferring the physical shares or coupons to the buyer. No provision was made for futures trading in coupons. Subjects were given initial cash balances of 500 laboratory dollars (L$). In some sessions, subjects were charged an interest rate of ten percent on negative cash balances at the end of any period; in other sessions no interest was charged on negative balances.[6]

During the accounting subperiod, subjects decided how many coupons to use to reduce costs in the current period. Then they recorded their trading activity, production decision, and profits and their running balances of cash, coupons and shares. At the end of the accounting subperiod the completed records were collected together with the physical coupons used and the coupon dividend for the next period was paid. At the end of the session, subjects were paid their cash balances, converted into Canadian dollars (C$) at a rate which was announced at the start of period 1, together with a show-up fee of C$5.00.

Ten sessions were conducted, each lasting about three hours. Five of the sessions were training sessions. In these sessions, the first hour was devoted to carefully explaining the instructions, and the remaining two hours were used for six trading periods. When subjects were recruited for training sessions they were told that they would be called back after they were trained to participate in another session. The five sessions for which results are reported used

[6]Our original design implemented the ten percent interest charge on negative cash balances. We dropped the charge after observing one subject who purchased shares at high prices early in the experiment and who became progressively more indebted because of high debt service charges. We also noted that the interest charge made it more difficult to compute the perfect foresight competitive equilibrium (PFCE) price.

trained subjects. Subjects were given an opportunity to review the written instructions, after which twelve trading periods were conducted.

Six of the subjects in the first training session and in the first twelve-period session were graduate students in economics. One was a graduate student in English. The subjects in all other sessions were undergraduate students at McMaster University. Earnings in each session averaged about C$25 per subject.

We compared the results of our twelve-period sessions to the results of five sessions carried out at the University of Colorado under the direction of Jamie Brown Kruse and Mark Cronshaw and three sessions carried out at the University of Arizona under the direction of Robert Franciosi, R. Mark Isaac, David Pingry, and Stanley Reynolds.[7] A common set of technological parameters was used in all the sessions. That is, all sessions involved ten subjects representing five firms trading for twelve periods. The Colorado and McMaster subjects had identical production cost schedules. The Arizona subjects were given equivalent information relating profits directly to coupon use. Neither the Colorado nor the Arizona experiment involved shares. Both the Colorado and Arizona sessions were conducted using networked personal computers to enter decisions, to determine market outcomes, and to record data. The McMaster sessions were conducted manually. Subjects interacted directly and maintained their own records of transactions, costs, and profits.

There were significant differences in the market institution implemented at each centre. At McMaster, the unstructured trading environment pictured in the NERA reports was modelled by the multiple unit open outcry market, described above, in which subjects negotiated trades in the centre of the room. At Colorado, subjects participated in a computerized call market. Each period, they were required to submit one third of their permit allocation to the market. In addition they submitted up to five separate bids for permits and up to five separate voluntary offers of permits. This information was aggregated into market supply and demand curves by a central computer, which then ranked the bids and offers and conducted trades according to EPA rules. At Arizona, subjects participated sequentially in two markets each period. First, they

[7] The sessions discussed here formed part of larger research projects at both institutions.

traded permits in a computerized double auction environment, in which bids and offers were made and accepted in real time. Then they participated in a revenue neutral call auction in which they submitted a bidding schedule and offered a mandatory one-third of their permits. This was intended to model the dual nature of trading under the Clean Air Act Amendments.

The designs also differed in the training given to participants. At McMaster, subjects were trained by participating in a six-period training session in which earnings depended upon performance. Subjects at Colorado were trained in sessions in which banking of permits was permitted, but there was no trading. Subjects at Arizona were trained by reading instructions on their computer screens and by participating in four practice periods in which earnings did not depend on performance.

III. Benchmarks

A. Equilibria

Since we are testbedding a proposed institution rather than testing a specific theory we have no specific predictions. Instead we compare the performance of the experimental market to five benchmarks.

The *command-and-control (CC)* benchmark represents the performance of the market if neither trading nor banking occurs. In this case all coupons are used by the subject to whom they are issued in the period when they are received. System abatement cost is L$32,832 and firms earn L$16,568 in profits. The *perfect foresight competitive equilibrium (PFCE)* represents performance if subjects trade and bank optimally. System abatement costs are minimized at L$22,080 or 67.3% of the command-and-control solution and firms earn L$27,300 in profits. 40 coupons are used in each period and the price is between L$70 (the marginal cost of the last unit of abatement for firm type 4) and L$72 (the marginal cost of an extra unit of abatement for firm type 2).

The *banking only equilibrium (BOE)* represents performance if subjects do not trade, but use their allocated coupons optimally over time. Since cost schedules do not change over time and there is no discount rate on profits, the optimal banking only strategy is to allocate the 48 available coupons equally over the 12 periods. This requires banking two coupons in each of periods one through four and using one of the banked coupons in each of periods five through twelve. System abatement cost is L$31,104 or 94.7% of the command and control cost and firms earn L$18,296 in profits.

The *myopic competitive equilibrium (MCE)* represents performance if subjects trade optimally in each period but do not bank. System abatement cost falls to L$24,338, 74.1% of the command-and-control solution. The MCE price is between L$38 and L$36 in the first four periods and between L$90 and L$104 in periods five through 12.

Following Cronshaw and Brown Kruse (1992, 16) we define an *adapted competitive equilibrium (ACE)* for each period in the session. The ACE is the perfect foresight competitive equilibrium conditional on the current inventory of coupons. This equilibrium can be readily calculated for any specific period by adding the total coupons remaining to be distributed to the current inventory, allocating them equally over the remaining periods, and reading the price off the aggregate demand schedule for coupons in the current period. If coupons are overused in the early periods of a session, the ACE price will rise above the PFCE price.

Table 4 summarizes the system abatement costs for each of the first four benchmarks and the corresponding cost savings relative to the CC equilibrium. The ACE cannot be reported, since it changes as each session evolves. The cost reduction index reported in Table 4 is the cost saving expressed as a percentage of the PFCE cost saving.

B. Share Prices

When interest is neither charged on negative cash balances nor paid on positive cash balances, the value of a share should equal the undiscounted value of the coupons it will yield. If there is perfect arbitrage between share and coupon markets and if the market institution provides sufficient information to yield a PFCE, the price of a share in any period should equal that period's coupon price multiplied by the number of coupons the share will yield. If the share price is normalized by dividing by the coupon yield, the coupon price and share price should be equal. One measure of the performance of the market institution is the extent to which the coupon and normalized share prices converge.

When interest is charged on traders' negative cash balances, the normalized share price will be below the coupon price. Over time, the difference between the normalized share price and the coupon price should diminish. Because of the difficulties inherent in measuring the appropriate discounted value of a share in any period, a precise price is not computed for the sessions in which interest is charged. A useful comparison, however, is whether the normalized share prices in the ET1 sessions (when interest was charged on negative balances) systematically lie below the coupon prices. In the ET2 sessions (when interest was not charged on negative cash balances), the normalized share prices should equal coupon prices.

IV. Results

We first present the general behaviour of prices and coupon use in the McMaster sessions, then compare our results with those obtained in Colorado and Arizona.

A McMaster Results

Figures 1 through 5 present the share, coupon and adapted competitive equilibrium prices observed in the McMaster sessions. Share prices have been normalized and are expressed in laboratory dollars per coupon equivalent. The mid-point of the Perfect Foresight Competitive Equilibrium price range (shown by the horizontal line) is L$71 in all sessions.

In the first session (ET1-1), coupon prices remained somewhat below the PFCE price and considerably below the ACE price, which rose steadily over most of the experiment. A rising ACE price indicates that subjects banking less than the optimal number of coupons. There was a wider variance in share prices, some of which were above ACE. Session ET1-2 had a much wider spread of prices, with share prices often deviating substantially from coupon prices. The ACE price stayed close to the PFCE price until late in the session. Most of the trading in Session ET1-3 occurred early in the experiment. Later prices show a very wide scatter. The ACE price stayed close to the PFCE price. In Sessions ET2-4 and ET2-5 the interest charged on negative balances was removed. Prices varied widely. In Session ET2-4 there was a pronounced downward trend in prices (recall that an efficient price path would be constant at L$71). In Session ET2-5 the spread of prices is wide again, share prices tend to be below coupon prices, and the ACE price rises sharply in the middle periods of the experiment. Thus the interest charge does not appear to have reduced share prices in the early periods. In summary, Figures 1-5 indicate an institution which produces highly variable prices and little arbitrage between share and coupon prices.

Despite the relatively poor price behaviour, subjects achieved a fairly efficient allocation of coupons over time. Figure 6 reports the mean deviations from ACE coupon use over the twelve periods. After four periods of over-use, coupon use and banking tend to converge to the ACE level. This indicates an institution which generally achieves quite good optimization of coupon use over time.

B. Comparison to Colorado and Arizona Results

a. Efficiency

Table 5 reports the cost reduction index achieved in the McMaster, Colorado, and Arizona sessions. Several facts seem noteworthy.

1. Positive cost savings were realized in all experiments. All of the market institutions performed better than the command-and-control benchmark.

2. There is considerable variation in the cost savings realized, from 7.5% of potential for the lowest efficiency Arizona session to 92.9% for the highest efficiency McMaster session.

3. Average cost savings are clearly higher in the McMaster experiment than in the Colorado experiment, and higher in the Colorado experiment than in the Arizona experiment.

4. None of the market institutions came close to achieving all the potential cost savings. Average cost savings were 26.4% at Arizona, 56.3% at Colorado, and 74.0% at McMaster.

5. Only two of the sessions (McMaster sessions ET1-1 and ET1-2) obtained greater cost savings than those achievable under a myopic, no-banking, equilibrium.

These results indicate that all the market institutions tested were "successful" in achieving at least some cost savings over the command-and-control benchmark. Nevertheless, there is a remarkable variation in efficiency realized, both within and across experimental designs. While the McMaster institution clearly achieved the highest cost reduction, none of the institutions succeeded in achieving all of the potential gains from the emissions trading environment.

b. Coupon Use and Banking

The pattern of aggregate coupon use and banking was quite different in the three centres. Figure 6 compares the mean and root mean squared deviations from ACE coupon use. In general, the McMaster sessions exhibited some over-use (and underbanking) of coupons in the early periods of the experiments. In later periods the actual use is remarkably close to the ACE. The results at Arizona and Colorado are quite different. At Arizona there is very substantial over-use of coupons during the early periods of the experiment and under-use during the later periods. Some of the under-use in the later periods simply balances the over-use at the beginning, but it is noteworthy that average coupon use is even below the ACE use for five of the last six periods. The data clearly suggest that the Arizona laboratory market was unable to capture the potential gains from banking. At Colorado, the situation is reversed. Figure 6 shows that actual coupon use is systematically and substantially below the ACE use. This suggests that Colorado subjects engaged in substantial over-banking throughout the experiment. Figure 6 shows that the root mean square deviation from ACE at McMaster is always less than at Colorado, and less than at Arizona in ten of 12 periods.

c. Prices

Figures 7, 8, and 9 present the mean and root mean squared deviations of prices from their ACE levels. We have already seen the substantial variance in individual transactions prices in the McMaster market. Despite this, Figure 7 shows that average coupon prices at McMaster did not deviate far from the ACE level. Mean share prices varied somewhat more widely, but this may reflect the smaller number of shares traded. The root mean squared deviation of coupon prices from ACE levels lies consistently in a band between ten and 20 laboratory dollars. The Arizona price data are dramatically different. Coupon prices in both the double auction market (solid line) , which corresponds to the private market in emissions allowances, and the revenue neutral auction (dotted line), which corresponds to the EPA auction, are far below ACE levels in the first half of the of the experiment. Moreover, mean auction prices are substantially below the mean private market prices. The root mean square deviations are generally greater than 20. The Colorado price data are more stable, first falling below, then rising above the ACE level. The root mean squared deviations are comparable to the McMaster experiments.

The adapted competitive equilibrium price of coupons is a measure of the marginal abatement cost in the industry. In general, it seems that the Colorado data are the best indicators of marginal abatement cost and the Arizona prices are clearly the worst. The McMaster prices approximate marginal abatement cost on average, but exhibit wide variance. Overall, then, the price results from all three experiments suggest that prices are not highly successful in summarizing and conveying information about abatement costs.

V. Discussion

This experiment has shown that the key features of a market institution proposed for NOx trading in the Windsor-Quebec corridor can implemented in a laboratory setting. The features include tradable and bankable coupons, tradable shares, and a private market in both coupons and shares. Moreover, the laboratory implementation of the trading plan exhibits higher cost savings than do laboratory implementations of the U.S. EPA plan using the same technological parameters. The prices generated in the McMaster sessions are not good predictors of system marginal abatement cost, but neither were the prices generated in the Arizona and Colorado sessions. In this section we consider explanations for the differences between our results and those obtained at Colorado and Arizona. We conclude with a brief discussion of policy implications and further research.

A. Differences Among McMaster, Colorado and Arizona Sessions

The McMaster sessions exhibited higher efficiencies and more effective banking decisions than were observed in the other experiments. McMaster coupon prices were approximately as close to ACE as the Colorado permit prices and substantially closer to ACE than the Arizona prices in the early periods of each session.

All three experiments used the same number of firms, with the same abatement cost parameters, and the same endowments of coupons. The experiments differed in administration, in training of subjects, and in the market institution modelled. The McMaster sessions were administered manually. The Colorado and Arizona sessions were administered using a network of personal computers. We do not believe this was a substantial factor in explaining differences. On the other hand, the good McMaster performance may be explained by the more intensive training of the McMaster subjects or the cognitively less demanding McMaster institution.

Participants in all three experiments may be described as "experienced". However, the training of subjects differed in the centres. As described earlier, the McMaster subjects had all participated in a training session during which they received detailed instruction and payoffs based on their performance in a shortened version of the experimental market. In contrast, the Colorado subjects were trained in banking-only sessions prior to their introduction to the market environment whose data is reported in Cronshaw and Brown Kruse (1992). Participants were selected for the trading-with-banking sessions from among the subjects in the banking-only sessions who performed well (the subjects who could make money by banking coupon). The selected subjects were then given instruction in the trading-with-banking session which concentrated on learning how to manipulate the computing technology. This instruction lasted approximately thirty minutes. (Cronshaw and Brown Kruse, 1992, Appendix I). The trading-with-banking session then began. The Arizona traders were trained differently. They were given an unlimited length of time to practice with the auction market software, and then participated in three practice sessions. They were paid $15 for this training period. The subjects for subsequent sessions were selected from trained subjects who scored sufficiently high on a written test of their understanding of the instructions.

Relative to the McMaster participants, the Arizona and Colorado participants were inexperienced. The Arizona and Colorado sessions include subjects who were participating in the institution for the first time or subjects who may have been familiar with the institution, but who never had to make decisions which yielded real rewards. In addition, the Colorado banking-only training sessions may have introduced a framing effect. Colorado subjects were selected if they demonstrated that they knew how to bank coupons. It is possible that this was viewed as a desirable activity, and participants responded to the more complicated environment by banking coupons.

Differences in market institutions may also explain some of the difference in performance. The Colorado environment seems the least complex. Subjects participated in only one market, and the call auction institution did not put pressing demands on their time and attention. Subjects needed only to allocate their coupons over time and to decide on the marginal value of additional coupons. The McMaster environment was more complex in allowing continuous trading in both shares and coupons throughout the period. There was no mandatory transmission to a revenue neutral auction, however. The Arizona trading environment may have been the cognitively most complex environment. Subjects needed to develop rules-of-thumb to guide their bidding during the double auction and to develop procedures to maintain consistency across this market and the sealed bid auction. To do this, subjects must know their marginal valuation for the next unit to be acquired. They must decide how to treat permits that have been assigned to the firm but withdrawn for mandatory transmission to the sealed bid auction. Since the mandatory units (or revenue in excess of their marginal value) can be recovered in the revenue neutral auction (RNA) by bidding true marginal valuations, a good case can be made for considering them to be owned already. In this case banking decisions should proceed from a trial solution in which all of a subjects' coupons are allocated evenly over the remaining periods. Yet the computer screen presented to subjects in the Arizona experiment flagged as "owned" only coupons remaining after mandatory transmission to the market. This may have caused subjects to operate from a trial solution in which there were fewer banked units and more units offered for sale in early periods.

The mediocre performance of price in the McMaster institution may be due in part to the lack of public information about trading prices. The open outcry institution, as it was implemented for the five sessions reported here, does not assure complete dissemination of price and quantity information to all participants in the coupon and share markets. The open outcry property of the institution increases the likelihood that more information is disseminated than in the laboratory markets described by Chamberlin (1948) and Joyce (1983), upon which our institution is patterned. However, substantially less information is disseminated than in a double auction market. Accordingly, prices do not unambiguously adjust towards the PFCE or ACE prices.

Information alone may not be sufficient to lead to successful arbitrage across the markets for shares and coupons. In the Arizona experiment, arbitrage between permits traded in the continuous double auction market and the end-of-period revenue-neutral, discriminative sealed bid auction was not complete. These are both markets which provide full information to participants on bids, offers, and contract prices. This suggests that the opportunity to make banking decisions may make arbitrage decisions difficult for traders in two markets, even if contract price information is fully revealed.

The experimental method permits further investigation of these alternative explanations. Such investigation requires a series of experiments in which subjects receive a common training and then participate in market institutions which vary in only one dimension at a time. We are actively pursuing such a research program.

B. Policy Implications

Perhaps the most important implication flows from the finding that costs were reduced in every session. To this extent, the theoretical underpinnings of the tradable emission plans are supported in laboratory experiments. The second most important implication is that the market institution chosen to implement a tradable emissions permit plan may greatly influence the success of the plan. More specific implications arise from some of the other experimental findings.

In general, the prices generated in the McMaster sessions were not good approximations to the system marginal cost of abatement. This is unfortunate, since it is commonly claimed that tradable emissions permit plans promote dynamic efficiency by providing clear price signals to developers of new technology. The wide dispersion in prices and lack of arbitrage between coupons and shares is probably due, in part, to the lack of public information about successful contracts. This suggests it is important for authorities to ensure that emission trading occurs in institutions which provide good information on current transaction prices.

The results of the McMaster sessions confirm previous findings (Hale and Bjornstad, 1991; Brown Kruse and Cronshaw, 1991) that coupon banking does not lead to substantial gains over myopic competitive equilibrium for this parameter set. Joyce (1983) reports that the efficiency of Chamberlinian markets is comparable to oral double auctions. Since oral double auctions are known to produce highly efficient outcomes in single period trading with no inventory management, the reduced efficiencies found in all three experiments reported here may be ascribed to the market institutions. The common factor in all three experiments is the dynamic linkage among periods created by banking coupons. This suggests that banking reduces, or at least does not improve, performance in markets similar to the laboratory environment we implemented. That environment, however, did not reflect conditions under which banking is most important. A major function of banking is alleviating unexpected short or long positions in coupons towards the end of accounting periods. In work conducted contemporaneously with ours, Carlson *et al.* (1993) show that serious price spikes and troughs can develop in permit markets in which there is no banking and in which firms learn about their actual emissions only after having produced them. A plan for overlapping expiry dates appears to eliminate the problem. Some method of overlapping permits or a well functioning market in futures is probably needed to enforce good banking decisions. Future research can clarify this issue.

C. Extensions

The work reported in this paper constitutes only the beginning of a larger scale experimental investigation of emission trading with coupons and shares.[8] Political pressure to implement emissions trading plans is growing, and research directed towards identifying the best market environment may have a substantial payoff. Our immediate intention is to complete our investigation of the coupon/share trading scheme in a three-way factorial design contrasting shares against no shares, banking against no banking., and emission trading before or after firms learn of their permit requirements. Many other design factors remain to be investigated. One could study the advantages and disadvantages of shares and coupons when the demand for coupons has a random component, the impact on cost saving if the open outcry institution is replaced with another pricing institution , the impact on cost saving if subjects are sophisticated traders (employees of corporations who would ultimately be responsible for making decisions about the purchase of coupons and banking coupons), the impact of subject training on performance, the impact on cost saving of alternative distributions of shares across firms, and the impact on cost saving and trading patterns if the industry has one large high-cost firm. Systematic investigations of this nature can greatly increase the confidence with which new trading programs can be introduced.

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References

Barakat and Chamberlin in association with AER*X (20 September 1991). Study of Atmospheric Emission Trading Programs in the United States: Final Report. Canadian Council of Ministers of the Environment.

Brown Kruse, Jamie; Cronshaw, Mark (1991). Permit Market Experiments Preliminary Report. University of Colorado, Department of Economics.

Canada (1992). Economic Instruments for Environmental Protection: Discussion Paper. Minister of Supply and Services, Canada. Cat. No. En21-119/1992E.

Carlson, Dale; Olmstead, Nancy; Forman, Charles; Ledyard, John; Plott, Charles; Porter, David; Sholz, Anne (1993) An Analysis and Recommendation for the Terms of the RECLAIM Trading Credit. Report submitted to South Coast Air Quality Management District, California, Contract No. R-C93074.

Chamberlin, Edward H. (1948). "An Experimental Imperfect Market". Journal of Political Economy 56: 95-108.

Cronshaw, Mark B.; Brown Kruse, Jamie (1992). An Experimental Analysis of Emission Permits with Banking and the Clean Air Act Amendments of 1990. University of Colorado, Department of Economics, typescript. May 26.

Cropper, Maureen L.; Oates, Wallace E. (1992). Environmental Economics: A Survey. Journal of Economic Literature 30(2):675-740.

Dales, John H. (1968) Pollution, Property and Prices. Toronto: University of Toronto Press.

Davis, Douglas; Holt, Charles (1993). Experimental Economics. Princeton, NJ: Princeton University Press.

Franciosi, R.; Isaac, R. Mark; Pingry, David E.; Reynolds, Stanley S. (1993a). An Experimental Investigation of the Hahn-Noll Revenue Neutral Auction. Journal of Environmental Economics and Management 24: 1-24.

Franciosi, R.; Isaac, R. Mark; Pingry, David E.; Reynolds, Stanley S. (1993b). Extension of Research into Marketable Emissions Permits. University of Arizona, Department of Economics, typescript.

Hahn, Robert W. (1988). Promoting Efficiency and Equity through institutional design. Policy Sciences 21:41-66.

Hahn, Robert W. (1989). Economic Prescriptions for Environmental Problems: How the Patient Followed the Doctor's Orders. Journal of Economic Perspecitives 3(2): 95-114.

Hahn, Robert; Noll, Roger G. (1982). Designing a Market for Tradable Emission Permits in Reform of Environmental Regulation. Wesley Magat (ed.) Cambridge, MA: Ballinger.

Hahn, Robert; Noll, Roger G. (1990). Environmental Markets in the Year 2000. Journal of Risk and Uncertainty 3:351-367.

Hahn, Robert; Hester, Gordon L. (1989) Where Did All the Markets Go? An Analysis of EPA's Emissions Trading Program. Yale Journal of Regulation 6, 109-53.

Hale, Douglas R.; Bjornstad, David J. (1991). Marketable Permits for Controlling Sulphur Dioxide Emissions. Oak Ridge National Laboratory, Energy Division. Typescript.

Joyce, Patrick (1983). Information and Behavior in Experimental Markets. Journal of Economic Behavior and Organization 4: 411-424.

Montgomery, W. David. (1972). "Markets in Licenses and Efficient Pollution Control Programs". Journal of Economic Theory 5(3): 395-418.

Nichols, Albert L. (1992). Emissions Trading Program for Stationary Sources of NOx in Ontario. Cambridge, MA: National Economic Research Associates.

Nichols, Albert L.; Harrison, David (1990a). Using Emissions Trading to Reduce Ground-Level Ozone in Canada: A Feasibility Analysis. Cambridge, MA: National Economic Research Associates, Inc.

Nichols, Albert L.; Harrison, David (1990b). The Impact on Ontario Hydro of Emissions Trading for Nitrogen Oxides: A Preliminary Analysis. Cambridge, MA: National Economic Research Associates, Inc.

Plott, Charles R. (1989). An Updated Review of Industrial Organization: Applications of Experimental Methods. Chapter 19 in R. Schmalensee and R.D. Willig (eds) Handbook of Industrial Organization Vol II. Elsevier Science Publishers.

Plott, Charles R. (1994) Market Architectures, Institutional Landscapes and Testbed Experiments. Economic Theory 4 (1),2-10.

Roth, Alvin E. (1988). Laboratory Experimentation in Economics: A Methodological Overview. Economic Journal 98(393), 974-1031.

Tietenberg, Thomas (1980) Transferable Discharge Permits and the Control of Stationary Source Air Pollution. Land Economics 5, 391-416.

Tietenberg, Thomas (1985) Emissions Trading: An Exercise in Reforming Pollution Policy. Washington, D.C.:Resources for the Future

Tietenberg, Thomas (1993). Environmental and Natural Resource Economics 3rd ed. Harper-Collins.

United States, Environmental Protection Agency (40 CFR) Part 73, (1991) "Auctions, Direct Sales, and Independent Power Producers Written Guarantee Regulations and Request for Delegation of Proposals to Administer the Auctions and Direct Sale; Rule and Notice," Federal Register, pp. 65592-65609 (December 17).

United States, Environmental Protection Agency(1993) "EPA and Chicago Board of Trade Announce Results of First Acid Rain Allowance Auctions". Press Release, 30 March.

Table 1. Comparison of NERA Proposals and EPA Allowance Market

Item	NERA	EPA
Pollutant	NOx	SOx
Market Scope	Large Stationary Sources Southern Ontario	Utilities USA
Instrument(s) Traded	Coupons (permits) Shares (entitlements)	Allowances (permits)
Market Instititution(s)	Private Negotiation	(1) EPA Revenue Neutral Call Action with discriminative pricing (2) Private Negotiation
Compulsory Transmission	No	2.8% of shares
Status	Proposed	Effective 1995 First Auction, 1993

Table 2. Comparison of Experimental Designs: Colorado, Arizona, McMaster

Item	Colorado	Arizona	McMaster
Instrument	Coupons (Permits)	Coupons (Permits)	Coupons (Permits) Shares
Method Used to Induce Values	Abatement Costs	Marginal Valuation	Abatement Cost
Banking of Coupons	Permitted	Permitted	Permitted
Markets	1. Coupons	1. Private Market 2. Gov't Auction	1. Private Coupon Mkt 2. Private Share Mkt
Trading Method	Computerized Call Market	Sequential Computerized Single Unit Double Auction for 1, Call Market for 2.	Simultaneous manual "Chamberlinian" multiple unit open outcry markets for shares and coupons
Number of Subjects	10	10	10
Firm Types	5	5	5
Valuation Schedules	Common with McMaster	Common with Colorado except converted to marginal valuation and divided by 10	Common with Colorado
Coupons/Subject	6 in periods 1-4 3 in periods 5-12	as in Colorado	as in Colorado
Number of Periods	12	12	12
Number of Sessions	5	3	5
Training	Participation in Banking only session	4 Sample periods without payment	Participation in 6 period version of same experiment

Table 3 Marginal Abatement Cost Savings (in lab dollars)

COUPONS USED	FIRM TYPE				
	1	2	3	4	5
1	38	152	76	190	228
2	34	136	68	170	204
3	30	120	60	150	180
4	26	104	52	130	156
5	22	88	44	110	132
6	18	72	36	90	108
7	14	56	28	70	84
8	10	40	20	50	60
9	6	24	12	30	36
10	2	8	4	10	12

Note: Each coupon used permits the firm to reduce abatement by one unit (thereby emitting one unit of waste). A firm can abate, at most, ten units of waste. Abatement equals ten minus the number of coupons used.

Table 4. Benchmark Costs and Cost Savings

Benchmark	System Abatement Cost (L$)	Cost Relative to Command and Control	Cost Reduction Index
Banking Only Equilibrium	31096	94.7%	16.1%
Myopic Competitive Equilibrium	24336	74.1%	79.0%
Perfect Foresight Competitive Equilibrium	22080	67.3%	100%
Command and Control	32832	100.0%	-

Table 5. Actual Cost Savings

McMaster		Colorado		Arizona	
Session	Cost Reduction Index	Session	Cost Reduction Index	Session	Cost Reduction Index
ET1-1	74.1	1	29.9	R10	24.7
ET1-2	82.8	3	54.8	R11	7.5
ET1-3	92.9	5	70.9	R12	46.9
ET2-4	55.0	6	60.0		
ET2-5	65.1	7	65.9		
Mean	74.0		56.3		26.4