# ABSTRACT

GILLON, DANA LEE. Modeling and Analysis of $NO_X$ Emissions Trading to Achieve Ozone Standards. (Under direction of Dr. S. Ranji Ranjithan, Chair, and Dr. E. Downey Brill, Co-chair)

Emission trading programs are incentive-based policy instruments implemented to achieve environmental targets cost-effectively. In these programs, also known as transferable discharge permit (TDP), emission-reduction trading, and cap and trade programs, participants are required to meet established emission reductions goals through control measures or by acquiring TDPs from sources in the market that over-control. TDP programs encourage development and application of innovative control technologies and allow pollution sources more flexibility in complying with regulations. One potential drawback to a market-driven policy such as TDP is that the geographical distribution of emissions resulting from trades could locally degrade air quality if the market is not designed properly. Since such an outcome is generally undesirable, the ability for regulators to predict environmental impacts of trading prior to implementation is very important. The goal of this thesis is to present a general framework for using mathematical optimization to model and analyze different market design features for TDP programs including the potential use of trading restrictions to control the geographic distribution of permits. This framework will provide regulators with a way to identify effective market designs and implement more robust and reliable TDP programs. An important component of this framework is the use of Modeling to Generate Alternatives (MGA) to identify the range of trading outcomes that may occur in response to a TDP program.

A case study using this framework was conducted for NOx emission trading in the Charlotte, North Carolina region. The study analyzed alternative trading outcomes generated using MGA, investigated limitations on source size and type in the trading program, and tested the use of zoning restrictions as a way to control the geographical distribution of permits.

Trading outcomes were evaluated with respect to cost, air quality, robustness, and reliability. Results found that TDPs could be used to meet both emission limits of NOx and an ambient standard for ozone with all or a limited number of sources trading. Additionally, trading restrictions in the form of geographic zones were not particularly good at reducing local air quality impacts in the Charlotte region, although this result is believed to be (in part) attributable to the limited size of the trading region.

# MODELING AND ANALYSIS OF $NO_X$ EMISSION TRADING TO ACHIEVE OZONE STANDARDS

by

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# Biography

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As part of his research assistantship, Mr. Gillon has participated in the Civil Engineering Department's Decision Support and High Performance Computing Research Groups. His research interests are related to optimization, mathematical programming and incentive-based regulation in air quality management. His contributions to the research groups include: integration of a trading simulation interface into the Strategy Development Tool; implementation and automation of MIP solvers and MGA models into an existing decision support framework; and investigation of alternative techniques to identify least-cost management strategies for ozone.

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# 1 EXECUTIVE SUMMARY

Poor air quality is a growing problem in many urban areas. Ozone, a principal component of photochemical smog, is a pollutant of concern because it has deleterious human respiratory effects and can damage vegetation. Some cities and states have started ozone forecasting as a way to mitigate health effects and promote abatement practices, e.g. mandatory carpooling, free public transportation, and staying indoors on high-risk days. In addition, federal regulatory agencies are requiring each state to submit a State Implementation Plan (SIP), which is a plan or strategy to reduce emissions from point and mobile sources and to meet National Ambient Air Quality Standards (NAAQS) for ozone. In the near future, individual states and multi-state regions may employ relatively innovative policies such as emission trading programs to achieve point source emission reductions cost-effectively.

These programs, also known as cap-and-trade and transferable discharge permit (TDP) programs, are incentive-based policy instruments used to achieve environmental benefits in a cost-effective manner. Compared to command and control (CAC) policies, these programs encourage increased application of innovative control technologies and allow pollution sources more flexibility in complying with regulations.

A TDP is defined as a "property right" to emit a specific amount of pollutant over a finite lifetime and is treated as a marketable commodity. Program participants are required to meet established emission reduction goals through employing control measures (i.e., apply a control technology or a treatment process) or by acquiring TDPs from sources in the market that over-control. One potential drawback of TDP programs for pollutants that are non-uniformly mixed is that the spatial distribution of emissions resulting from TDP transfers may lead to localized degradation of air quality. In the past, researchers and regulators have dealt with local air quality problems resulting from emissions trading by using ambient-weighted TDP programs, which incorporate the impact of a source's emissions on air quality (i.e., transfer coefficients), to prevent trades that degrade air quality. For the case of nonlinear pollutants such as ozone, it is very difficult to resolve the relationship between emissions and air quality. Ozone transfer

coefficients are dynamic and nonlinear, which complicates the use of an ambient-weighted trading program.

The research presented in this thesis focuses on developing a framework to analyze emission trading as a means of achieving environmental benefits in a cost-effective manner. Different mathematical programming approaches for predicting potential outcomes of an emissions trading market are compared. Two of the mathematical programming techniques used to predict potential trading outcomes (i.e., the spatial distributions of emissions) are least-cost (ELC) optimization and Modeling to Generate Alternatives (MGA). ELC optimization predicts the trading outcome that will occur in a market assuming "perfect trading." The "perfect trading" assumption implies perfect information, no transaction costs, no regional economic impact, perfect competition, and full compliance. In practice, actual trading programs do not behave ideally and, consequently, cost savings realized due to emission trading may be much less than that predicted by ELC models (Tietenberg, 1985). These differences in actual and simulated control costs are likely attributable to uncertainties in engineering data (i.e., emission rates and control efficiencies), insufficient representation of the trading market restrictions, and omission of transaction costs from the LC model formulation.

Given uncertainties in engineering data and other unmodeled issues, MGA provides an excellent technique to forecast alternative trading outcomes that could occur. In applying MGA to emission trading, an upper limit on control costs (i.e., X% greater than LC) is specified and mathematical optimization is used to generate a small set of alternative trading outcomes that are very different with respect to their respective geographical or spatial distribution of emissions. These alternatives represent a spectrum of permit distributions that may result under a TDP program and give the analyst additional information about the potential behavior of the market (Loughlin et al., 1997). For instance, alternatives that show extreme shifts in the locations of emissions may suggest that the distribution of permits should be restricted geographically to prevent local air quality problems. Conversely, if the alternative trading outcomes are very similar with respect to air quality, there may be no need to control the geographic

distribution of permits.

A general iterative framework is established to show how to identify, test, and evaluate alternative trading outcomes with respect to environmental and economic impacts and reliability. Evaluation of alternative trading outcomes help regulators identify suitable market design criteria, suggest TDP implementation details, and determine the feasibility of emission trading to achieve ambient standards.

A case study was performed for the Charlotte, NC region to determine the effectiveness and feasibility of NOx emissions trading to achieve ambient ozone standards. Several market designs were tested for different NOx emission reduction levels. These designs included limitations on the size and type of sources, as well as geographical zoning restrictions on sources participating in the TDP program. Geographic restrictions are expected to limit localization of emissions reductions and thereby avoid local air quality variations. Trading outcomes were simulated using an ELC model to determine the emissions-trading benchmark. Alternative outcomes were simulated using MGA to identify the range of permit allocations that might occur for each market design.

Trading outcomes were evaluated with respect to cost, air quality, robustness, and reliability. TDP program costs were compared with a CAC uniform treatment (UT) policy. The 1-hour maximum ozone concentration was predicted with the Urban Airshed Model IV (UAM-IV) to gauge the impact of trades on ambient air quality. In addition, two meteorological episodes were simulated to assess the robustness of a market design with respect to variable meteorology. Cost and other evaluation functions were used to estimate collective compliance cost and number of transactions that might occur in the trading program.

Significant observations from the case study include:

- TDPs can be used to cost-effectively meet emission limits of NOx, providing considerable cost savings over CAC-UT
- Ambient standards for ozone can be achieved for both meteorological episodes using unrestricted trading among all sources or large sources (>100

tpy NOx) at NOx reduction levels of 30% or greater

- Limiting trading to large sources has little effect on the performance of the TDP program
- Trading restrictions in the form of geographic zones were not particularly good at reducing variability in local air quality in the Charlotte region, which is likely attributable to the limited size of the case-study trading region.

# 2 INTRODUCTION

Emission trading programs, also known as transferable discharge permit (TDP) programs, are incentive-based policy instruments implemented to achieve environmental targets in a cost-effective way. A TDP is a "property right" to emit a specific amount of a pollutant over a finite lifetime. In a TDP program, the environmental-management agency distributes a limited number of permits based on the desired percent reduction of a pollutant. For example, if 25% reduction of a pollutant is desired, then permits for only 75% of current emission levels will be distributed. Once distributed, permits are considered a marketable commodity. Sources can control above the reduction level and sell excess permits, or, if found to be more economical, choose to control less and buy permits. New or expanding sources can purchase TDPs to offset increased emissions. The result is a more flexible means for new and existing sources to meet required emission levels. In addition, TDP programs encourage the invention of innovative, cost-effective control technologies by implicitly rewarding sources for reducing more than a target amount.

TDPs should be very attractive from a regulatory standpoint because regulators control the amount of pollution emitted in the trading region through controlling the number of outstanding permits. Regulators may also choose to reduce or buy-back permits in successive years and, thus, reduce the quantity of emissions in the trading region over time. Environmental advocates can also influence environmental quality by purchasing permits, resulting in less net emissions.

Prior to implementing emission-trading policy, regulators should study the emission trading scenarios and the market properties or characteristics that maximize net benefits as a result of trading. The purpose of this research is to develop a general framework regulators can use to analyze and design TDP programs for air quality management. Market design parameters considered in this framework include the quantity of TDPs initialized, types of trading restrictions, and the sizes and types of sources that participate in trading. A set of market design parameters or characteristics is

referred to as a market design. Each market design will affect the allocation of permits and will result in distinct impacts on the air quality and cost-effectiveness. Through an iterative analysis, market designs that have acceptable environmental and economic implications are identified for implementation.

This paper is divided into 5 sections. The remainder of this section provides background on the management of ozone, the use of mathematical models and optimization in air quality management, TDP programs, and trading restrictions. Section 3 introduces an iterative framework that will help regulators test alternative market designs and then elaborates on each component of the framework. In the framework, trading is simulated using emissions least-cost (ELC) optimization and a closely-related technique called Modeling to Generate Alternatives (MGA) that generates a set of alternative trading outcomes. These outcomes are tested to measure environmental and economic ramifications of a market outcome and to assess reliability as defined by their likelihood of meeting air quality criteria when considering uncertainty. The goal is to identify robust market designs that maintain environmental quality and promote cost-effective allocations of permits. In Section 4, the iterative framework is applied to a case study for the Charlotte, NC region. Section 5 states some general observations about the framework including limitations and suggestions for enhancements.

### 2.1 Traditional Management Approaches for Ozone

After the passage of the Clean Air Act (CAA) in 1977, ambient concentrations of most criteria air pollutants (CAPs) declined significantly with ozone being the exception. The principal distinction between the other CAPs and ozone is the manner in which they are emitted and formed. Ozone is not emitted directly, but is instead formed in a series of nonlinear photochemical reactions with volatile organic compounds (VOCs) and nitrogen oxides (NOx), catalyzed by sunlight. Ozone formation is also a function of the location of precursor emission sources. In this paper, the dependence of ozone formation on emission location is referred to as “location effects.”

Traditionally, command and control (CAC) approaches have been used to control

ozone. In CAC regulations, the environmental management authority instructs air pollution sources to control ozone precursors by a certain percentage, e.g. 25% reduction of baseline emissions, or apply a specific control technology, e.g. Best Available Control Technology (BACT). These regulations do not account for the geographical locations where control technologies are used, and therefore, are ineffective at reducing ozone concentrations to desired levels. In addition, the economic implications of these CAC policies have not been thoroughly considered (Tietenberg, 1985).

A possible resolution for regulators to address location effects and cost-effectiveness is to identify the controls at individual sources that cost-effectively meet a desired ozone concentration. The regulatory agency could then force sources to apply location-specific controls using CAC policy. The next section introduces some considerations and limitations of generating cost-effective control strategies to meet emission and air quality targets.

### 2.2 Optimization in Air Quality Management

For a relatively small airshed, it may be possible to identify cost-effective control strategies using trial-and-error approaches. In today's airsheds that contain thousands of sources, however, a more systematic search method is needed to identify good emission control strategies.

Mathematical optimization is one approach that can be used for this purpose. Mathematical models to identify cost-effective strategies for meeting emission reduction targets are called Emissions Least Cost (ELC) models. The major drawback of ELC-derived strategies is that air quality is not explicitly accounted for in the search process; thus, ambient standards may be violated in the ELC solution. In addition, while controls meet emission reduction targets at lowest cost, ELC-derived strategies may not be the lowest cost approach to reach the ambient target. These strategies may place expensive controls on sources where there is little air quality impact, and, consequently, require higher overall emission reduction and costs than strategies that implicitly account for source-location effects.

An alternative technique is called Ambient Least Cost (ALC) Optimization. ALC strategies minimize the cost of meeting an air quality standard (Atkinson and Lewis, 1974). ALC problems are more difficult to formulate because the relationship between emissions at the source and ambient concentrations needs to be represented within the optimization model.

While ELC and ALC strategies identify cost-effective control strategies, these strategies may be challenged by emitters due to potential inequities in the amount of pollution reduced and cost burdens among sources in similar industrial classes, penalizing sources differently. ALC strategies could require very different control levels at sources within the same industry. Additionally, optimized control strategies provide sources with little flexibility in meeting required emission levels. Emission-trading programs offer a cost-effective and more equitable alternative to CAC regulation. Section 2.3 will describe the application and evolution of emission trading for managing non-uniformly mixed or location-dependent pollutants.

## 2.3 Transferable Discharge Permit Programs

### *2.3.1* Types of TDP programs

Dales (1968) introduced the notion of a transferable rights and emission trading programs for environmental pollution in the late 60's and early 70's. Early research focused on the potential cost savings and public and private implications of such programs, generally without regard for the complexity of the physical and chemical mechanisms that govern the fate of pollutants in the environment. Tietenberg (1980) recognized the necessity to consider location effects of the sources when the goal is to achieve a specified ambient concentration. He defines two classes of permit design: Emissions Permit Systems (EPS) and Ambient Permit Systems (APS). In both EPS and APS, sources with marginal emissions control costs lower than the market-clearing permit price would control beyond the requirement and acquire excess permits to either sell or use later. These types of sources are called *sellers*. Alternatively, a source with a marginal control cost higher than the permit price would seek to buy additional permits

from a seller at a price no greater than their marginal cost. These types of sources are called *buyers*. Theoretically, permit allocations among sellers and buyers in an emissions trading market will result in the least-cost emissions control strategy.

EPS designs are based on the release of a specified amount of pollution to the environment without regard to ambient concentration (Tietenberg, 1994). In an EPS, a source could buy one unit of emissions from another source and emit an equivalent amount. In contrast, in APS designs, permit value is based on the impact of a polluter on air quality at a receptor location. Traded permits within APS designs are typically re-valued to ensure zero net change in the ambient pollutant concentration. An APS is designed to be used in a scenario with non-uniformly mixed pollutants having non-negligible source-location effects.

### *2.3.2* Emission trading and non-uniformly mixed pollutants

TDP programs have been applied to SOx control (Hansjugens, 1998). National-scale sulfur dioxide trades, however, have caused some regional and local air quality problems resulting from geographical or spatial shifting of emissions across regions. These air quality problems are a result of the market design, which treats emission permits equally and independent of location. The Northeast US has experienced air quality and acid deposition problems from increased emission rates in the Midwest US, which occur because market mechanisms are not present to prevent sources in the Midwest or Northeast US from buying TDPs from outside the region instead of controlling emissions.

The impacts of SOx emissions on environmental quality at a given receptor site depend on source locations and can be assumed reasonably to be a linear function of the amount of pollution emitted from a particular source. Impacts, which also depend on geographical location and other physical and chemical properties of the source and the surrounding environment, can be predicted and quantified using linear transfer coefficients. These source-level coefficients specify the change in deposition at a receptor due to a unit change in emission at that source. Had an APS been implemented

instead of an EPS for SOx management, regulators could have used transfer coefficients to revalue TDPs after a trade to ensure deposition constraints are not violated.

Establishing an environmentally and economically effective TDP market for ozone management is more difficult. Ozone, unlike SOx, is a nonlinearly-reactive pollutant. Transfer coefficients for ozone are nonlinear functions of spatial and temporal variables so that a unit change in NOx or VOC emissions at a source may not result in a linearly related amount of change in ozone concentration at a receptor. In fact, ambient concentration of ozone at a receptor might increase as a result of a reduction in NOx emissions at a source. Therefore, it is very likely that changes in emission locations resulting from trades might have unpredictable and nonlinear impacts on air quality.

A more plausible design for a permit program for ozone is an EPS to trade ozone precursors, primarily NOx and VOCs, to achieve target emission reduction levels. When using such a trading approach, it may be desirable to use an air quality model to predict ambient ozone levels after a single or a series of trades to ensure that air quality is not degraded. The regulatory agency would probably reserve the right to preclude trades that may adversely affect air quality or may control the distribution of emissions by setting trading zones to prevent trades that might transfer emissions entitlements over large geographical areas. Suggestions for restricted trading are discussed in the following section.

#### *2.3.3* Restricted trading

In a properly functioning trading program, the interference of the regulatory or environmental management agency (i.e. state or federal government agency charged with supervising trades) on the location or distribution of permits should be minimized to achieve the most economical solution (Ortolano, 1997). If the authority limits trading opportunities for a participant, then the process of identifying potential trading partners and consummating cost-minimizing trades becomes more resource-intensive. In addition, cost-effective trades may be disallowed making the achievement of the LC outcome impossible. On the other hand, from an environmental perspective, certain cost-reducing trades may deteriorate air quality in portions of the region to levels below the air

quality standard. Localized areas where the air quality is below the standard are called "hot spots." Formation of pollution "hot spots" can be avoided by evaluating the impact of a trade on ambient air quality before consummation of a trade (called *case-by-case approval or analysis*) or by delineating restrictive zones within which permits are freely-traded (called *zoned trading)*. Zoned trading involves designation of a region or zone where permits are applicable and trades are not allowed to occur across the boundaries of a zone. This approach would require less supervision than a case-by-case protocol and the environmental management agency would not have to test air quality after each trade. Ideally, such a program would maintain target air quality within the region and allow as many cost-minimizing trades as possible**.** Examples of current and proposed geographically zoned trading programs are presented in the next section.

#### *2.3.4* Examples of trading restrictions for non-uniformly mixed pollutants

The South Coast Air Quality Management District (SCAQMD) in California has developed a system for simulating ozone precursor trading under the Regional Clean Air Incentives Market (RECLAIM). Their system contains an Emission Trading Model (ETM) linked with the Urban Airshed Model (UAM). These models simulate zoned, simultaneous, multilateral trading behavior using supply and demand theory. The final permit allocation is tested using UAM to predict ozone concentrations. The implemented program identifies a very sophisticated and comprehensive zoned pollution control policy. In the trading region, wind patterns are typically west to east and trades can only take place downwind (Johnson and Pekelney, 1995). Results indicate that zoning restrictions are an effective and practical technique for dealing with complex environmental systems where changes in spatial distributions of emissions can significantly impact environmental quality. A zoning approach is particularly easy to implement in RECLAIM because the region has steady meteorology and conforms well to a two-zone market. In regions with more variable wind patterns, however, approaches that are more robust may be needed to prevent deleterious environmental impact from emission trading.

The Ozone Transport and Assessment Group (OTAG) has proposed a cap-and-

trade program for $NO_x$ (OTAG, 1997). This program sets an emissions cap on a specific region or state and allows inter-region and intra-region (zoned) trades such that the total emissions budget (cap) for a given zone is not exceeded. This policy would be effective because violation of ambient standard is unlikely since emissions can not exceed the cap for any particular zone. A cap-and-trade program provides both the certainty of achieving emission reductions and maximum flexibility and cost-savings for sources.

Developing functional emission trading programs like RECLAIM and OTAG requires models to predict potential trading outcomes and scientific and cost analyses to assess the economic and environmental implications of trading. Section 3 introduces a framework and models that allow regulators to analyze emission trading and identify market designs that will lead to acceptable economic and environmental impact.

# 3 MODELING AND ANALYSIS OF EMISSION TRADING MARKETS

Market-driven regulatory policy such as TDP programs for non-uniformly mixed pollutants can cause shifts in the location of emissions that lead to localized air quality problems. In evaluating a potential trading program, a regulator will want to know

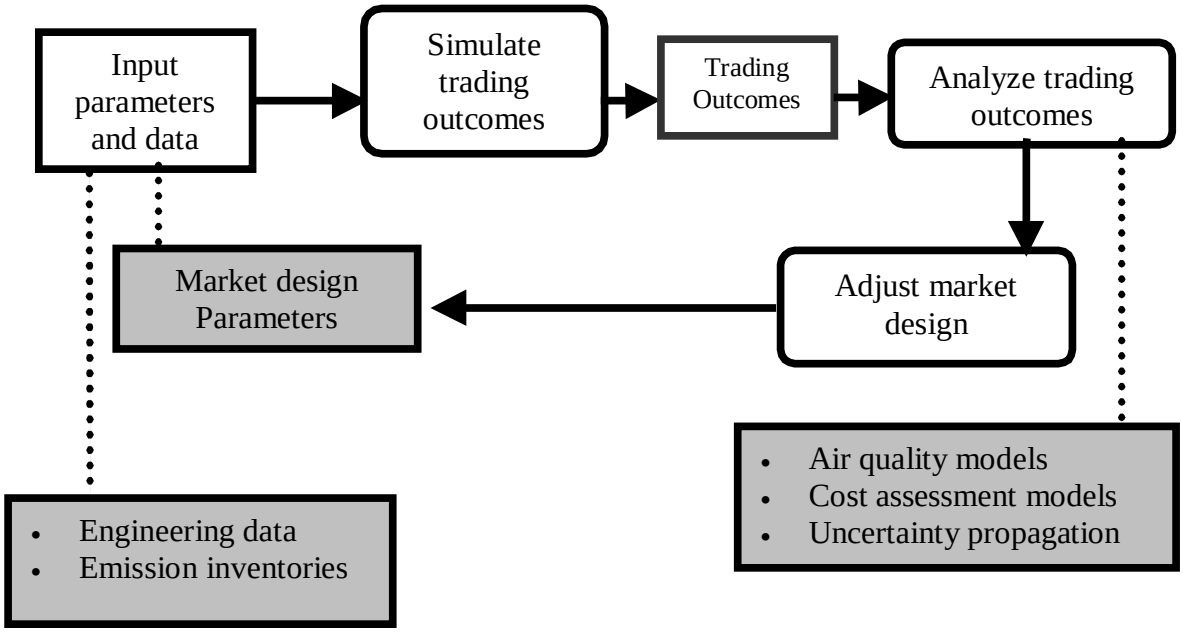



**Figure 1**. Iterative Framework for analyzing alternative TDP market designs

a priori how a policy will affect the environment. One way to prevent local hot spots is to design robust TDP programs that can reliably achieve regulatory goals through controlling permit distribution with restricted trading. Figure 1 shows a framework that can be used iteratively to test alternative trading outcomes and identify a suitable market design. The components of this framework are described below. The input parameters and data are discussed in Section 3.1. Section 3.2 introduces the techniques that could be used to simulate trading outcomes in response to a TDP implementation and Section 3.3 describes some criteria to evaluate the overall-effectiveness of a TDP market design.

## 3.1 Input Parameters and Data

This section gives a background on the typical input data and types and uses of different design parameters for TDP programs. Although there are many other market-design considerations, the issues presented here were selected because they are likely to be used in TDP programs with non-uniformly mixed pollutants.

### *3.1.1* Engineering data and emissions inventory

The input to a quantitative analysis of air pollutant emissions and control includes engineering data and an emissions inventory. Engineering data includes a list of control technologies, control costs and associated removal efficiencies at each source. Emission inventories consist of estimated or measured values of the emission rates, information about stack characteristics, and other details necessary to adequately describe the physical system. These data are typically inputs that are required for cost assessment and air quality modeling.

### *3.1.2* Market Design Parameters

#### 3.1.2.1 *Source participation*

Several criteria may be used to define the numbers and types of sources that participate in a TDP program. Participants may be selected based on source strength, source industrial classification (SIC), geographic location, and other systematic groupings or classifications.

In particular, source strength or size is the grouping method most commonly mentioned in literature. Tietenberg (1996) suggests that smaller sources should not participate in trading programs unless the cumulative effect of small sources is *large enough* to warrant their participation. For instance, SCAQMD requires sources greater than 4 tons of pollution per year to participate in RECLAIM, yet it is not clear if cumulative economic and environmental effects of smaller sources were considered in setting the size cutoff. Whether a source is large enough to participate is a subjective issue that must be determined by regulators charged with designing or implementing a TDP program.

#### 3.1.2.2 *Trading restrictions*

Section 2.3.3 introduced two general types of trading restrictions: case by case approval and zoning. Although case-by-case approval would prevent any violation of the standard, the negative implications (i.e., increased transaction costs to predict the air quality impact of an individual trade and disallowing trades that possibly lead to cost-effective permit allocations) might make it a less attractive option than zoning. Therefore, zoning restrictions will be the focus of analyses in this research.

Zones can be defined based on political or geographical boundaries at varying scales. Zones based on political boundaries (e.g. states or counties) may be the easiest to implement through a State Implementation Plan (SIP). Geographical boundaries may be most appropriate in cases where the airshed follows the terrain.

In zoned trading, it is possible to delineate zones in a manner that makes it infeasible for a zone to meet its reduction or emissions goal (i.e., even if maximum controls are applied at all sources). In such case, the regulatory agency could: 1) re-delineate the zones to ensure all zones have feasible emission reduction targets, or 2) force sources in the non-compliance zone to apply a particular control device, such as Maximum Achievable Control Technology (MACT) or meet the Lowest Achievable Emissions Rate (LAER).

Another relevant issue for large-scale zoning (e.g., state or regional scale) is the possibility that even intra-zone trades, resulting in emissions reallocation within the zone, could deteriorate air quality below the standard. This situation may be mitigated by resizing zones, introducing sub-zones within each zone to further control permit distribution, or requiring different reduction levels in each zone.

Environmental and economic ramifications of trading restrictions considering pollutant transport, inhibited trades, inequity, and potential unfeasibility of trading zones require the analyst to predict possible outcomes of restricted trading and evaluate their performance. Their performance then needs to be compared with the performance of trading outcomes for markets with different or no restrictions. These alternative sets of restrictions can be tested separately or in combination within the framework shown in Figure 1.

3.1.2.3 *Quantity of TDPs*

From a regulatory point of view, it is important to identify the maximum allowable emissions in the trading region. A regulator may wish to know the number of TDPs to be allocated in the market to reach a desired air quality standard or estimate permissible limits on industrial growth. One procedure for establishing an emissions limit is to generate potential trading outcomes and determine the impact on air quality (Figure 1). Air quality model predictions help pinpoint the emissions limit that will achieve the ambient standard. For example, allowable emissions are set at X% of uncontrolled or baseline emissions. Predicted outcomes are tested with an air quality model to estimate the number of times a year the air quality standard is exceeded. If the regulatory agency is satisfied with that number of exceedences, then the emissions limit is assumed sufficient. Alternatively, if the number of exceedences is excessive, then the agency may reduce the allowable emissions or restrict trades from occurring using a technique described in Section 3.1.2.2. In general, the environmental management agency must select an appropriate limit so air quality violations and allowable growth are at acceptable levels.

## 3.2 Simulation of Emission Trading Program Outcomes

### *3.2.1* Least-cost outcomes

This section presents two mathematical modeling approaches to predict the outcomes of emission trading programs. Dales (1968) showed that the final allocation of resources in a free-trade system would be the most efficient, or least cost (LC), allocation. McGartland and Oates (1983) used this concept of efficient allocation to simulate the outcome of a trading market by searching for the minimum cost solution. The least cost model for this analysis is formulated as a mixed integer program (MIP). The mathematical program is as follows:

Emissions Least Cost Model Formulation**:**

$$\text{Minimize} \qquad \text{Cost} = \sum_i \sum_j C_i \left[ x_{i,j} u_i \right] \tag{1}$$

$$\text{s.t.} \qquad \sum_i \left[ u_i * \sum_j \left[ (1 - e_{i,j}) * x_{i,j} \right] \right] \leq T \tag{2}$$

$$\sum_j x_{i,j} = 1 \qquad \forall i \tag{3}$$

$$x_{i,j} \in \{0,1\} \qquad \forall i, j \tag{4}$$

where

$C_i$ = cost to source which includes process $i$

$x_{i,j}$ = binary variable representing control option $j$ applied to process $i$ ( =1 if control $j$ is applied at $i$, else =0)

$u_i$ = uncontrolled emissions rate on process $i$ [tons per year (tpy)]

$e_{i,j}$ = efficiency of control option $j$ on process $i$ [fraction]

$T$ = target precursor emissions for region [tpy]

$i$ = index for process

$j$ = index for control option on a process ($j$=0 represents no emissions control)

The term $T$ is calculated by

$$T = CE - BE*EFF \tag{5}$$

where

$CE$ = emissions from participating sources in trading region that are controllable [tpy]

*BE* = baseline emissions of all participants in the trading region [tpy]

*EFF* =desired reduction in overall precursor emissions [fraction]

The objective of the MIP-ELC model is to minimize cost as shown in Equation (1). A cost is associated with applying a control technology on a process. This is a function of the type of control and the size of the process. The total cost to a source is the sum of the costs for the processes at that source. The model is constrained according to Equations (2)-(4). Equation (2) states that aggregate precursor emissions must be below the target, *T*. *T* is defined according to Equation (5) describing the collective reduction target. Not all sources need to control to meet this target. This definition of *T* allows uncontrollable sources to participate in the market as buyers to meet collective reduction requirements. Lastly, Equation (3) constrains the model to select no more than one control option for each process.

### *3.2.2* Alternative outcomes of trading programs

Tietenberg (1985) analyzed cost differences between LC models and actual programs by re-examining "perfect trading" assumptions like no transaction costs, no regional economic impact, perfect competition and full compliance. He found that actual trading programs do not behave "perfectly" and, therefore, realized cost savings due to emission trading may be much less than predicted by least cost models (Tietenberg, 1985). Other case studies have also examined the divergence of predicted least cost solutions and the control costs in actual programs (Atkinson and Tietenberg, 1991). Although proposed or actual programs did not achieve the least cost benchmark, the final allocation was within 50% of predicted cost in some cases. The cost difference between actual and simulated trading markets is likely attributed to a lack of full information on control costs and data (e.g., uncertainties in emissions rates, control efficiencies, and other engineering data), insufficient representation of trading restrictions in simulation models, and omission of transaction costs from the LC model formulation.

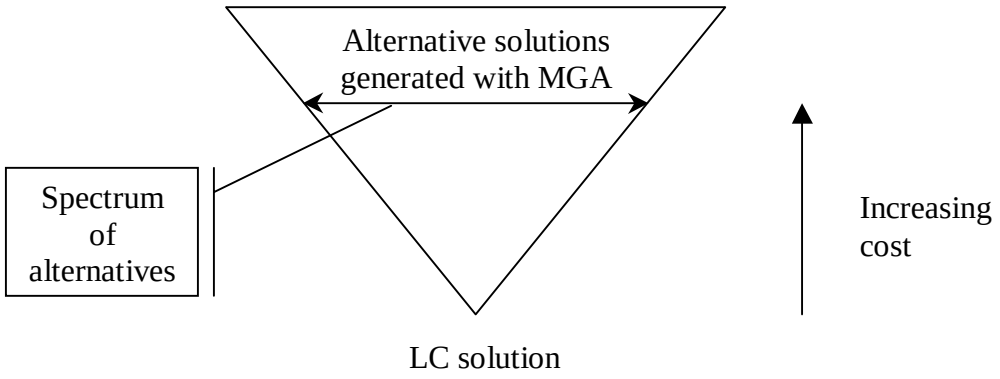



**Figure 2.** Graphical representation of the relationship between LC and MGA solutions

Due to uncertainties in engineering data and the other unmodeled issues in LC models, an alternative and more comprehensive approach to modeling emission trading is needed. Modeling to Generate Alternatives (MGA) is a mathematical programming technique that can be used to analyze the impact of implementing a policy instrument or new regulation when uncertainties and unmodeled issues exist (Brill et al., 1982, 1990). Unlike the LC modeling approach that generally provides only one "optimal" solution, MGA permits the analyst to generate a set of possible outcomes or alternatives that are very different from one another. MGA in an emission trading context constrains control costs to be within some fraction (cost relaxation) of the ELC solution and generates a small set of alternative trading outcomes that are very different with respect to the geographical distribution of emissions. These alternatives represent a spectrum of permit distributions that may result in response to a TDP program and give the analyst additional information about the potential behavior of the market (Loughlin et al., 1997). The relationship between LC and MGA solutions is shown in Figure 2. One can see that LC optimization generally yields only one outcome for trading, which is represented by the tip of the triangle. If costs are allowed to exceed the LC (relaxed cost), additional trading outcomes, which are represented by the width of the triangle at any relaxed cost value, can be predicted. If trading does not achieve the least-cost allocation, then the number of potentially different outcomes increases with decreasing cost-effectiveness. This is one

reason why MGA might be a better technique for modeling TDP programs when imperfect trading conditions are present and the LC allocation is unlikely to occur. Figure 3 depicts the procedure for generating alternative outcomes using MGA. The MGA formulation is given below:

Model for generating alternatives

$$\text{Minimize} \qquad \sum_{(i,j) \in K} u_i x_{i,j} \tag{6}$$

$$\text{s.t.} \quad \sum_i \sum_j C_i \left[ x_{i,j} u_i \right] \leq C^T \tag{7}$$

$$\sum_i \left[ u_i * \sum_j \left[ (1 - e_{i,j}) * x_{i,j} \right] \right] \leq T \tag{8}$$

$$\sum_j x_{i,j} = 1 \qquad \forall\, i \tag{9}$$

$$x_{i,j} \in \{0, 1\} \qquad \forall\, i, j \tag{10}$$

Where

K = set of index combinations ($i$,$j$) determined by the difference method

$C^T$ = allowable maximum cost of an alternative

$C_i$ = cost to source which includes process $i$

$x_{i,j}$ = binary variable representing control option $j$ applied to process $i$ ( =1 if control $j$ is applied at $i$, else =0)

$u_i$ = uncontrolled emissions rate on process $i$ [tons per year (tpy)]

$e_{i,j}$ = efficiency of control option $j$ on process $i$ [fraction]

$T$ = target precursor emissions for region [tpy]

$i$ = index for process

$j$ = index for control option on a process ($j$=0 represents no emissions control)

The goal of MGA is to maximize the difference between the current solution and all previous alternatives. Equation (6) forces the currently generated solution to contain as many different controlled sources from previous solutions as possible. There are many ways to define the difference between two outcomes. Some examples are described by Brill et al. (1982) and Hildebrandt (1996).

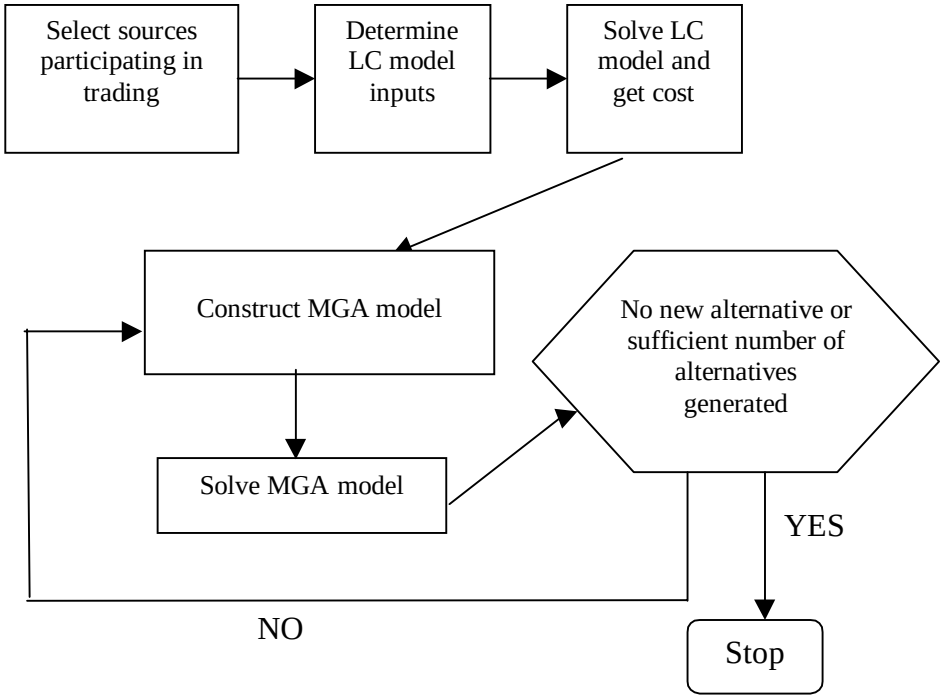



**Figure 3.** Procedure for generating alternative market outcomes using MGA

Equation (7) is called the cost constraint. The cost constraint forces alternatives to have costs below the bound $C^T$. Equations (8), (9), and (10) were defined for the ELC model in Section 3.2.1. Notice that the only differences between the MGA and ELC models are the addition of the cost constraint and a new objective function.

### 3.3 Criteria for Evaluating TDP Programs Outcomes

This section presents criteria that can be used to evaluate the effectiveness of

alternative TDP program outcomes. Emission trading programs can lead to many spatially distinct permit allocations depending on the control costs, behavior, and sizes and locations of sources in the trading region. This type of market-driven program could lead to very different emissions distributions and thus result in distinct impacts on the air quality, human exposure, and materials damage in a particular region. The focus of regulators will predominantly be the ambient air quality impact, but, issues such as cost, market activity, and reliability with respect to meeting emissions targets may be investigated to refine a market design.

### *3.3.1* Air quality

For a given trading outcome, the resulting air quality can be predicted using an air quality model. An example of an air quality model that can be used to predict ozone levels is the Urban Airshed Model (UAM), an EPA-approved numerical grid model, which is widely used for regulatory purposes. UAM can do multi-day simulation of ozone formation and decay and provide detailed information about the magnitude and location of 1-hr peak ozone levels (Scheffe et al., 1993).

### *3.3.2* Reliability in meeting emission reduction target

Reliability is defined as the likelihood that the trading outcome will meet an emission reduction target. Trading outcomes that achieve emissions reductions more reliably, with a higher likelihood of success, will be better candidates for implementation. Regulators can use reliability estimates to identify market designs that are likely result in acceptable trading outcomes in a reliable manner.

### *3.3.3* Robustness with respect to meteorology

The distribution of emissions that occurs in response to emission trading is uncertain and can lead to a range of air quality impacts. Air quality impacts vary significantly with the meteorological episode. To account for variable meteorology, the analyst could test the alternative trading outcomes for different meteorological episodes. The regulatory agency may use air quality predictions for multiple episodes to identify robust market designs that are stable with respect to variable meteorology and uncertain geographical distribution of emissions. They may decide to allow no exceedences (very conservative) or allow some of the time to be in violation. In addition, regulators must

decide between two possible definitions of robustness: binary and "matter of degree." Binary would mean that any ozone concentration above the standard is not acceptable. "Matter of degree" metric would specify how high ozone predictions are above the standard and use the amount over the standard to rate the quality of that market design.

### *3.3.4* Program and Transaction Costs

TDP programs involve control costs and permit costs. If source ***A*** has a low marginal cost relative to the permit price, ***A*** would choose to control beyond the requirements and sell extra permits for reimbursement. On the other hand, source ***B*** has a relatively high marginal cost or no technologically feasible controls, it would chose to buy permits from a seller like ***A***. This selling and buying process results in no net change in program costs since ***A*** will sell permits to compensate for higher control costs, but ***B*** will incur equivalent costs to purchase ***A***'s permits. Consequently, the overall program costs will simply be the control costs of ***A*** and ***B***. This simplification of trading costs does not account for either transaction costs due to such issues as contracting, finding trading partners, or profit-seeking behavior by sellers.

Transaction costs can adversely affect the performance of a TDP program (Stavins, 1990). These costs depend on the difficulty of gathering information about potential trading partners and the number of permits traded among them, as well as writing up a contract and getting approval from the environmental management agency. A potential surrogate metric of transaction costs is the number of transactions. In the cost model, the minimum number of transactions is estimated by the difference in emissions reduction and initially allocated permits for *sources that choose to control their emissions beyond the required emission reduction target*. The minimum number of transactions is:

$$Q = \sum_{i \in I} \sum_{j} (e_{ij} - IA_i) * u_i \qquad (11)$$

where

Q = minimum number of transactions

$I$ = set of processes where emissions are controlled beyond requirement

$e_{ij}$ = fractional removal efficiency of in-place control $j$ on process $i$

$IA_i$ = the initial number of permit allocated to a sources as fraction of uncontrolled emissions

$u_i$ = uncontrolled emissions of process $i$ [tpy]

$i$ = index for process

$j$ = index for control option on a process

This is the minimum number of transactions because trades occur simultaneously and multilaterally. No model of the path of a permit to its final owner is included. For example, consider the case of two sources willing to trade. Source ***A*** controls beyond the emission target and source ***B***, whose control costs at the margin are greater than permit price, buys extra permits. ***B*** will buy permits from a source that controls above the emission reduction target but not necessarily source ***A***. It is possible that a source ***C*** initially bought ***A***'s permits and then sold them to ***B***. This would mean that twice the number of transactions occur than the model predicts. Thus, the predicted number of transactions [Equation (11)] is the **minimum** number of transactions to attain a given trading outcome. The significance of the number of transactions is that it describes the potential magnitude of transaction costs and provides information about the amount of market activity (trading) that might occur.

# 4 CASE STUDIES OF NOx EMISSION TRADING

Application of the general iterative framework, which is summarized in Figure 1, can provide information to regulators about suitable design and implementation details to yield reliable and robust trading markets. This section is intended to show how the iterative framework can be applied to a case study and describe how the results could be used in a regulatory context.

## 4.1 General Information on the Case Study

An illustrative case that was based on information associated with the Charlotte, NC region is used to evaluate the feasibility and effectiveness of NOx TDP programs for achieving ozone standards in an urban area. This study demonstrates how the framework could be used to identify reliable and effective market designs for a TDP program.

Currently, the Charlotte region is classified as a non-attainment area for ozone. Air quality modeling has suggested that ozone formation in Charlotte is limited by the amount of available NOx emissions in the atmosphere. These properties made Charlotte a good candidate for NOx emissions trading to achieve ozone standards.

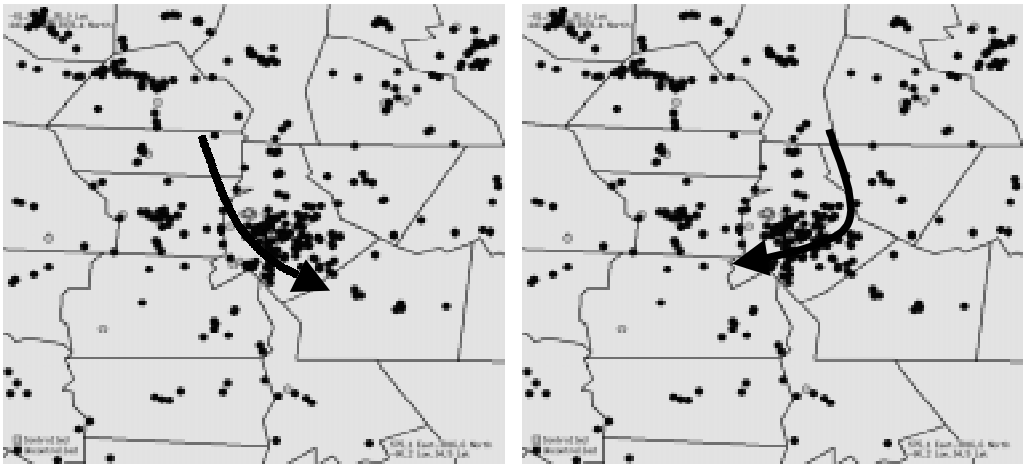
The case study was performed on the Charlotte, NC region, which consists of 19 counties in North and South Carolina. The NC counties included all or parts of Caldwell, Burke, Alexander, Davidson, Davie, Catawba, Cabarrus, Lincoln, Stanly, Rowan, Gaston, Union, and Mecklenburg counties. The SC region included portions of Cherokee, Chester, Lancaster, York, Richland, and Union counties.

The emissions data used in the study were 1990 emission rates obtained from the North Carolina Department of Environment and Natural Resources (NC DENR). The data set contained growth factors for projecting emissions to 1999 levels. Only NOx control options were considered while VOC emissions were left uncontrolled.

Engineering data including a list of discrete control technologies, control costs and associated removal efficiencies at each source were obtained from the EPA's Emission Reduction and Cost Assessment Model (ERCAM) (ERCAM-NOx 1994). Control costs were expressed in dollars-per-ton of NOx removed. Tables 5 and 6 in the appendix (Section 8.1.2) list the Charlotte emission inventory in input format and NOx control cost information from ERCAM, respectively.

Market outcomes were simulated using an ELC model and MGA with 10, 20, and 30% cost relaxation as described in Section 3.2. Trading outcomes were displayed using the Strategy Development Tool (SDT) (Loughlin et al., 1995). The outcomes were then evaluated using the following four criteria:

- **Air quality:** Air quality was predicted for each outcome using a 3-day UAM-IV simulation to predict the 1-hour maximum ozone concentration in the region. Two different meteorological episodes were modeled to estimate the impact of variable meteorology on ambient ozone concentrations resulting from trading. Meteorological data were acquired from MCNC and NC DENR and were based on historical worst-case meteorological episodes. Figure 4 is a visual representation of the trend in wind patterns for the modeled episodes.



(a) (b)

**Figure 4.** General wind pattern for modeled meteorological (a) episode 1 and (b) episode 2.

- **Program Cost:** The TDP program costs were estimated using ERCAM control cost data. The predicted allocation of permits from the simulation models specified the emission controls to be used at each source. Source control costs were calculated based on the marginal control cost for the control technology being used and the amount of pollutant being removed. Total program costs were calculated as the sum of control costs for all sources.

- **Number of Transactions:** Market activity was modeled by determining the minimum number of transactions to reach the trading outcome using Equation 11 (Section 3.3.4). The units for the number of transactions are in tons of emissions traded.

- **Reliability:** The reliability of meeting the emission targets depended on the types of sources and the levels of control they select. Uncertainties were propagated using a Monte Carlo sampling technique with 250 samples seeded with the same random seed for each scenario. Uncontrolled emission levels were assumed to follow a log-normal distribution with a standard deviation of 20% of the nominal value given in the ERCAM control data. Log-normal distribution ensured all samples from the emission distribution were positive. Control efficiency was assumed to be log-normally distributed with a standard deviation of 10% of the value provided in ERCAM. In addition, samples from the control efficiency distributions were required to be between 0 and 1. Power plants were assumed to have less variable emission levels and control efficiency. This was implemented by giving power plant emissions and control efficiencies half the variability of other sources. A measure of reliability expressed as a probability of meeting the total emission target reduction is then estimated for each outcome of a TDP program.

A scenario (base case) was established to provide a basis for comparison of trading outcomes. The base case consisted of the Charlotte emissions inventory with no controls on VOC or NOx emissions. The base case which did not include any Title IV or V emission controls, produced a peak 1-hour ozone value of 128.9 ppb for Episode 1 and 129.1 ppb for Episode 2 as shown in Table 1.

A CAC uniform treatment (UT) cost benchmark scenario was also established. Uniform treatment, which requires all sources to control the same percentage of their emissions, was selected to compare with a TDP program because both policies are considered fairly equitable and UT has historically been a commonly-used environmental management approach. A CAC-UT scenario for a given target reduction level was developed by applying the control technology that removed either at the target reduction level or at the next highest reduction level over the target. For example, consider an emission reduction target of 20% NOx reduction. If a source does not have a control option to remove exactly 20%, then that source is forced to apply the control option that removes at the next level over 20%. The minimum NOx emissions reduction that could be achieved with this uniform treatment policy is 30%. UT treatment and TDP control costs are compared in Tables 1 and 2.

### 4.2 Case Study I: Open-Market, Unrestricted Trading

A case study with unrestricted trading was performed as a preliminary investigation. No limits or restrictions were imposed on trading, i.e., any source was allowed to trade with any other source. All NOx point sources in the Charlotte region were allowed to trade without restrictions. The initial quantity of permits was set equal to 50% reduction from baseline NOx emissions, i.e., the target emission reduction is 50% of emissions from all sources.

To simulate trading, an ELC optimization model [Equations (1)-(5)] was formulated with a constraint on emissions [Equation (2)] that specified 50% NOx reduction. The MIP model was solved for the least–cost solution using the CPLEX

solver. The resulting outcome was evaluated using the evaluation criteria defined earlier in Section 4.1. Results are summarized in Table 1. A sample ELC model is provided in the appendix (Section 8.1.3).

**Table 1.** LC and alternative results for all sources participating in unrestricted trading

| Outcome | NOx emissions limit [as % reduction from baseline] | CACUT Cost [$M] | TDP pro-gram Cost [$M] | Air quality [ppb $O_3$] | | Minimum Number of Trans-actions [tpy] | Reliability [% likelihood meeting emissions target] |
|---|---|---|---|---|---|---|---|
| | | | | Episode 1 | Episode 2 | | |
| **Base Case** | 0% | | - | 128.9 | 129.1 | - | - |
| **ELC trading outcome** | 10% | - | 2.81 | 125.6 | 128.2 | 6524 | 55.2 |
| | 20% | - | 6.06 | 123.9 | 125.7 | 9615 | 50.4 |
| | 30% | 17.7 | 10.4 | 122 | 124.4 | 9252 | 48 |
| | 40% | 37.5 | 32.9 | 119.2 | 123.9 | 8329 | 46.4 |
| | 50% | 157 | 99.8 | 117.4 | 123.2 | 2314 | 48 |
| **Alternative trading outcome** | 10% | - | 3.65 | 125 | 127 | 6592 | 48 |
| | 20% | - | 7.88 | 123.5 | 125.3 | 9768 | 47.6 |
| | 30% | 17.7 | 13.5 | 121.4 | 124.5 | 9763 | 47.2 |
| | 40% | 37.5 | 42.8 | 119.1 | 123.7 | 7319 | 48.8 |
| | 50% | 157 | 130 | 115.8 | 123.3 | 1734 | 46.8 |

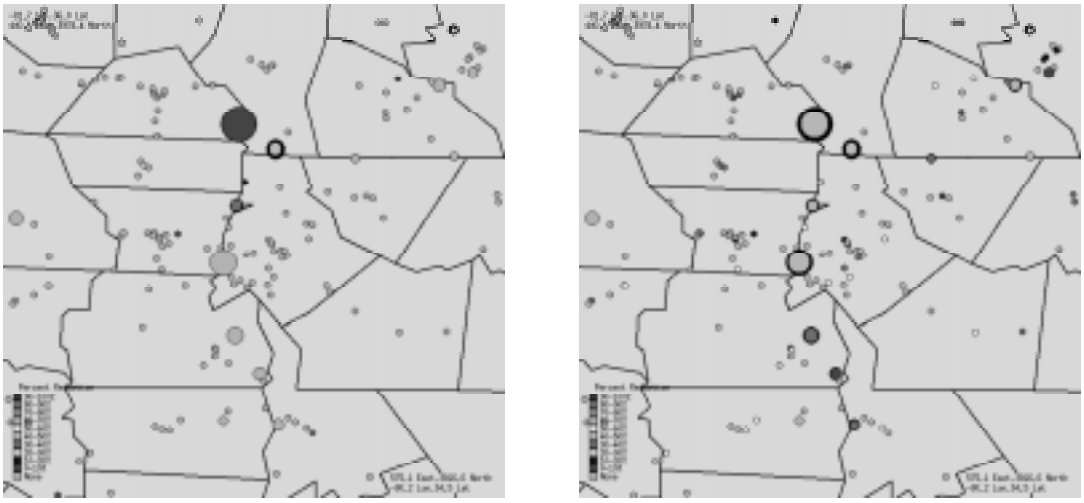
The estimated cost for achieving 50% NOx reduction through emissions trading was $99.8M, which is significantly less than the CAC-UT benchmark of $157M. Ozone concentrations were predicted to be 117.4 and 123.2 ppb for episodes 1 and 2, respectively. Predicted ozone levels, which show improvement over base-case outcomes, are below the 1-hour ozone NAAQS of 124.9 ppb. The likelihood of meeting the emissions target was 48% and at least 2314 transactions occurred to reach a least-cost

outcome.

Scenarios corresponding to 10, 20, 30, and 40% reduction in NOx emissions were similarly analyzed, and the results are summarized in Table 1.

The following observations were made about the results in Table 1:

- TDP programs provide significant cost savings over the CAC-UT benchmark
- an ozone standard of 124.9 ppb can be achieved for both meteorological episodes at 30% or greater NOx reduction
- a 20% NOx reduction can achieve the ozone standard for meteorological Episode 1
- market activity, indicated by the number of transactions, varies depending on the reduction level
- the reliability is fairly low (less than 56%) for all scenarios
- going from 40 to 50% NOx reduction increases the TDP program control costs by threefold



(a) (b)

**Figure 5.** Emissions distributions (ELC outcomes) for (a) 10% and (b) 40% NOx reduction

Figure 5(a) and (b) show the emissions distributions resulting from unrestricted

trading between all point sources to achieve 10% and 40% NOx reductions, respectively. In this figure, sources are located on the map according to their geographical location. The size of the circle is shown proportional to the corresponding source strength and the shade of gray color of the circle corresponds to the source-level emissions reduction. For example, circles with the lightest shade are sources where no control is applied while the circles with the darkest shade are sources that are applying the greatest level of emissions reduction. At 10% reduction, large sources tend to have the highest burden of control as shown by the small quantity of large, dark shaded circles in Figure 5(a). At 40% reduction, several smaller sources apply control technologies as shown by a larger number of dark shaded circles in Figure 5(b).

The ELC scenarios in Table 1 were repeated to simulate unrestricted trading between large sources. Only sources with emissions rates greater than 100 ton per year (tpy) of NOx were allowed to trade. Small sources (less than 100tpy) were uncontrolled, but their emissions remained as input to UAM. The goal was to determine if small sources (less than 100 tpy) played a significant role in trading.

The ELC model was set-up using the limited number of large sources. A 10% NOx reduction excluding small source emissions, i.e., 10% reduction of large source emissions, was calculated and added as ELC model constraint [Equation (2)]. Then the model was solved using CPLEX to obtain a least-cost outcome from trading among large sources. This procedure was repeated for 20-50% NOx reduction scenarios. Outcomes are evaluated using the criteria introduced in Section 4.1. The results are summarized in Table 2.

**Table 2.** ELC results for large sources (> 100tpy NOx emissions) participating in unrestricted trading

| Outcome | NOx emissions limit [as % reduction from baseline] | CAC UT Cost [$M] | TDP pro-gram Cost [$M] | Air quality [ppb $O_3$] | | Number of transactions [tpy] | Reliability [% likelihood not meeting emissions target] |
|---|---|---|---|---|---|---|---|
| | | | | Episode 1 | Episode 2 | | |
| **Base Case** | 0% | - | - | 128.9 | 129.1 | - | - |
| **ELC trading outcome** | 10% | - | 2.77 | 125.2 | 127.3 | 6346 | 53.2 |
| | 20% | - | 5.87 | 123.4 | 125.6 | 9353 | 47.6 |
| | 30% | 17.7 | 9.48 | 122 | 124.4 | 8996 | 46 |
| | 40% | 37.5 | 30.3 | 119.3 | 124 | 8114 | 47.6 |
| | 50% | 157 | 95.3 | 118.2 | 123.2 | 2223 | 46.4 |

Comparing similarities among the results in Table 1 and Table 2, the following observations can be made:

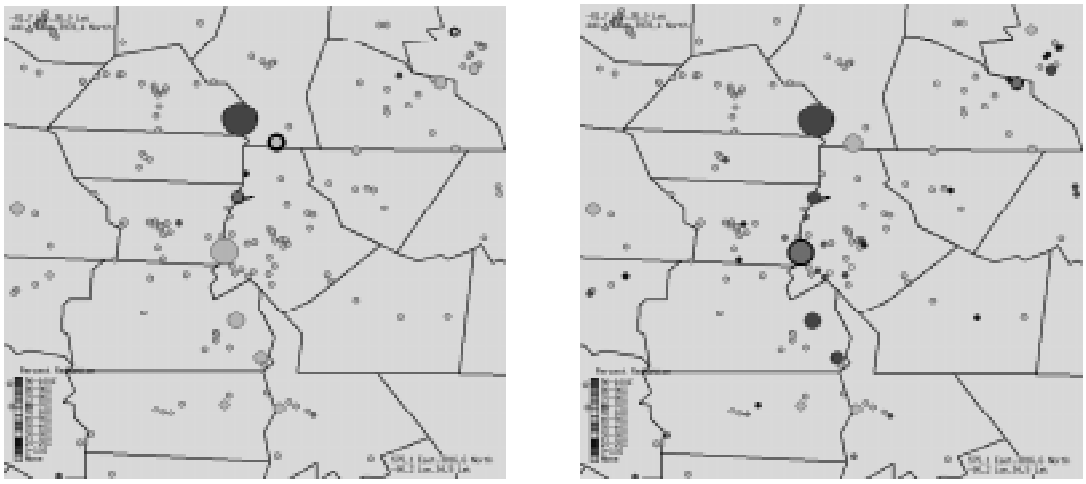
- Cost savings due to emission trading are possible even when only large sources are considered
- an ozone standard of 124.9 ppb can be achieved for both meteorological episodes at 30% or greater NOx reduction
- 20% NOx reduction can achieve the ozone standard for meteorological Episode 1
- both cases have a comparable levels of market activity
- Limiting source participation using a size cutoff of 100 tpy NOx has relatively small effect on the overall performance of the trading program

Results in Figure 5, Table 2, and the top portion of Table 1 represent the outcomes of perfect trading as simulated by the ELC model. As discussed in Section 3.2.2, modeling trading with ELC models includes assumptions that may likely be invalid

under realistic trading conditions. To determine the outcomes of trading under more realistic settings, additional outcomes for the previously modeled scenarios were generated using the MGA technique. Application of MGA was expected to provide a *more realistic set* of outcomes that were very different in terms of emissions distribution.

As part of this case study, the MGA technique (Section 3.2.2) was applied to scenarios with all sources trading in an unrestricted market. The MGA objective function was formulated to maximize the number of sources that switch from control to no control in alternative outcomes**.** To achieve this switching, difference was defined as follows: If process $i$ was controlled using technology $j$ ($x_{i,j}$ =1) and the selected control was not the no-control option ($j$≠0), then every process at the source, which contains process $i$, is added to the set of processes $K$. Every control option for processes in $K$, except no-control options [i.e., $x_{i,j}$, $\forall i \in K$, $\forall j$ >0 ], were added to the objective with the respective weight $u_i$ based on process size. If process $i$ was controlled using technology $j$ ($x_{i,j}$ =1) and the no control option was selected ($j$=0), then the variable $x_{i,j}$ was not added to the objective. This difference technique ensured larger processes were less likely to be controlled in alternative solutions and attempted to force sources to switch from no emissions control to control rather than change between control options. The control cost was constrained to be within 30% relaxation from the cost of the ELC solution. The MGA model [Equations (6)-(10)] was solved using CPLEX to obtain an alternative outcome. As expected, defining and weighting the MGA objective in this manner caused more extreme shifts in the distribution of emissions in alternative outcomes. The objective function was updated again with sources that controlled processes in the alternative using the procedure described above. For the second alternative, however, sources that were controlled in both the ELC solution and the first alternative are penalized by an additional factor of 10 to drive repeatedly controlled sources out of the next alternative. The updated MGA model was solved again to obtain a second alternative. Each trading outcome was evaluated with the criteria presented in Section 4.1. This procedure was repeated for different NOx reduction levels ranging from 10 to

50%. A sample MGA model to generate the first alternative is presented in the appendix (Section 8.1.4).



(a) (b)

**Figure 6.** Emission distribution for (a) LC and (b) alternative market outcome

Table 1 contains results from evaluating the ELC and first alternative outcome for a series of different reduction levels. An important observation is that air quality can vary while costs remain nearly the same. For example, the ozone concentrations for the 50% reduction scenarios range from 117.4 ppb for ELC to 115.8 ppb for the alternative. Such variability might be interpreted as a sign that the market, while performing at near LC, can lead to unpredictable ozone levels. This variability might be reduced using zoned trading restrictions. The level of market activity represented by the number of transactions is similar for both ELC and MGA outcomes. Although a similar number of transactions occurred, the final distribution is quite different as noted from the variability in ozone concentration. Lastly, the reliability in meeting emissions target is similar between the least cost and the alternative trading outcomes.

Figure 6(a) and (b) shows different emissions distributions that could occur under

the same unrestricted market design to achieve 10% NOx reduction allowing all sources to trade. Figure 6(a) is the LC outcome that is achieved with only a few sources controlling emissions depicted by the small number of dark-shaded circles. On the other hand, Figure 6(b) is an alternative emissions distribution that might occur in the same market identified by the MGA method. The alternative outcome, 6(b), suggests that the same 10% reduction can be achieved using a different set of controls in which a greater number of smaller sources control. It is important to note that some sources control emissions in one outcome and do nothing in another. This is analogous to a source opting to trade or not. The source might decide to offset all emissions with permits or control up to the requirement.

An unrestricted market design appears to give alternative trading outcomes that have similar, but not necessarily the same, performance. This may suggest that such designs are robust. For the 50% reduction case, however, there is a range of air quality values that indicate that the market design, if implemented, might lead to air quality variability. This may be particularly important when a market design leads to different trading outcomes that are above and below the standard. Such variability in air quality predictions indicates the potential need for trading restrictions to restrict the geographic distribution of permits. The next section addresses the use of trading restrictions applied to the case study as a method for controlling the distribution of permits and overall-market performance.

### 4.3 Case Study II: Controlling the distribution of TDPs

A second case study was implemented to test trading restrictions as a means to inhibit extreme shifts in location of emissions in the market and prevent negative impacts on air quality.

In this case study, zones were set based on geographical and political boundaries and knowledge of the typical meteorological conditions in the region. The episodes tested in the case study have typically north to south wind patterns; hence, the flow of

permits was restricted using north/south zones where permits were not allowed to be traded across zone boundaries. Second, to make the implementation of zones more feasible from a political standpoint, the boundaries of the zones followed county boundaries. Zone boundaries were screened to ensure target emissions could be reached within each zone. The map in Figure 7 and Table 3 shows the delineation of zones geographically. In Table 3, FIP codes beginning with 37 and 45 are North Carolina and South Carolina counties, respectively.

**Table 3.** Zoning boundaries for Charlotte case study using restrictive trading zones

| **Northern Zone** | | **Southern Zone** | |
|---|---|---|---|
| **FIP county code** | **Name** | **FIP county code** | **Name** |
| 37027 | Caldwell | 37071 | Gaston |
| 37023 | Burke | 37179 | Union (NC) |
| 37003 | Alexander | 37119 | Mecklenburg |
| 37057 | Davidson | 45021 | Cherokee |
| 37059 | Davie | 45023 | Chester |
| 37035 | Catawba | 45057 | Lancaster |
| 37025 | Cabarrus | 45091 | York |
| 37109 | Lincoln | 45079 | Richland |
| 37167 | Stanly | 45087 | Union (SC) |
| 37159 | Rowan | | |

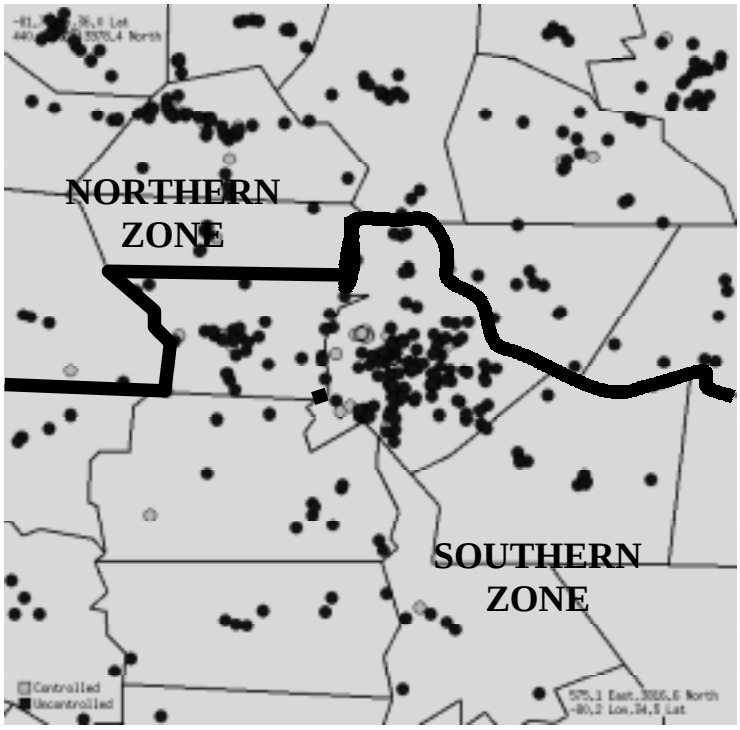


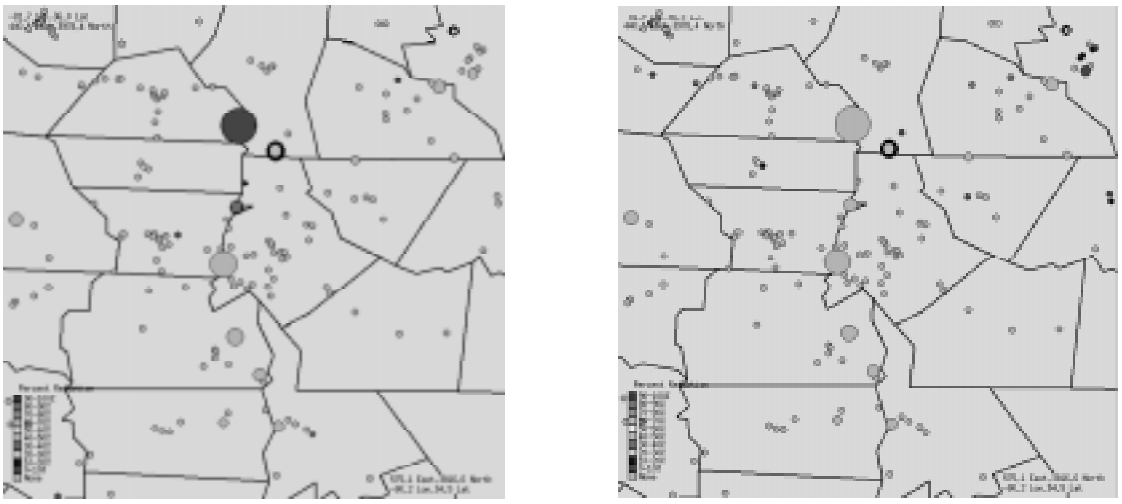

**Figure 7.** Zone boundaries for Charlotte case study using restrictive trading zones

Restricted trading among all sources to achieve a 10% NOx reduction was tested, and the results were compared to those with no restrictions. Zoned trading simulations were applied in the similar manner as unrestricted simulation from Section 4.2. Since each zone was a distinct and independent unit with no cross-boundary trades, each was treated as a separate trading region. Then, these outcomes from each zone were combined to generate an overall outcome for the entire trading region.

**Table 4.** LC and alternative results for restrictive and unrestrictive trading

| Trading restrictions | NOx emissions limit [as % reduction from baseline] | Cost [$M] | Air quality [ppb $O_3$] | | Number of trans-actions [tpy] | Reliability[% likelihood meeting emissions target] |
|---|---|---|---|---|---|---|
| | | | Episode 1 | Episode 2 | | |
| **Unrestricted** | 10% LC | 2.81 | 125.6 | 128.2 | 6524 | 55.2 |
| | 10% Alternative 1 | 3.65 | 126.8 | 126.5 | 6061 | 54 |
| | 10% Alternative 2 | 3.65 | 125 | 127 | 6592 | 48 |
| **Zoned** | 10% LC | 3.07 | 126 | 129.3 | 6835 | 71.6 |
| | 10% Alternative 1 | 3.94 | 126.7 | 126.9 | 6307 | 61.2 |
| | 10% Alternative 2 | 3.94 | 126.1 | 126.5 | 6334 | 44 |

Results in Table 4 results show that cost increases due to trading restrictions. Trading restrictions are likely to prevent some trades across the zone boundaries, and thereby not resulting in the most cost-effective outcome. For both episodes, the magnitude and variability of ozone predictions for restrictive trading increases in the presence of zone restrictions. The level of reliability, however, increases as a result of zoning. One reason why the reliability level increases under zoned trading is that the actual emission reduction percentages are greater than 10% for the least-cost and first alternative. In Table 4, the NOx reduction percentages for LC and first alternative outcome are actually 10.5 and 10.3%, respectively. The additional emissions reduction resulting from these higher emission reduction levels may contribute to improved reliability.



(a) (b)

**Figure 8.** Unrestricted (a) and zoned (b) emissions distributions for all sources trading in a unrestricted market to meet 10% NOx reduction

Figure 8 shows the distribution of emissions for 10% NOx reduction as a result of all sources trading in restrictive and unrestrictive markets. The purpose of this figure is to demonstrate how restrictions affect the trading outcome. It is important to note that in the unrestricted scenario, emissions are controlled mostly in the center of the region. Conversely, zoned trading results in control of emissions across the domain rather than in one particular area. Geographic north/south zoned trading restrictions do not appear to be beneficial for the Charlotte region. Restrictions tend to distribute the final emissions evenly across the region and among the larger and smaller sources. This may be unfavorable if peak ozone levels occur directly downwind of large sources with less reduction. Alternative rezoning can be done to encourage larger sources to reduce their emissions and sell permits to smaller sources. No zoning may achieve the same result due to more economies of scale of emissions reduction at larger sources.

# 5 GENERAL OBSERVATIONS

## 5.1 Limitations

The models used to simulate trading in this research have limitations. The optimization-based trading models assumed all trades took place simultaneously and multilaterally, i.e., permits were traded at the same time among multiple sources. This is a typical assumption in trading prediction models. Johnson and Pekelney (1996) hypothesized that most trades would be multilateral and simultaneous in an emission trading market. In reality, some trades might occur in a sequential manner between two sources, known as bilateral and sequential trading. For example, Butraw and Harrison (1997) used a stochastic technique with a mechanism that matched potential trading partners to simulate bilateral and sequential trading.

Another limitation of LC and MGA techniques is that cost predictions only account for control costs. In this research, the cost models assume no profit-seeking behavior by sellers. Since the permit price would be determined by the market, models that predict permit prices could be used to calculate program cost in the presence of profit seeking behavior. Given the market permit price, the collective and individual compliance costs could be predicted more accurately.

Additionally, in these case studies, baseline emissions levels did not reflect preexisting control technologies. This is not a limitation of the models used in the analysis, but only the case study inputs. This could be fixed by incorporating updated emissions inventories that include control technologies already in-place.

## 5.2 Potential applications

The TDP modeling framework established in this paper have several potential applications. Primarily, they could be used at state or federal levels as tools to investigate the impact of a TDP program on compliance cost, air quality, and other criteria. In such analyses, regulators could determine the feasibility of TDP programs to meet regulatory goals and identify market designs that are reliable and robust.

These tools could also be applied by industries as a management tool. The techniques used in this paper could allow an industry to find the most cost-effective way to manage their collective air emissions by identifying processes with low control cost to meet a specified reduction requirement. To meet a total emissions target by an industry, these tools can be applied to find ways to offset emissions from a process with treatment that is more expensive by additional removal of emissions from a process with a relatively cheaper control option. In addition, alternative solutions identified using MGA provide an industry alternative control strategies that might be more favorable with respect to other issues such as feasibility, reliability and other unmodeled issues.

### 5.3 Future investigations

Further studies are warranted to address the current limitations of this framework. Case studies using preexisting Title VI and V controls in-place could provide information about the effectiveness of trading in the present setting. The air quality model used in the analysis could be altered to predict 8-hour average ozone concentration to test effectiveness and feasibility of NOx emissions trading to meet the newly promulgated 84.9 ppb 8-hour average standard. To estimate more realistic TDP program costs, permit cost model could be incorporated into the framework to back-calculate the permit price. This could then be used to calculate the costs of control and permits (compliance costs) at individual sources. Compliance cost estimates could be compared for different sources to determine any inequities that may result from trading.

Also, the current formulations of the ELC and MGA models could be modified to allow inter-region trading, which is being proposed in the OTAG trading rule. An OTAG regional-scale case study would provide states with information about the effect of trading on local or regional air quality, help identify which states will buy and sell permits, and determine whether the proposed rule will be effective in meeting state and federal objectives.

In addition to examining the reliability of meeting an emissions target, the study could be expanded to include reliability estimates of meeting an air quality target.

Probabilistic simulations of an air quality model can be included within the framework to make those estimates for a post-analysis. Further, these reliability estimation procedures could be incorporated into the optimization models for TDP trading simulation to account for reliability at the TDP program design stage.

# 6 CONCLUSIONS

Modeling emission-trading programs is an important component in developing effective and functional market-based environmental regulation. Emission trading provides incentives, flexibility, and cost savings to sources attempting to comply with emission reductions required by state and federal implementation plans. A TDP program will result in a spatial allocation of TDPs that depends on the design, structure, and characteristics of the trading market. It is necessary for regulators to model TDP programs and predict the effect of trading on the economic and environmental conditions of the region prior to implementation.

The traditional technique of least-cost optimization was used to model emission trading. Use of LC models to simulate trading programs assumes ideal, and not necessarily realistic, trading conditions and outcomes. An alternative mathematical programming technique, MGA, provides a tool to generate a set of alternative trading outcomes that are more likely to be realized in an implemented trading market. Alternative trading outcomes generated using MGA are very different with respect to the spatial distribution of emissions and permits. Consequently, the effect of trading can be assessed more thoroughly, finding a spectrum of very different set of trading outcomes. Alternative outcomes identified using LC and MGA modeling techniques are incorporated in an iterative framework to evaluate the impact of different emission trading market designs from an economic and environmental standpoint. In particular, trading restrictions are investigated to determine the need and benefit of controlling the distribution of permits.

A case study conducted on NOx emission trading in the Charlotte NC region found that TDPs could be used to cost-effectively meet both emission limits of NOx and an ambient standard for ozone. Additionally, trading restrictions in the form of geographic zones were not particularly good at reducing air quality variation in the Charlotte region. It is anticipated that zoning restrictions will be more useful on a larger scale such as state or regional-level trading.

This research establishes a framework and introduces models to provide regulators with a method for designing and evaluating emission-trading markets to achieve regulatory goals. Additional case studies and analyses involving multiple pollutants, different spatial scales, different airshed characteristics will provide more conclusive information about the applicability and functionality of TDP programs for managing today's complex and growing air pollution problems.

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# 8 APPENDICES

## 8.1 Case Study Information and Input Data

### *8.1.1* Selecting Case Study Area

Charlotte area has several properties that are amenable to implementation and analysis of NOx emission trading. Charlotte has been the focus of years of ongoing research to determine strategies that could be implemented to meet federal ozone standards. The following reasons provide logic for using Charlotte as the case study domain:

1) Charlotte is a classified a non-attainment region for ozone
2) Charlotte is NOx-limited meaning ozone formation is limited by the amount of available NOx in the atmosphere.
3) Charlotte emissions and meteorological data are freely available.
4) The State of North Carolina is looking at TDP programs as a potential policy instrument for meeting reductions specified in the SIP.

### *8.1.2* Input data sources, emissions inventory and meteorological episode specifications

8.1.2.1 *Emission data*

The emissions data are 1990 Charlotte, NC emission rates obtained from the State of North Carolina for use in a project at NC State. That data set contains growth factors for projecting emissions to 1999 levels. Table 5 is a sample of the emission inventory used in the case study.

**Table 5.** Sample selection from Charlotte emission inventory

| FIP (county) | SIC | Plant ID | SCC | Stack # | Species | Selected control option | pod | Size (tpy) | Size (tph) | UTM X-coord. | UTM Y-coord. | Group # | Process id | Number of control options |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 37071 | 4911 | 39 | 10100202 | 3 | 42602 | -1 | 246 | 3569.335205 | 0.407458 | 498.90 | 3893.90 | -1 | 25646 | 6 |
| 37071 | 4911 | 39 | 10100202 | 4 | 42602 | -1 | 246 | 4088.364990 | 0.466708 | 498.90 | 3893.90 | -1 | 25647 | 6 |
| 37071 | 4911 | 39 | 10100202 | 5 | 42602 | -1 | 246 | 4104.060059 | 0.468500 | 498.90 | 3893.90 | -1 | 25648 | 6 |
| 37159 | 4911 | 4 | 10100202 | 2 | 42602 | -1 | 246 | 2004.945068 | 0.228875 | 556.40 | 3952.20 | -1 | 25650 | 6 |
| 37035 | 4911 | 73 | 10100202 | 1 | 42602 | -1 | 246 | 5821.385254 | 0.664542 | 503.10 | 3939.10 | -1 | 25654 | 6 |
| 37035 | 4911 | 73 | 10100202 | 2 | 42602 | -1 | 246 | 5297.244629 | 0.604708 | 503.10 | 3939.10 | -1 | 25655 | 6 |
| 37035 | 4911 | 73 | 10100202 | 3 | 42602 | -1 | 246 | 2248.034912 | 0.256625 | 503.10 | 3939.10 | -1 | 25656 | 6 |
| 37035 | 4911 | 73 | 10100202 | 4 | 42602 | -1 | 246 | 9886.754883 | 1.128625 | 503.10 | 3939.10 | -1 | 25657 | 6 |
| 37071 | 4911 | 40 | 10100202 | 2 | 42602 | -1 | 246 | 1811.130005 | 0.206750 | 502.40 | 3912.80 | -1 | 25658 | 6 |
| 37071 | 4911 | 40 | 20200101 | 6 | 42602 | -1 | 239 | 127.750000 | 0.014583 | 502.40 | 3912.80 | -1 | 25659 | 2 |
| 37071 | 4911 | 40 | 20200101 | 7 | 42602 | -1 | 239 | 159.869995 | 0.018250 | 502.40 | 3912.80 | -1 | 25660 | 2 |
| 37057 | 2511 | 24 | 10200401 | 1 | 42602 | -1 | 232 | 1.000000 | 0.000479 | 568.10 | 3964.30 | -1 | 27469 | 3 |
| 37057 | 2511 | 49 | 10200906 | 1 | 42602 | -1 | 0 | 2.000000 | 0.000959 | 562.40 | 3957.70 | -1 | 27474 | 0 |
| 37057 | 2511 | 50 | 10200906 | 3 | 42602 | -1 | 0 | 2.000000 | 0.000959 | 567.30 | 3964.00 | -1 | 27484 | 0 |
| 37057 | 2511 | 50 | 10200906 | 4 | 42602 | -1 | 0 | 1.000000 | 0.000479 | 567.30 | 3964.00 | -1 | 27487 | 0 |
| 37057 | 2511 | 245 | 10200906 | 1 | 42602 | -1 | 0 | 1.000000 | 0.000479 | 564.60 | 3961.70 | -1 | 27490 | 0 |
| 37057 | 2511 | 245 | 10200401 | 2 | 42602 | -1 | 232 | 1.000000 | 0.000000 | 564.60 | 3961.70 | -1 | 27492 | 3 |
| 37057 | 2511 | 87 | 10200906 | 1 | 42602 | -1 | 0 | 1.000000 | 0.000384 | 566.80 | 3958.30 | -1 | 27501 | 0 |
| 37057 | 2511 | 87 | 10200906 | 2 | 42602 | -1 | 0 | 1.000000 | 0.000384 | 566.80 | 3958.30 | -1 | 27504 | 0 |
| 37057 | 3229 | 109 | 30501212 | 1 | 42602 | -1 | 0 | 72.000000 | 0.008219 | 565.40 | 3956.80 | -1 | 27527 | 0 |
| 37057 | 3229 | 109 | 30501212 | 2 | 42602 | -1 | 0 | 96.000000 | 0.010959 | 565.40 | 3956.80 | -1 | 27530 | 0 |
| 37057 | 3229 | 109 | 30501212 | 3 | 42602 | -1 | 0 | 106.000000 | 0.012100 | 565.40 | 3956.80 | -1 | 27533 | 0 |
| 37057 | 3229 | 109 | 30501212 | 4 | 42602 | -1 | 0 | 29.000000 | 0.003311 | 565.40 | 3956.80 | -1 | 27536 | 0 |
| 37057 | 3229 | 109 | 30501212 | 5 | 42602 | -1 | 0 | 46.000000 | 0.005251 | 565.40 | 3956.80 | -1 | 27539 | 0 |
| 37057 | 3229 | 109 | 30501212 | 6 | 42602 | -1 | 0 | 2.000000 | 0.000228 | 565.40 | 3956.80 | -1 | 27542 | 0 |
| 37057 | 3229 | 109 | 30501212 | 7 | 42602 | -1 | 0 | 185.000000 | 0.021119 | 565.40 | 3956.80 | -1 | 27545 | 0 |
| 37057 | 3229 | 109 | 30501212 | 8 | 42602 | -1 | 0 | 122.000000 | 0.013927 | 565.40 | 3956.80 | -1 | 27548 | 0 |
| 37057 | 3229 | 109 | 30501212 | 9 | 42602 | -1 | 0 | 293.000000 | 0.033447 | 565.40 | 3956.80 | -1 | 27551 | 0 |
| 37057 | 3229 | 109 | 30501215 | 10 | 42602 | -1 | 0 | 31.000000 | 0.003539 | 565.40 | 3956.80 | -1 | 27554 | 0 |
| 37057 | 3229 | 109 | 30501215 | 11 | 42602 | -1 | 0 | 31.000000 | 0.003539 | 565.40 | 3956.80 | -1 | 27557 | 0 |
| 37057 | 3229 | 109 | 30501215 | 12 | 42602 | -1 | 0 | 31.000000 | 0.003539 | 565.40 | 3956.80 | -1 | 27560 | 0 |

8.1.2.2 *Control data*

Cost and control technology data are obtained from the EPA's Emission Reduction Cost Assessment Model (ERCAM). The following table contains the control information used in the case study of the Charlotte region.

**Table 6.** ERCAM Control data

| Pod | option number | removal efficiency (%) | Marginal control cost ($/ton) | Control type | Boiler type |
|---|---|---|---|---|---|
| 250 | 1 | 0.25 | $ 540 | BOOS | UtilboilerOil-G |
| 250 | 2 | 0.35 | $ 1320 | FGR | UtilboilerOil-G |
| 250 | 3 | 0.35 | $ 985 | LNB | UtilboilerOil-G |
| 250 | 4 | 0.33 | $ 3050 | BOOS+FGR | UtilboilerOil-G |
| 250 | 5 | 0.42 | $ 940 | SNCR | UtilboilerOil-G |
| 250 | 6 | 0.5 | $ 3400 | LNB+FGR+OFA | UtilboilerOil-G |
| 249 | 1 | 0.28 | $ 370 | BOOS | UtilboilerOilwa |
| 249 | 2 | 0.33 | $ 660 | FGR | UtilboilerOilwa |
| 249 | 3 | 0.39 | $ 1225 | LNB | UtilboilerOilwa |
| 249 | 4 | 0.39 | $ 645 | BOOS+FGR | UtilboilerOilwa |
| 249 | 5 | 0.39 | $ 885 | SNCR | UtilboilerOilwa |
| 249 | 6 | 0.61 | $ 1750 | LNB+FGR+OFA | UtilboilerOilwa |
| 247 | 1 | 0.29 | $ 880 | LNB | Utilboilerpulvc |
| 247 | 2 | 0.38 | $ 1005 | LNB+OFA | Utilboilerpulvc |
| 247 | 3 | 0.42 | $ 945 | SNCR | Utilboilerpulvc |
| 247 | 4 | 0.5 | $ 1645 | NGR | Utilboilerpulvc |
| 246 | 1 | 0.21 | $ 775 | OFA | Utilboilerpulvc |
| 246 | 2 | 0.39 | $ 845 | SNCR | Utilboilerpulvc |
| 246 | 3 | 0.45 | $ 305 | LNB | Utilboilerpulvc |
| 246 | 4 | 0.53 | $ 535 | LNB+OFA | Utilboilerpulvc |
| 246 | 5 | 0.53 | $ 955 | NGR | Utilboilerpulvc |
| 245 | 1 | 0.34 | $ 1650 | LNBFGR | Processheatreso |
| 245 | 2 | 0.37 | $ 858 | LowNOxBurners | Processheatreso |
| 245 | 3 | 0.6 | $ 1280 | SelNonCatalytic | Processheatreso |
| 245 | 4 | 0.73 | $ 442 | UltraLowNOxBurn | Processheatreso |
| 245 | 5 | 0.75 | $ 4340 | SelectNonCataly | Processheatreso |
| 245 | 6 | 0.75 | $ 1450 | LNB&SNCR | Processheatreso |
| 244 | 1 | 0.45 | $ 1180 | LowNOxBurners | Processheatdiso |
| 244 | 2 | 0.48 | $ 2010 | LNB&SNCR | Processheatdiso |
| 244 | 3 | 0.6 | $ 2000 | SelNonCatalytic | Processheatdiso |
| 244 | 4 | 0.74 | $ 735 | UltraLowNOxBurn | Processheatdiso |
| 244 | 5 | 0.75 | $ 7280 | SelectNonCataly | Processheatdiso |
| 244 | 6 | 0.78 | $ 2230 | LNB&SNCR | Processheatdiso |
| 243 | 1 | 0.5 | $ 788 | LowNOxBurners | Processheatng |

| | | | | | |
|---|---|---|---|---|---|
| 243 | 2 | 0.55 | $ 1136 | LNBFGR | Processheatng |
| 243 | 3 | 0.6 | $ 981 | SelNonCatalytic | Processheatng |
| 243 | 4 | 0.75 | $ 532 | UltraLowNOxBurn | Processheatng |
| 243 | 5 | 0.75 | $ 4023 | SelectNonCataly | Processheatng |
| 243 | 6 | 0.8 | $ 1229 | LNB&SNCR | Processheatng |
| 242 | 1 | 0.7 | $ 1166 | Water | Gasturbineoil |
| 241 | 1 | 0.76 | $ 1072 | Water | Gasturbineng |
| 241 | 2 | 0.8 | $ 715 | Steam | Gasturbineng |
| 241 | 3 | 0.84 | $ 236 | LowNOxBurners | Gasturbineng |
| 241 | 4 | 0.94 | $ 12171 | SelectNonCataly | Gasturbineng |
| 241 | 5 | 0.95 | $ 5954 | SelectNonCataly | Gasturbineng |
| 240 | 1 | 0.25 | $ 518 | IR2500 | Interncomboil |
| 239 | 1 | 0.25 | $ 518 | IR10012500 | Interncomboil |
| 238 | 1 | 0.25 | $ 518 | IR11000 | Internalcombng |
| 237 | 1 | 0.2 | $ 584 | A/Fratio2500hp | Internalcombng |
| 237 | 2 | 0.2 | $ 497 | IR2500 | Internalcombng |
| 237 | 3 | 0.3 | $ 551 | A/FIR2500 | Internalcombng |
| 237 | 4 | 0.9 | $ 599 | SelectNonCataly | Internalcombng |
| 237 | 5 | 0.87 | $ 218 | L-Emedium | Internalcombng |
| 236 | 1 | 0.2 | $ 584 | A/Fratio1001250 | Internalcombng |
| 236 | 2 | 0.2 | $ 497 | IR10012500 | Internalcombng |
| 236 | 3 | 0.3 | $ 551 | A/F&IR10012500 | Internalcombng |
| 236 | 4 | 0.9 | $ 599 | SelectNonCataly | Internalcombng |
| 236 | 5 | 0.87 | $ 218 | L-Emedium | Internalcombng |
| 235 | 1 | 0.2 | $ 584 | A/Fratio1000hp | Internalcombng |
| 235 | 2 | 0.2 | $ 497 | IR11000 | Internalcombng |
| 235 | 3 | 0.3 | $ 551 | A/F&IR11000 | Internalcombng |
| 235 | 4 | 0.9 | $ 599 | NonSelCatalytic | Internalcombng |
| 235 | 5 | 0.87 | $ 218 | L-Emedium | Internalcombng |
| 234 | 1 | 0.5 | $ 770 | LowNOxBurners | Boilernaturalga |
| 234 | 2 | 0.6 | $ 1490 | LNB&FGR | Boilernaturalga |
| 233 | 1 | 0.5 | $ 1180 | LowNOxBurners | Boilerdistoil |
| 233 | 2 | 0.6 | $ 2350 | LNB&FGR | Boilerdistoil |
| 232 | 1 | 0.5 | $ 620 | LowNOxBurners | Boilerresoil |
| 232 | 2 | 0.6 | $ 1280 | LNB&FGR | Boilerresoil |
| 232 | 3 | 0.8 | $ 3339 | selnoncatalitic | boilerpulvcoal |
| 230 | 1 | 0.5 | $ 1350 | lnb | Boilerpulvcoal |
| 230 | 2 | 0.6 | $ 2860 | SelNonCatalytic | Boilerpulvcoal |

### *8.1.3* ELC optimization model

Section 3.2.1 introduced the general model formulation for ELC optimization. The objective is to minimize cost subject to constraints on emission levels, control technology

availability, and feasibility. Each process in the inventory is given an index number where C72 corresponds to the cost incurred to a source by controlling process 72, and X72_1 is a binary variable equal to 1 if control option 1 is applied to process 72 and equals 0 otherwise. A sample MIP-ELC model for unrestricted trading between power plants to achieve 10% NOx emission reduction is:

```
MIN COST
ST
TOTAL_NOX=35234.886719
+C72+C73+C74+C76+C80+C81+C82+C83+C84+C85+C86+C4161+C4162+C4163+C4164
-COST=0
+EM72+EM73+EM74+EM76+EM80+EM81+EM82+EM83+EM84+EM85
+EM86+EM4161+EM4162+EM4163+EM4164-TOTAL_NOX<=0
X72_0+X72_1+X72_2+X72_3+X72_4+X72_5+X72_6=1
0X72_0+580909.250X72_1+1176274.375X72_2+489891.250X72_3+1012084.938X72_
4+1806618.875X72_5+6866151.500X72_6-C72=0
1X72_0+0.832X72_1+0.688X72_2+0.640X72_3+0.576X72_4+0.576X72_5+0.368X72_
6-EFF72=0
EM72-3569.335EFF72=0
X73_0+X73_1+X73_2+X73_3+X73_4+X73_5+X73_6=1
0X73_0+665381.375X73_1+1347320.625X73_2+561128.125X73_3+1159255.875X73_
4+2069325.750X73_5+7864583.500X73_6-C73=0
1X73_0+0.832X73_1+0.688X73_2+0.640X73_3+0.576X73_4+0.576X73_5+0.368X73_
6-EFF73=0
EM73-4088.365EFF73=0
X74_0+X74_1+X74_2+X74_3+X74_4+X74_5+X74_6=1
0X74_0+667935.750X74_1+1352493.000X74_2+563282.250X74_3+1163706.250X74_
4+2077269.875X74_5+7894775.000X74_6-C74=0
1X74_0+0.832X74_1+0.688X74_2+0.640X74_3+0.576X74_4+0.576X74_5+0.368X74_
6-EFF74=0
EM74-4104.060EFF74=0
X76_0+X76_1+X76_2+X76_3+X76_4+X76_5+X76_6=1
0X76_0+326304.781X76_1+660729.625X76_2+275178.719X76_3+568502.125X76_4+
1014802.875X76_5+3856812.500X76_6-C76=0
1X76_0+0.832X76_1+0.688X76_2+0.640X76_3+0.576X76_4+0.576X76_5+0.368X76_
6-EFF76=0
EM76-2004.945EFF76=0
X80_0+X80_1+X80_2+X80_3+X80_4+X80_5+X80_6=1
0X80_0+947430.375X80_1+1918437.375X80_2+798985.125X80_3+1650653.625X80_
4+2946494.000X80_5+11198308.000X80_6-C80=0
1X80_0+0.832X80_1+0.688X80_2+0.640X80_3+0.576X80_4+0.576X80_5+0.368X80_
6-EFF80=0
EM80-5821.385EFF80=0
X81_0+X81_1+X81_2+X81_3+X81_4+X81_5+X81_6=1
0X81_0+862126.500X81_1+1745706.875X81_2+727046.812X81_3+1502033.750X81_
4+2681200.250X81_5+10190045.000X81_6-C81=0
1X81_0+0.832X81_1+0.688X81_2+0.640X81_3+0.576X81_4+0.576X81_5+0.368X81_
6-EFF81=0
EM81-5297.245EFF81=0
X82_0+X82_1+X82_2+X82_3+X82_4+X82_5+X82_6=1
0X82_0+365867.656X82_1+740839.875X82_2+308542.781X82_3+637430.250X82_4+
```

```
1137842.750X82_5+4324432.500X82_6-C82=0
1X82_0+0.832X82_1+0.688X82_2+0.640X82_3+0.576X82_4+0.576X82_5+0.368X82_
6-EFF82=0
EM82-2248.035EFF82=0
X83_0+X83_1+X83_2+X83_3+X83_4+X83_5+X83_6=1
0X83_0+1609069.250X83_1+3258180.000X83_2+1356957.125X83_3+2803389.250X8
3_4+5004181.000X83_5+19018656.000X83_6-C83=0
1X83_0+0.832X83_1+0.688X83_2+0.640X83_3+0.576X83_4+0.576X83_5+0.368X83_
6-EFF83=0
EM83-9886.755EFF83=0
X84_0+X84_1+X84_2+X84_3+X84_4+X84_5+X84_6=1
0X84_0+294761.406X84_1+596857.875X84_2+248577.578X84_3+513545.875X84_4+
916703.375X84_5+3483980.250X84_6-C84=0
1X84_0+0.832X84_1+0.688X84_2+0.640X84_3+0.576X84_4+0.576X84_5+0.368X84_
6-EFF84=0
EM84-1811.130EFF84=0
X85_0+X85_1+X85_2=1
0X85_0+16543.625X85_1+157388.000X85_2-C85=0
1X85_0+0.800X85_1+0.360X85_2-EFF85=0
EM85-127.750EFF85=0
X86_0+X86_1+X86_2=1
0X86_0+20703.164X86_1+196959.844X86_2-C86=0
1X86_0+0.800X86_1+0.360X86_2-EFF86=0
EM86-159.870EFF86=0
X4161_0+X4161_1+X4161_2=1
0X4161_0+129.500X4161_1+1232.000X4161_2-C4161=0
1X4161_0+0.800X4161_1+0.360X4161_2-EFF4161=0
EM4161-1.000EFF4161=0
X4162_0+X4162_1+X4162_2=1
0X4162_0+129.500X4162_1+1232.000X4162_2-C4162=0
1X4162_0+0.800X4162_1+0.360X4162_2-EFF4162=0
EM4162-1.000EFF4162=0
X4163_0+X4163_1+X4163_2=1
0X4163_0+1424.500X4163_1+13552.000X4163_2-C4163=0
1X4163_0+0.800X4163_1+0.360X4163_2-EFF4163=0
EM4163-11.000EFF4163=0
X4164_0+X4164_1+X4164_2=1
0X4164_0+2331.000X4164_1+22176.000X4164_2-C4164=0
1X4164_0+0.800X4164_1+0.360X4164_2-EFF4164=0
EM4164-18.000EFF4164=0
INTEGERS
X72_0
X72_1
X72_2
X72_3
X72_4
X72_5
X72_6
X73_0
X73_1
X73_2
X73_3
X73_4
X73_5
```

X73_6
X74_0
X74_1
X74_2
X74_3
X74_4
X74_5
X74_6
X76_0
X76_1
X76_2
X76_3
X76_4
X76_5
X76_6
X80_0
X80_1
X80_2
X80_3
X80_4
X80_5
X80_6
X81_0
X81_1
X81_2
X81_3
X81_4
X81_5
X81_6
X82_0
X82_1
X82_2
X82_3
X82_4
X82_5
X82_6
X83_0
X83_1
X83_2
X83_3
X83_4
X83_5
X83_6
X84_0
X84_1
X84_2
X84_3
X84_4
X84_5
X84_6
X85_0
X85_1
X85_2
X86_0

```
X86_1
X86_2
X4161_0
X4161_1
X4161_2
X4162_0
X4162_1
X4162_2
X4163_0
X4163_1
X4163_2
X4164_0
X4164_1
X4164_2
END
```

The above MIP model is optimized using CPLEX. The output file from CPLEX specifies selected control options and the cost of controlling each process.

```
Welcome to CPLEX Linear Optimizer 4.0.9
  with Mixed Integer Solver
Copyright (c) CPLEX Optimization, Inc., 1989-1995
CPLEX is a registered trademark of CPLEX Optimization, Inc.

Type 'help' for a list of available commands.
Type 'help' followed by a command name for more
information on commands.

CPLEX> Logfile 'cplex.log' closed.
CPLEX> Problem '/tmp/dlgillon/g1_10_ip.lp' read.
Read time =    0.02 sec.
CPLEX> New value for branch and bound node limit: 100000
CPLEX> New value for SOS scan indicator: yes
CPLEX> MIP Presolve eliminated 17 rows and 17 columns.
Aggregator did 15 substitutions.
Reduced MIP has 31 rows, 96 columns, and 192 nonzeros.
Presolve time =    0.00 sec.
Using conservative initial basis.
Found 15 SOS sets with 81 members.

        Nodes                                         Cuts/
   Node  Left     Objective  IInf  Best Integer     Best Node    ItCnt

      0     0  1492589.1808     3                1492589.1808       80
*    28    22  5664880.8120     0  5664880.8120  1492589.1808      164
*    38    14  1722824.7810     0  1722824.7810  1492589.1862      194
*    42    16  1699805.5310     0  1699805.5310  1492589.1862      203
*    52    17  1565507.7810     0  1565507.7810  1492589.1894      218
*    74    27  1494580.7810     0  1494580.7810  1492589.1913      255
    100    31        cutoff        1494580.7810  1492589.2193      276
*   192     1  1493541.2810     0  1493541.2810  1492919.2154      320
```

```
Integer optimal solution:  Objective =    1.4935412810e+06
Solution time =    0.11 sec.    Iterations = 320   Nodes = 193

CPLEX> Variable Name           Solution Value
COST                     1493541.281000
TOTAL_NOX                  35234.886719
C72                       489891.250000
C76                       275178.719000
C81                       727046.812000
C4163                       1424.500000
EM72                        2284.374400
EM73                        4088.365000
EM74                        4104.060000
EM76                        1283.164800
EM80                        5821.385000
EM81                        3390.236800
EM82                        2248.035000
EM83                        9886.755000
EM84                        1811.130000
EM85                         127.750000
EM86                         159.870000
EM4161                         1.000000
EM4162                         1.000000
EM4163                         8.800000
EM4164                        18.000000
X72_3                          1.000000
EFF72                          0.640000
X73_0                          1.000000
EFF73                          1.000000
X74_0                          1.000000
EFF74                          1.000000
X76_3                          1.000000
EFF76                          0.640000
X80_0                          1.000000
EFF80                          1.000000
X81_3                          1.000000
EFF81                          0.640000
X82_0                          1.000000
EFF82                          1.000000
X83_0                          1.000000
EFF83                          1.000000
X84_0                          1.000000
EFF84                          1.000000
X85_0                          1.000000
EFF85                          1.000000
X86_0                          1.000000
EFF86                          1.000000
X4161_0                        1.000000
EFF4161                        1.000000
X4162_0                        1.000000
EFF4162                        1.000000
X4163_1                        1.000000
EFF4163                        0.800000
X4164_0                        1.000000
```

```
EFF4164                       1.000000
All other variables in the range 1-128 are zero.
CPLEX>
```

### *8.1.4* MGA model

The sample model input is given below. Note the cost is constrained at 30% relaxation from ELC outcome.

```
MIN +3569X72_1+3569X72_2+3569X72_3+3569X72_4+3569X72_5+3569X72_6
+4088X73_1+4088X73_2+4088X73_3+4088X73_4+4088X73_5+4088X73_6
+4104X74_1+4104X74_2+4104X74_3+4104X74_4+4104X74_5+4104X74_6
+2004X76_1+2004X76_2+2004X76_3+2004X76_4+2004X76_5+2004X76_6
+5821X80_1+5821X80_2+5821X80_3+5821X80_4+5821X80_5+5821X80_6
+5297X81_1+5297X81_2+5297X81_3+5297X81_4+5297X81_5+5297X81_6
+9886X83_1+9886X83_2+9886X83_3+9886X83_4+9886X83_5+9886X83_6
+1X4161_1+1X4161_2+1X4162_1+1X4162_2+11X4163_1+11X4163_2
+18X4164_1+18X4164_2+22X4493_1
ST
TOTAL_NOX=35234.886719
COST<=1941603.500000
+C72+C73+C74+C76+C80+C81+C82+C83+C84+C85+C86+C4161+C4162+C4163+C4164
-COST=0
+EM72+EM73+EM74+EM76+EM80+EM81+EM82+EM83+EM84+EM85
+EM86+EM4161+EM4162+EM4163+EM4164-TOTAL_NOX<=0
X72_0+X72_1+X72_2+X72_3+X72_4+X72_5+X72_6=1
0X72_0+580909.250X72_1+1176274.375X72_2+489891.250X72_3+1012084.938X72_
4+1806618.875X72_5+6866151.500X72_6-C72=0
1X72_0+0.832X72_1+0.688X72_2+0.640X72_3+0.576X72_4+0.576X72_5+0.368X72_
6-EFF72=0
EM72-3569.335EFF72=0
X73_0+X73_1+X73_2+X73_3+X73_4+X73_5+X73_6=1
0X73_0+665381.375X73_1+1347320.625X73_2+561128.125X73_3+1159255.875X73_
4+2069325.750X73_5+7864583.500X73_6-C73=0
1X73_0+0.832X73_1+0.688X73_2+0.640X73_3+0.576X73_4+0.576X73_5+0.368X73_
6-EFF73=0
EM73-4088.365EFF73=0
X74_0+X74_1+X74_2+X74_3+X74_4+X74_5+X74_6=1
0X74_0+667935.750X74_1+1352493.000X74_2+563282.250X74_3+1163706.250X74_
4+2077269.875X74_5+7894775.000X74_6-C74=0
1X74_0+0.832X74_1+0.688X74_2+0.640X74_3+0.576X74_4+0.576X74_5+0.368X74_
6-EFF74=0
EM74-4104.060EFF74=0
X76_0+X76_1+X76_2+X76_3+X76_4+X76_5+X76_6=1
0X76_0+326304.781X76_1+660729.625X76_2+275178.719X76_3+568502.125X76_4+
1014802.875X76_5+3856812.500X76_6-C76=0
1X76_0+0.832X76_1+0.688X76_2+0.640X76_3+0.576X76_4+0.576X76_5+0.368X76_
6-EFF76=0
EM76-2004.945EFF76=0
X80_0+X80_1+X80_2+X80_3+X80_4+X80_5+X80_6=1
```

```
0X80_0+947430.375X80_1+1918437.375X80_2+798985.125X80_3+1650653.625X80_
4+2946494.000X80_5+11198308.000X80_6-C80=0
1X80_0+0.832X80_1+0.688X80_2+0.640X80_3+0.576X80_4+0.576X80_5+0.368X80_
6-EFF80=0
EM80-5821.385EFF80=0
X81_0+X81_1+X81_2+X81_3+X81_4+X81_5+X81_6=1
0X81_0+862126.500X81_1+1745706.875X81_2+727046.812X81_3+1502033.750X81_
4+2681200.250X81_5+10190045.000X81_6-C81=0
1X81_0+0.832X81_1+0.688X81_2+0.640X81_3+0.576X81_4+0.576X81_5+0.368X81_
6-EFF81=0
EM81-5297.245EFF81=0
X82_0+X82_1+X82_2+X82_3+X82_4+X82_5+X82_6=1
0X82_0+365867.656X82_1+740839.875X82_2+308542.781X82_3+637430.250X82_4+
1137842.750X82_5+4324432.500X82_6-C82=0
1X82_0+0.832X82_1+0.688X82_2+0.640X82_3+0.576X82_4+0.576X82_5+0.368X82_
6-EFF82=0
EM82-2248.035EFF82=0
X83_0+X83_1+X83_2+X83_3+X83_4+X83_5+X83_6=1
0X83_0+1609069.250X83_1+3258180.000X83_2+1356957.125X83_3+2803389.250X8
3_4+5004181.000X83_5+19018656.000X83_6-C83=0
1X83_0+0.832X83_1+0.688X83_2+0.640X83_3+0.576X83_4+0.576X83_5+0.368X83_
6-EFF83=0
EM83-9886.755EFF83=0
X84_0+X84_1+X84_2+X84_3+X84_4+X84_5+X84_6=1
0X84_0+294761.406X84_1+596857.875X84_2+248577.578X84_3+513545.875X84_4+
916703.375X84_5+3483980.250X84_6-C84=0
1X84_0+0.832X84_1+0.688X84_2+0.640X84_3+0.576X84_4+0.576X84_5+0.368X84_
6-EFF84=0
EM84-1811.130EFF84=0
X85_0+X85_1+X85_2=1
0X85_0+16543.625X85_1+157388.000X85_2-C85=0
1X85_0+0.800X85_1+0.360X85_2-EFF85=0
EM85-127.750EFF85=0
X86_0+X86_1+X86_2=1
0X86_0+20703.164X86_1+196959.844X86_2-C86=0
1X86_0+0.800X86_1+0.360X86_2-EFF86=0
EM86-159.870EFF86=0
X4161_0+X4161_1+X4161_2=1
0X4161_0+129.500X4161_1+1232.000X4161_2-C4161=0
1X4161_0+0.800X4161_1+0.360X4161_2-EFF4161=0
EM4161-1.000EFF4161=0
X4162_0+X4162_1+X4162_2=1
0X4162_0+129.500X4162_1+1232.000X4162_2-C4162=0
1X4162_0+0.800X4162_1+0.360X4162_2-EFF4162=0
EM4162-1.000EFF4162=0
X4163_0+X4163_1+X4163_2=1
0X4163_0+1424.500X4163_1+13552.000X4163_2-C4163=0
1X4163_0+0.800X4163_1+0.360X4163_2-EFF4163=0
EM4163-11.000EFF4163=0
X4164_0+X4164_1+X4164_2=1
0X4164_0+2331.000X4164_1+22176.000X4164_2-C4164=0
1X4164_0+0.800X4164_1+0.360X4164_2-EFF4164=0
EM4164-18.000EFF4164=0
INTEGERS
```

X72_0
X72_1
X72_2
X72_3
X72_4
X72_5
X72_6
X73_0
X73_1
X73_2
X73_3
X73_4
X73_5
X73_6
X74_0
X74_1
X74_2
X74_3
X74_4
X74_5
X74_6
X76_0
X76_1
X76_2
X76_3
X76_4
X76_5
X76_6
X80_0
X80_1
X80_2
X80_3
X80_4
X80_5
X80_6
X81_0
X81_1
X81_2
X81_3
X81_4
X81_5
X81_6
X82_0
X82_1
X82_2
X82_3
X82_4
X82_5
X82_6
X83_0
X83_1
X83_2
X83_3
X83_4

```
X83_5
X83_6
X84_0
X84_1
X84_2
X84_3
X84_4
X84_5
X84_6
X85_0
X85_1
X85_2
X86_0
X86_1
X86_2
X4161_0
X4161_1
X4161_2
X4162_0
X4162_1
X4162_2
X4163_0
X4163_1
X4163_2
X4164_0
X4164_1
X4164_2
END
```

Again, the MGA model is solved using CPLEX. The output file is:

```
Welcome to CPLEX Linear Optimizer 4.0.9
with Mixed Integer Solver
Copyright (c) CPLEX Optimization, Inc., 1989-1995
CPLEX is a registered trademark of CPLEX Optimization, Inc.

Type 'help' for a list of available commands.
Type 'help' followed by a command name for more
information on commands.

CPLEX> Logfile 'cplex.log' closed.
CPLEX> Problem '/tmp/dlgillon/g1_10_ip.lp_alt0.lp' read.
Read time =    0.02 sec.
CPLEX> New value for branch and bound node limit: 100000
CPLEX> New value for SOS scan indicator: yes
CPLEX> MIP Presolve eliminated 2 rows and 18 columns.
Aggregator did 15 substitutions.
Reduced MIP has 47 rows, 96 columns, and 241 nonzeros.
Presolve time =    0.00 sec.
Using conservative initial basis.
Found 15 SOS sets with 65 members.
```

```
Using rounding heuristic, 63 variables fixed:

        Nodes                                         Cuts/
   Node  Left     Objective  IInf  Best Integer     Best Node    ItCnt

      0+    0    infeasible                                       96

Done with heuristic.

        Nodes                                         Cuts/
   Node  Left     Objective  IInf  Best Integer     Best Node    ItCnt

      0     0     6022.2110     6                  6022.2110       96
*    14     5     7673.0000     0     7673.0000    6022.2110      140
*    53    18     6108.0000     0     6108.0000    6022.2253      296
    100    23        cutoff           6108.0000    6023.1985      475
*   170     0     6092.0000     0     6092.0000                   567

Integer optimal solution:  Objective =    6.0920000000e+03
Solution time =    0.15 sec.    Iterations = 567   Nodes = 170

CPLEX> Variable Name           Solution Value
X73_3                             1.000000
X76_3                             1.000000
TOTAL_NOX                     35234.886719
COST                        1935818.141000
C73                          561128.125000
C76                          275178.719000
C82                          637430.250000
C84                          248577.578000
C85                           16543.625000
C86                          196959.844000
EM72                           3569.335000
EM73                           2616.553600
EM74                           4104.060000
EM76                           1283.164800
EM80                           5821.385000
EM81                           5297.245000
EM82                           1294.868160
EM83                           9886.755000
EM84                           1159.123200
EM85                            102.200000
EM86                             57.553200
EM4161                            1.000000
EM4162                            1.000000
EM4163                           11.000000
EM4164                           18.000000
X72_0                             1.000000
EFF72                             1.000000
EFF73                             0.640000
X74_0                             1.000000
EFF74                             1.000000
EFF76                             0.640000
X80_0                             1.000000
```

```
EFF80                         1.000000
X81_0                         1.000000
EFF81                         1.000000
X82_4                         1.000000
EFF82                         0.576000
X83_0                         1.000000
EFF83                         1.000000
X84_3                         1.000000
EFF84                         0.640000
X85_1                         1.000000
EFF85                         0.800000
X86_2                         1.000000
EFF86                         0.360000
X4161_0                       1.000000
EFF4161                       1.000000
X4162_0                       1.000000
EFF4162                       1.000000
X4163_0                       1.000000
EFF4163                       1.000000
X4164_0                       1.000000
EFF4164                       1.000000
All other variables in the range 1-129 are zero.
CPLEX>
```

### *8.1.5* Additional information related to zoned trading restrictions

The primary and potentially most crucial step in the design or implementation of a zoned trading market is to define zone boundaries or groupings. Zoning can be done systematically or randomly. Loughlin et al. (1997) proposed a mathematical programming model that may be used to identify optimally restrictive trading zones. Optimal zones would minimize likelihood of exceeding the standard and allow as many cost-reducing trades as possible. Another alternative approach is to delineate zones manually. Manual delineation can be repeated in an iterative process to identify robust boundaries. For example, an analyst could set the boundaries, simulate trades within the zones, test resulting air quality, and, if needed, re-select zones iteratively in the framework (Figure 1) until satisfied with air quality predictions and other performance criteria.

### 8.2 Tabulated Results from Case Studies

The different market designs tested in the case studies are summarized in table 7. Table 8-25 contains results from each of the scenarios tested for each market design.

**Table 7.** Summary of Case Study Scenarios

| **Trading Restrictions** | **Participating sources** | **Allowable NOx emissions** [reduction from baseline emission levels] |
|---|---|---|
| NONE | All | 10% 20% 30% 40% 50% |
| NONE | Power Plants only (SIC 4911) | Same |
| NONE | Source size greater than 100tpy NOx | Same |
| Geographical | All | Same |
| Geographical | Power Plants only (SIC 4911) | Same |
| Geographical | Source size greater than 100tpy NOx | Same |

**Table 8.** Unrestrictive Trading Results: All point sources with 10% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.68 | 5.68 | 5.68 | 11.39 | 11.36 | 11.35 | 17.03 | 17.03 | 17.03 | 22.71 | 22.71 | 22.71 | 28.39 | 28.39 | 28.39 |
| | Point Source | 10 | 10 | 10 | 20.06 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Grouped | | | | | | | | | | | | | | | |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 125.6 | 127.1 | 126.5 | 123.9 | 124.3 | 124.7 | 122 | 121.6 | 122.2 | 119.2 | 119.4 | 119.5 | 117.4 | 116.4 | 116.4 |
| | Episode 2 | 128.2 | 128.7 | 126.7 | 125.7 | 125 | 125.6 | 124.4 | 124.3 | 124.5 | 123.9 | 124 | 124 | 123.2 | 123.3 | 123.3 |
| NUMBER OF TRANSACTIONS | | 6524 | 6216 | 6275 | 9615 | 9475 | 9478 | 9252 | 9534 | 9123 | 8329 | 7996 | 7995 | 2314 | 1925 | 1919 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 55.2 | 48 | 48 | 50.4 | 47.2 | 46.8 | 47.6 | 47.6 | 47.8 | 47.6 | 47.2 | 47.2 | 48 | 47.6 | 47.6 |
| COST | | 2.81 | 3.09 | 3.09 | 6.06 | 6.67 | 6.67 | 10.37 | 11.4 | 11.4 | 32.91 | 36.2 | 36.2 | 99.76 | 109.74 | 109.74 |

**Table 9.** Unrestrictive Trading Results: Point sources greater than 100 tons NOx per year with 10% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.52 | 11.04 | 11.04 | 11.04 | 16.56 | 16.59 | 16.56 | 22.08 | 22.08 | 22.08 | 27.6 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.72 | 19.45 | 19.45 | 19.45 | 29.17 | 29.22 | 29.17 | 38.89 | 38.89 | 38.89 | 48.61 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20 | 20 | 20 | 30 | 30.1 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 125.2 | 125.2 | 125.7 | 123.4 | 123.8 | 124.7 | 122 | 121.8 | 122.4 | 119.3 | 119.3 | 119.4 | 118.2 | 116.5 | 116.2 |
| | Episode 2 | 127.3 | 127 | 127.1 | 125.6 | 125 | 125.6 | 124.4 | 124.3 | 124.6 | 124 | 124.1 | 124 | 123.2 | 123.7 | 123.7 |
| NUMBER OF TRANSACTIONS | | 6346 | 6356 | 6009 | 9353 | 9349 | 9233 | 8996 | 9333 | 8870 | 8114 | 7765 | 7765 | 2223 | 2025 | 2023 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 53.2 | 53.2 | 45.6 | 47.6 | 49.2 | 47.6 | 46 | 46.4 | 46 | 47.8 | 47.2 | 47.2 | 46.2 | 45.2 | 45.2 |
| COST | | 2.77 | 3.04 | 3.05 | 5.87 | 6.45 | 6.45 | 9.48 | 10.37 | 10.43 | 30.25 | 33.28 | 33.28 | 95.32 | 104.85 | 104.84 |

**Table 10.** Unrestrictive Trading Results: Power plants (SIC 4911) with 10% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 3.57 | 3.73 | 3.84 | 7.14 | 7.16 | 7.14 | 10.74 | 10.71 | 10.92 | 13.7 | 14.31 | 14.32 | 17.84 | 17.89 | 17.92 |
| | Point Source | 6.29 | 6.57 | 6.77 | 12.58 | 12.61 | 12.58 | 18.91 | 18.86 | 19.23 | 24.13 | 25.21 | 25.22 | 31.43 | 31.52 | 31.56 |
| | Grouped | 10 | 10.4 | 10.8 | 20 | 20.1 | 20 | 30.1 | 30 | 30.6 | 38.4 | 40.1 | 40.1 | 50 | 50.1 | 50.2 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 127.4 | 126.4 | 126.8 | 125.2 | 126.1 | 126.3 | 124.2 | 124.9 | 124.4 | 123.4 | 123.2 | 123.6 | 121.9 | 121.4 | 121.4 |
| | Episode 2 | 127.3 | 127.3 | 126.9 | 127.1 | 125.6 | 125.6 | 125.8 | 125.9 | 125.9 | 125.6 | 125.4 | 125.4 | 125 | 125.4 | 125.4 |
| NUMBER OF TRANSACTIONS | | 3806 | 3976 | 4100 | 5443 | 5516 | 5496 | 4908 | 4571 | 5097 | 3171 | 4093 | 4122 | 745 | 709 | 709 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 49.2 | 79.6 | 93.2 | 46 | 45.8 | 45.6 | 46.8 | 45.2 | 59.6 | --- | 51.6 | 51.6 | 52.4 | 51.6 | 48.8 |
| COST | | 2.04 | 2.13 | 2.19 | 4.07 | 4.47 | 4.41 | 6.12 | 6.7 | 6.56 | 10.39 | 13.31 | 13.57 | 46.78 | 50.81 | 51.35 |

**Table 11.** Unrestrictive Trading Results: All point sources with 20% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.68 | 5.79 | 5.69 | 11.39 | 11.35 | 11.35 | 17.03 | 17.03 | 17.03 | 22.71 | 22.71 | 22.71 | 28.39 | 28.39 | 28.39 |
| | Point Source | 10 | 10.2 | 10.01 | 20.06 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Grouped | | | | | | | | | | | | | | | |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 125.6 | 126.6 | 127.3 | 123.9 | 123.2 | 124.7 | 122 | 121.7 | 121.3 | 119.2 | 119.5 | 119.3 | 117.4 | 116.4 | 116.1 |
| | Episode 2 | 128.2 | 126.6 | 127.3 | 125.7 | 125.8 | 125.6 | 124.4 | 124.4 | 124.4 | 123.9 | 123.7 | 123.6 | 123.2 | 123.2 | 123.3 |
| NUMBER OF TRANSACTIONS | | 6524 | 6236 | 6160 | 9615 | 9621 | 9501 | 9252 | 9809 | 9618 | 8329 | 7657 | 7647 | 2314 | 2180 | 2160 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 55.2 | 56 | 44.8 | 50.4 | 48.8 | 48 | 47.2 | 48 | 47.6 | 47.6 | 46.4 | 46.4 | 48 | 47.8 | 46.8 |
| COST | | 2.81 | 3.37 | 3.26 | 6.06 | 7.27 | 7.27 | 10.37 | 12.44 | 12.44 | 32.91 | 39.49 | 39.49 | 99.76 | 119.71 | 119.69 |

**Table 12.** Unrestrictive Trading Results: Point sources greater than 100 tons NOx per year with 20% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.61 | 5.52 | 11.04 | 11.04 | 11.04 | 16.56 | 16.56 | 16.56 | 22.08 | 22.08 | 22.08 | 27.6 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.72 | 19.45 | 19.45 | 19.45 | 29.17 | 29.22 | 29.17 | 38.89 | 38.89 | 38.89 | 48.61 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 125.2 | 125.1 | 126.9 | 123.4 | 124.2 | 123.5 | 122.7 | 121.7 | 121.7 | 119.3 | 120.7 | 120.7 | 118.2 | 116.4 | 116.6 |
| | Episode 2 | 127.3 | 126.9 | 127.1 | 125.6 | 126 | 125.5 | 124.7 | 124.4 | 124.5 | 124 | 123.7 | 123.7 | 123.2 | 123.2 | 123.2 |
| NUMBER OF TRANSACTIONS | | 6346 | 6458 | 5889 | 9353 | 9328 | 9440 | 8996 | 9164 | 9342 | 8114 | 7534 | 7535 | 2223 | 2107 | 2093 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 53.2 | 55.2 | 46 | 47.6 | 49.2 | 49.2 | 46 | 47.8 | 46.4 | 47.6 | 48 | 48 | 46.4 | 45.3 | 45.2 |
| COST | | 2.77 | 3.33 | 3.25 | 5.87 | 7.04 | 7.04 | 9.48 | 11.38 | 11.38 | 30.25 | 36.3 | 36.3 | 95.32 | 114.37 | 114.38 |

**Table 13.** Unrestrictive Trading Results: Power plants (SIC 4911) with 20% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 3.57 | 3.73 | 3.59 | 7.14 | 7.21 | 7.22 | 10.74 | 10.71 | 10.71 | 13.7 | 14.33 | 14.31 | 17.84 | 17.85 | 17.87 |
| | Point Source | 6.29 | 6.57 | 6.32 | 12.58 | 12.71 | 12.71 | 18.91 | 18.86 | 18.86 | 24.13 | 25.23 | 25.2 | 31.43 | 31.43 | 31.48 |
| | Grouped | 10 | 10.4 | 10 | 20 | 20.2 | 20.2 | 30.1 | 30 | 30 | 38.4 | 40.1 | 40.1 | 50 | 50 | 50.1 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 127.4 | 126.4 | 126.8 | 125.2 | 125.9 | 126.1 | 124.2 | 124.1 | 124.1 | 123.4 | 123 | 123 | 121.9 | 121.8 | 121.1 |
| | Episode 2 | 127.3 | 127.3 | 126.5 | 127.1 | 125.4 | 125.6 | 125.8 | 126.3 | 126.3 | 125.6 | 125.3 | 125.4 | 125 | 124.5 | 125.1 |
| NUMBER OF TRANSACTIONS | | 3806 | 3976 | 3857 | 5443 | 5612 | 5507 | 4908 | 5257 | 5257 | 3171 | 4787 | 4812 | 746 | 562 | 563 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 49.2 | 79.6 | 52.8 | 46 | 54.4 | 54.8 | 46.8 | 45.6 | 44.8 | --- | 47.6 | 46.4 | 52.4 | 44.8 | 46 |
| COST | | 2.04 | 2.13 | 2.43 | 4.07 | 4.84 | 4.7 | 6.12 | 7.34 | 7.34 | 10.39 | 14.5 | 14.31 | 46.78 | 55.18 | 55.39 |

**Table 14.** Unrestrictive Trading Results: All point sources with 30% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.52 | 11.04 | 11.04 | 11.04 | 16.56 | 16.59 | 16.56 | 22.08 | 22.08 | 22.08 | 27.6 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.72 | 19.45 | 19.45 | 19.45 | 29.17 | 29.22 | 29.17 | 38.89 | 38.89 | 38.89 | 48.61 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20 | 20 | 20 | 30 | 30.1 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 125.2 | 125.2 | 125.7 | 123.4 | 123.8 | 124.7 | 122 | 121.8 | 122.4 | 119.3 | 119.3 | 119.4 | 118.2 | 116.5 | 116.2 |
| | Episode 2 | 127.3 | 127 | 127.1 | 125.6 | 125 | 125.6 | 124.4 | 124.3 | 124.6 | 124 | 124.1 | 124 | 123.2 | 123.7 | 123.7 |
| NUMBER OF TRANSACTIONS | | 6346 | 6356 | 6009 | 9353 | 9349 | 9233 | 8996 | 9333 | 8870 | 8114 | 7765 | 7765 | 2223 | 2025 | 2023 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 53.2 | 53.2 | 45.6 | 47.6 | 49.2 | 47.6 | 46 | 46.4 | 46 | 47.6 | 47.2 | 47.2 | 46.4 | 45.2 | 45.2 |
| COST | | 2.77 | 3.04 | 3.05 | 5.87 | 6.45 | 6.45 | 9.48 | 10.37 | 10.43 | 30.25 | 33.28 | 33.28 | 95.32 | 104.85 | 104.84 |

**Table 15.** Unrestrictive Trading Results: Point sources greater than 100 tons NOx per year with 30% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.52 | 11.04 | 11.04 | 11.04 | 16.56 | 16.56 | 16.56 | 22.08 | 22.08 | 22.08 | 27.6 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.72 | 19.45 | 19.44 | 19.44 | 29.17 | 29.17 | 29.17 | 38.89 | 38.89 | 38.89 | 48.61 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 125.2 | 125.6 | 126.8 | 123.4 | 123.8 | 124.3 | 122 | 121.8 | 121.4 | 119.3 | 120.7 | 120.3 | 118.2 | 116.5 | 116 |
| | Episode 2 | 127.3 | 126.9 | 126.5 | 125.6 | 125.5 | 125.6 | 124.4 | 124.6 | 124.7 | 124 | 123.7 | 123.6 | 123.2 | 123.2 | 123.3 |
| NUMBER OF TRANSACTIONS | | 6346 | 6309 | 5895 | 9353 | 9391 | 9393 | 8996 | 9417 | 9503 | 8114 | 7184 | 7185 | 2223 | 1704 | 1687 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 53.2 | 55.6 | 48 | 47.6 | 49.6 | 49.2 | 46 | 47.6 | 46.4 | 47.6 | 48.6 | 49.6 | 46.4 | 45.2 | 45.2 |
| COST | | 2.77 | 3.61 | 3.61 | 5.87 | 7.62 | 7.63 | 9.48 | 12.33 | 12.33 | 30.25 | 39.33 | 39.33 | 95.32 | 123.91 | 123.89 |

**Table 16.** Unrestrictive Trading Results: Power plants (SIC 4911) with 30% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 3.57 | 3.58 | 3.64 | 7.14 | 7.24 | 7.36 | 10.74 | 10.72 | 10.71 | 13.7 | 14.33 | 14.31 | 17.84 | 17.89 | 17.92 |
| | Point Source | 6.29 | 6.3 | 6.42 | 12.58 | 12.75 | 12.97 | 18.91 | 18.88 | 18.86 | 24.13 | 25.25 | 25.2 | 31.43 | 31.51 | 31.56 |
| | Grouped | 10 | 10 | 10.2 | 20 | 20.3 | 20.6 | 30.1 | 30 | 30 | 38.4 | 40.1 | 40.1 | 50 | 50.1 | 50.2 |
| | Group 1 | | | | | | | | | | | | | | | |
| | Group 2 | | | | | | | | | | | | | | | |
| MAXIMUM $O_3$ | Episode 1 | 127.4 | 126.7 | 126.4 | 125.2 | 126 | 126.1 | 124 | 124 | 124.2 | 123.4 | 123 | 123 | 121.9 | 120.5 | 120.5 |
| | Episode 2 | 127.3 | 126.9 | 127.3 | 127.1 | 125.5 | 125.5 | 125.8 | 126.2 | 126.2 | 125.6 | 125.3 | 125.4 | 125 | 125 | 125.4 |
| NUMBER OF TRANSACTIONS | | 3806 | 3752 | 3678 | 5443 | 5703 | 5836 | 4908 | 5366 | 5366 | 3171 | 4787 | 4812 | 745 | 526 | 174 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 49.2 | 52.8 | 52.2 | 46 | 54 | 54.8 | 46.8 | 46.6 | 44.8 | --- | 47.6 | 46.4 | 52.4 | 44.8 | 46 |
| COST | | 2.04 | 2.64 | 2.56 | 4.07 | 5.01 | 5.25 | 6.12 | 7.95 | 7.92 | 10.39 | 15.18 | 15.55 | 46.78 | 60.33 | 60.75 |

**Table 17.** Zoned Trading Results: All point sources with 10% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.97 | 5.68 | 5.68 | 11.43 | 11.5 | 11.46 | 17.1 | 17.06 | 17.03 | 22.71 | 22.71 | 22.71 | 27.28 | 28.39 | 28.39 |
| | Point Source | 10.51 | 10.01 | 10 | 20.12 | 20.26 | 20.18 | 30.12 | 30.04 | 30 | 40 | 40 | 40 | 48.05 | 50 | 50 |
| | Grouped | | | | | | | | | | | | | | | |
| | Group 1 | 10 | 10 | 10 | 20.2 | 20 | 20 | 30.2 | 30.1 | 30 | 40 | 40 | 40 | 46.8 | 50 | 50 |
| | Group 2 | 11.3 | 10 | 10 | 20 | 20.7 | 20.5 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| MAXIMUM $O_3$ | Episode 1 | 126 | 126.8 | 126.4 | 124.7 | 124.2 | 124.2 | 123.9 | 122.4 | 123.2 | 120.2 | 120.4 | 120.3 | 118.7 | 117.1 | 116.7 |
| | Episode 2 | 129.3 | 126.6 | 127.4 | 126.9 | 125.3 | 125.3 | 124.5 | 124 | 124 | 123.6 | 123.5 | 123.6 | 123.2 | 124.3 | 123.7 |
| NUMBER OF TRANSACTIONS | | 6835 | 6277 | 6271 | 9644 | 9730 | 9048 | 9206 | 9690 | 9398 | 8007 | 7906 | 7961 | 2465 | 2599 | 2627 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 71.6 | 47.8 | 48.8 | 48.8 | 47.6 | 44.8 | 46 | 45.8 | 47.8 | 44.4 | 45.4 | 48.8 | --- | 45.8 | 44.6 |
| COST | | 3.07 | 3.38 | 3.38 | 6.08 | 6.68 | 6.69 | 13.01 | 14.31 | 14.31 | 33.57 | 36.92 | 36.92 | 89.24 | 110.54 | 110.54 |

**Table 18.** Zoned Trading Results: Point sources greater than 100 tons NOx per year with 10% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.52 | 11.26 | 11.07 | 11.04 | 16.58 | 16.56 | 16.56 | 22.08 | 22.08 | 22.08 | 27.61 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.72 | 19.84 | 19.49 | 19.44 | 29.2 | 29.17 | 29.17 | 38.89 | 38.89 | 38.89 | 48.64 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20.4 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | 10 | 10 | 10 | 20 | 20 | 20 | 30.1 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 2 | 10 | 10 | 10 | 21 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| MAXIMUM $O_3$ | Episode 1 | 125.7 | 126 | 126 | 125.3 | 124.2 | 124.4 | 123.5 | 122.7 | 122.7 | 120.4 | 120.5 | 120.5 | 118.1 | 117.5 | 118.4 |
| | Episode 2 | 127.2 | 129.4 | 129 | 126.9 | 125.3 | 125.6 | 124.7 | 124 | 124 | 123.7 | 123.6 | 123.6 | 123.3 | 124.2 | 123.6 |
| NUMBER OF TRANSACTIONS | | 6350 | 6264 | 6270 | 9402 | 9378 | 9349 | 9135 | 9727 | 9730 | 7663 | 7720 | 7725 | 1964 | 2498 | 2214 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 45.2 | 48 | 45.6 | 54.2 | 48.8 | 44.6 | 45.6 | 44.8 | 48.4 | 46 | 48.8 | 47.6 | 45.2 | 43.6 | 44.4 |
| COST | | 2.9 | 3.18 | 3.19 | 6.05 | 6.64 | 6.65 | 12.36 | 13.59 | 13.59 | 31.95 | 35.14 | 35.15 | 100.55 | 110.59 | 110.57 |

**Table 19.** Zoned Trading Results: Power plants (SIC 4911) with 10% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 3.74 | 3.82 | 3.82 | 7.18 | 7.18 | 7.18 | 11.41 | 11.17 | 11.1 | 14.36 | 14.45 | 14.45 | 17.9 | 18 | 18 |
| | Point Source | 6.58 | 6.73 | 6.72 | 12.64 | 12.64 | 12.64 | 20.1 | 19.68 | 19.55 | 25.29 | 25.44 | 25.44 | 31.53 | 31.71 | 31.71 |
| | Grouped | 10.5 | 10.7 | 10.7 | 20.1 | 20.1 | 20.1 | 32 | 31.3 | 31.1 | 40.2 | 40.5 | 40.5 | 50.2 | 50.5 | 50.5 |
| | Group 1 | 10.1 | 10.8 | 10.8 | 20 | 20.2 | 20.2 | 32.8 | 31.4 | 31.4 | 40.4 | 40.5 | 40.4 | 50.3 | 50.5 | 50.5 |
| | Group 2 | 10.6 | 10.6 | 10.6 | 20.2 | 20 | 20 | 30.5 | 31.1 | 30.5 | 40 | 40.6 | 40.6 | 50 | 50.3 | 50.3 |
| MAXIMUM $O_3$ | Episode 1 | 127.4 | 126.5 | 126.5 | 125.9 | 125.9 | 125.9 | 125.6 | 125 | 125 | 123.5 | 123.2 | 123.2 | 121.2 | 121.8 | 121.8 |
| | Episode 2 | 127.3 | 127 | 127 | 126.3 | 126.2 | 126.3 | 125.6 | 125.6 | 125.6 | 125.4 | 125.3 | 125.3 | 125 | 124.9 | 124.9 |
| NUMBER OF TRANSACTIONS | | 3986 | 4071 | 4071 | 5455 | 5453 | 5455 | 5215 | 4915 | 4915 | 4074 | 4277 | 4277 | 717 | 690 | 690 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 62 | 83.8 | 83.8 | 58.8 | 60.6 | 58 | 92 | 84.8 | 84.8 | 48.8 | 53.4 | 53.4 | 53.2 | 63.8 | 63.8 |
| COST | | 2.13 | 2.18 | 2.18 | 4.1 | 4.13 | 4.1 | 6.5 | 6.85 | 6.63 | 12.64 | 13.77 | 13.77 | 48.47 | 52.62 | 52.62 |

**Table 20.** Zoned Trading Results: All point sources with 20% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.58 | 11.26 | 11.06 | 11.04 | 16.58 | 16.56 | 16.56 | 22.08 | 22.08 | 22.08 | 27.61 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.84 | 19.84 | 19.49 | 19.44 | 29.2 | 29.17 | 29.17 | 38.89 | 38.89 | 38.89 | 48.64 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20.4 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | 10 | 10 | 10.2 | 20 | 20 | 20 | 30.1 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 2 | 10 | 10 | 10 | 21 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| MAXIMUM $O_3$ | Episode 1 | 126 | 126 | 127.1 | 125.3 | 124.3 | 124.1 | 123.5 | 122.5 | 122.5 | 120.4 | 120.3 | 120.4 | 118.1 | 116.5 | 116.5 |
| | Episode 2 | 129.4 | 126.6 | 127.4 | 126.9 | 125.3 | 125.1 | 124.7 | 124 | 124.1 | 123.7 | 123.6 | 123.6 | 123.3 | 124.3 | 123.7 |
| NUMBER OF TRANSACTIONS | | 6350 | 5998 | 6111 | 9402 | 9417 | 9415 | 9135 | 9829 | 10018 | 7663 | 7487 | 7482 | 1964 | 2271 | 1960 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 45.2 | 48 | 45.6 | 55.2 | 47.8 | 46.4 | 45.6 | 44.8 | 48.4 | 46 | 47.8 | 43.8 | 45.2 | 43.6 | 44.6 |
| COST | | 2.9 | 3.46 | 3.43 | 6.05 | 7.16 | 7.25 | 12.36 | 14.83 | 14.83 | 31.95 | 38.34 | 38.34 | 100.55 | 118.41 | 118.07 |

**Table 21.** Zoned Trading Results: Point sources greater than 100 tons NOx per year with 20% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.58 | 11.26 | 11.06 | 11.04 | 16.58 | 16.56 | 16.56 | 22.08 | 22.08 | 22.08 | 27.61 | 27.6 | 27.6 |
| | Point Source | 9.72 | 9.72 | 9.84 | 19.84 | 19.49 | 19.44 | 29.2 | 29.17 | 29.17 | 38.89 | 38.89 | 38.89 | 48.64 | 48.61 | 48.61 |
| | Grouped | 10 | 10 | 10 | 20.4 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | 10 | 10 | 10.2 | 20 | 20 | 20 | 30.1 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 2 | 10 | 10 | 10 | 21 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| MAXIMUM $O_3$ | Episode 1 | 126 | 126 | 127.1 | 125.3 | 124.3 | 124.1 | 123.5 | 122.5 | 122.5 | 120.4 | 120.3 | 120.4 | 118.1 | 116.5 | 116.5 |
| | Episode 2 | 129.4 | 126.6 | 127.4 | 126.9 | 125.3 | 125.1 | 124.7 | 124 | 124.1 | 123.7 | 123.6 | 123.6 | 123.3 | 124.3 | 123.7 |
| NUMBER OF TRANSACTIONS | | 6350 | 5998 | 6111 | 9402 | 9417 | 9415 | 9135 | 9829 | 10018 | 7663 | 7487 | 7482 | 1964 | 2271 | 1960 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 45.2 | 48 | 45.6 | 55.2 | 47.8 | 46.4 | 45.6 | 44.8 | 48.4 | 46 | 47.8 | 43.8 | 45.2 | 43.6 | 44.4 |
| COST | | 2.9 | 3.46 | 3.43 | 6.05 | 7.16 | 7.25 | 12.36 | 14.83 | 14.83 | 31.95 | 38.34 | 38.34 | 100.55 | 118.41 | 118.07 |

**Table 22.** Zoned Trading Results: Power plants (SIC 4911) with 20% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 3.74 | 3.76 | 3.75 | 7.18 | 7.29 | 7.29 | 11.41 | 11.37 | 11.06 | 14.36 | 14.39 | 14.54 | 17.9 | 18.38 | 18.38 |
| | Point Source | 6.58 | 6.61 | 6.61 | 12.64 | 12.85 | 12.85 | 20.1 | 20.03 | 19.48 | 25.29 | 25.35 | 25.6 | 31.53 | 32.38 | 32.38 |
| | Grouped | 10.5 | 10.5 | 10.5 | 20.1 | 20.4 | 20.4 | 32 | 31.9 | 31 | 40.2 | 40.3 | 40.7 | 50.2 | 51.5 | 51.5 |
| | Group 1 | 10.4 | 10.8 | 10.8 | 20.2 | 20.7 | 20.7 | 32.8 | 31.4 | 30.5 | 40.4 | 40.2 | 40.4 | 50.3 | 52.2 | 52.2 |
| | Group 2 | 10.6 | 10.1 | 10.1 | 20 | 20 | 20 | 30.5 | 32.7 | 31.3 | 40 | 40.6 | 41.4 | 50 | 50.3 | 50.3 |
| MAXIMUM $O_3$ | Episode 1 | 127.4 | 126.5 | 126.5 | 125.9 | 125.9 | 125.9 | 125.6 | 125.4 | 125.5 | 123.5 | 123.2 | 123.5 | 121.2 | 121.8 | 121.8 |
| | Episode 2 | 127.3 | 127 | 127 | 126.3 | 126.2 | 126.3 | 125.6 | 125.5 | 125.6 | 125.4 | 125.3 | 125.3 | 125 | 124.9 | 124.9 |
| NUMBER OF TRANSACTIONS | | 3986 | 3916 | 3914 | 5455 | 5616 | 5616 | 5215 | 5380 | 5338 | 4074 | 4218 | 4402 | 717 | 630 | 630 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 84.6 | 51.2 | 48.8 | 48.4 | 48 | 46 | 92 | 84.8 | 58.4 | 48.8 | 53.4 | 62 | 46.8 | 63.8 | 63.8 |
| COST | | 2.13 | 2.33 | 2.33 | 4.1 | 4.53 | 4.5 | 6.5 | 7.7 | 7.19 | 12.64 | 14.42 | 15 | 48.47 | 57.82 | 57.82 |

**Table 23.** Zoned Trading Results: All point sources with 30% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.97 | 5.87 | 5.68 | 11.43 | 11.38 | 11.36 | 17.1 | 17.04 | 17.03 | 22.71 | 22.71 | 22.71 | 27.28 | 28.39 | 28.39 |
| | Point Source | 10.51 | 10.35 | 10 | 20.12 | 20.04 | 20 | 30.12 | 30 | 30 | 40 | 40 | 40 | 48.05 | 50 | 50 |
| | Grouped | | | | | | | | | | | | | | | |
| | Group 1 | 10 | 10 | 10 | 20.2 | 20.1 | 20 | 30.2 | 30 | 30 | 40 | 40 | 40 | 46.8 | 50 | 50 |
| | Group 2 | 11.3 | 11 | 10 | 20 | 20 | 20 | 30 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| MAXIMUM $O_3$ | Episode 1 | 126 | 126.7 | 126.1 | 124.7 | 124.3 | 124 | 123.9 | 122.4 | 122.3 | 120.2 | 120.4 | 120.3 | 118.7 | 116.2 | 116.4 |
| | Episode 2 | 129.3 | 126.9 | 126.5 | 126.9 | 125.4 | 125.1 | 124.5 | 124 | 124 | 123.6 | 123.5 | 123.5 | 123.2 | 124.2 | 123.4 |
| NUMBER OF TRANSACTIONS | | 6835 | 6307 | 6334 | 9644 | 9839 | 9716 | 9206 | 10577 | 10582 | 8007 | 7186 | 7142 | 2465 | 2163 | 1762 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 71.6 | 61.2 | 46 | 48 | 45.2 | 44 | 46 | 43.6 | 43.6 | 44.4 | 43.2 | 43.6 | 22.8 | 42.8 | 41.2 |
| COST | | 3.07 | 3.94 | 4 | 6.08 | 7.91 | 7.9 | 13.01 | 16.85 | 16.91 | 33.57 | 43.64 | 43.63 | 89.24 | 129.15 | 129.15 |

**Table 24.** Zoned Trading Results: Point sources greater than 100 tons NOx per year with 30% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 5.52 | 5.52 | 5.67 | 11.26 | 11.13 | 11.05 | 16.58 | 16.56 | 16.35 | 22.08 | 22.08 | 22.08 | 27.61 | 27.6 | 27.61 |
| | Point Source | 9.72 | 9.72 | 9.99 | 19.84 | 19.6 | 19.47 | 29.2 | 29.17 | 28.8 | 38.89 | 38.89 | 38.89 | 48.64 | 48.61 | 48.64 |
| | Grouped | 10 | 10 | 10.3 | 20.4 | 20.2 | 20 | 30 | 30 | 29.6 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 1 | 10 | 10 | 10.4 | 20 | 20.1 | 20 | 30.1 | 30 | 30 | 40 | 40 | 40 | 50 | 50 | 50 |
| | Group 2 | 10 | 10 | 10 | 21 | 20.2 | 20 | 30 | 30 | 29 | 40 | 40 | 40 | 50 | 50 | 50 |
| MAXIMUM $O_3$ | Episode 1 | 126 | 126.3 | 126.1 | 125.3 | 124.2 | 124.3 | 123.5 | 122.6 | 122.6 | 120.4 | 120.6 | 120.5 | 118.1 | 116.4 | 117.7 |
| | Episode 2 | 129.4 | 126.8 | 126.7 | 126.9 | 125.4 | 125.4 | 124.7 | 124.2 | 124.3 | 123.7 | 123.6 | 123.6 | 123.3 | 124.4 | 123.3 |
| NUMBER OF TRANSACTIONS | | 6350 | 5901 | 6119 | 9402 | 9640 | 9699 | 9135 | 9758 | 9473 | 7663 | 6951 | 6929 | 1964 | 2261 | 1336 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 45.2 | 46 | 61.6 | 55.2 | 48.4 | 45.6 | 48.8 | 44.4 | 37.2 | 46 | 43.6 | 43.6 | 45.2 | 45.2 | 45.2 |
| COST | | 2.9 | 3.77 | 3.7 | 6.05 | 7.77 | 7.85 | 12.36 | 16.06 | 15.36 | 31.95 | 41.54 | 41.48 | 100.55 | 130.46 | 130.63 |

**Table 25.** Zoned Trading Results: Power plants (SIC 4911) with 30% cost relaxation

| | | SCENARIO | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 10% REDUCTION | | | 20% REDUCTION | | | 30% REDUCTION | | | 40% REDUCTION | | | 50% REDUCTION | | |
| | | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 | Least-cost | Alt 1 | Alt 2 |
| % REDUCTION | Overall | 3.74 | 3.77 | 3.74 | 7.18 | 7.31 | 7.35 | 11.41 | 10.89 | 10.81 | 14.36 | 15.01 | 14.49 | 17.9 | 18.01 | 18.01 |
| | Point Source | 6.58 | 6.65 | 6.59 | 12.64 | 12.87 | 12.95 | 20.1 | 19.18 | 19.03 | 25.29 | 26.43 | 25.53 | 31.53 | 31.72 | 31.72 |
| | Grouped | 10.5 | 10.6 | 10.5 | 20.1 | 20.5 | 20.6 | 32 | 30.5 | 30.3 | 40.2 | 42.1 | 40.6 | 50.2 | 50.5 | 50.5 |
| | Group 1 | 10.4 | 10.8 | 10.8 | 20 | 20.7 | 20.7 | 32.8 | 30.1 | 30.1 | 40.4 | 42.2 | 40.2 | 50.3 | 50 | 50 |
| | Group 2 | 10.6 | 10.3 | 10 | 20.2 | 20 | 20.4 | 30.5 | 31.2 | 30.6 | 40 | 41.4 | 41.4 | 50 | 51.2 | 51.2 |
| MAXIMUM $O_3$ | Episode 1 | 127.4 | 126.5 | 126.5 | 125.9 | 125.7 | 126.3 | 125.6 | 124.7 | 124.7 | 123.5 | 123 | 123.2 | 121.2 | 120.6 | 120.6 |
| | Episode 2 | 127.3 | 127.3 | 127 | 126.3 | 126.2 | 126.4 | 125.6 | 125.6 | 125.6 | 125.4 | 125.3 | 125.3 | 125 | 124.7 | 124.7 |
| NUMBER OF TRANSACTIONS | | 3986 | 3911 | 3891 | 5455 | 5633 | 5378 | 5215 | 5443 | 5443 | 4074 | 5048 | 4363 | 717 | 296 | 296 |
| RELIABILITY IN MEETING EMISSIONS TARGET | | 83.6 | 90.4 | 84 | 48.4 | 62 | 68.4 | 92 | 58.4 | 52.4 | 48.8 | 84.8 | 56 | 46.8 | 52.4 | 52.4 |
| COST | | 2.13 | 2.4 | 2.35 | 4.1 | 4.58 | 5 | 6.5 | 8.01 | 7.77 | 12.64 | 16.24 | 16.39 | 48.47 | 61.35 | 61.35 |