To the Graduate Council:

I am submitting herewith a dissertation written by Carol Helen Norman entitled "Use of Episodic Controls to Lower Ozone Concentrations: Their Impact and Cost Effectiveness." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

Gregory D. Reed, Major Professor

We have read this dissertation
and recommend its acceptance:

Accepted for the Council:

Interim Vice Provost and
Dean of The Graduate School

Use of Episodic and Seasonal Controls to Lower Ozone Concentrations: Their Impact and Cost Effectiveness

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Carol Helen Norman
August 2000

DEDICATION

I dedicate my dissertation and degree

To my husband, Enrique,
For your love, patience and computer skills,
You are the best part of my Ph.D. journey.

To my Mom and Dad,
For your interest and excitement in whatever I do, for your love and encouragement,
You give life to every possibility. Thank you.

To my advisor, Greg,
For believing in me and supporting my dream,
Your guidance assured my finish.

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ABSTRACT

Episodic ozone controls are used temporarily when high concentrations of ozone are predicted to occur. More than 40 cities in the United States have implemented episodic control programs that are designed to educate the public about air pollution, attain and maintain air quality standards, and protect human health. No program has quantified the impact of episodic controls on ozone concentrations or their cost effectiveness as a control measure.

To quantify the impact of episodic controls in the East Tennessee Modeling Domain, the Urban Airshed Model was used to predict ozone concentrations resulting from a variety of control scenarios that simulated typical NO_x reduction technologies for point sources and area and mobile sources. Because ozone formation in the southeastern United States is NO_x -limited, only NO_x reductions were analyzed. A cost analysis was performed to estimate the cost effectiveness of the various control technologies in lowering ozone concentrations.

For peak ozone concentrations, NO_x emission reductions from elevated point sources made the largest impact on 1-hour and 8-hour average concentrations. Point source NO_x reductions were more cost effective in reducing peak ozone concentrations than were area and mobile source NO_x reductions. A 10 percent reduction in NO_x from area and mobile sources had no measurable impact of ozone concentration. For a maximum difference in ozone, occurring anywhere in the modeling domain, elevated point sources again made the largest impact on ozone concentration, about twice the impact predicted for 50

percent NO_x reductions from area and mobile sources. Cost effectiveness of achieving maximum differences in ozone concentrations was about the same for all the control technologies analyzed.

Each agency should perform a modeling analysis similar to the one in this research before implementing an episodic control program in order to determine which control techniques are most effective in achieving their goals under the controlling conditions in their region.

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LIST OF ABBREVIATIONS

ALAPCO	Association of Local Air Pollution Control Officers
BAAQMD	Bay Area Air Quality Management District
BTU	British thermal unit
^0C	degrees Centigrade
CAAA	Clean Air Act Amendments
CB-IV	carbon-bond chemical mechanism, version IV
CONAMA	Comision Nacional del Medio Ambiente
CO_2	carbon dioxide
CPI	Consumer Price Index
DEC	Digital Equipment Corporation
$	US dollars
EPA	Environmental Protection Agency
ETMD	East Tennessee Modeling Domain
^0F	degrees Fahrenheit
FAR	Flexible Attainment Region
GSMNP	Great Smoky Mountains National Park
km	kilometers
MARAMA	Mid-Atlantic Regional Air Management Association
MARTA	Metropolitan Atlanta Rapid Transit Authority
m/hr	meters per hour
mph	miles per hour

m/s	meters per second
MW	megawatt
NAAQS	National Ambient Air Quality Standard
NESCAUM	Northeast States for Coordinated Air Use Management
NO	nitrogen oxide
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
OTAG	Ozone Transport Assessment Group
OTR	Ozone Transport Region
PM-10	particulate matter with an aerodynamic diameter less than 10 micrometers
ppb	parts per billion
ppm	parts per million
RESPONSE	Real Environmental Strategies for Partners in Ozone Negation Systems
rfd	reformulated diesel
rfg	reformulated gasoline
RVP	Reid vapor pressure
SCAQMD	South Coast Air Quality Management District
SCR	selective catalytic reduction
SIP	State Implementation Plan
SNCR	selective non-catalytic reduction
SO_2	sulfur dioxide
STAPPA	State and Territorial air Pollution Program Administrators
VMT	vehicle miles traveled

tpd	tons per day
TVA	Tennessee Valley Authority
TYS	M^{c}Ghee-Tyson Airport
UAM	Urban Airshed Model
US	United States
UTM	Universal Transverse Mercator
VOC	volatile organic compound

1. INTRODUCTION

The on-going debate over the U.S. Environmental Protection Agency's (EPA) revision to the nation's air quality standard for ozone is of great importance to human and ecological health as well as to the nation's economy. EPA's revised standard affects both the absolute level of protection from the harmful effects of ozone and the method of calculating compliance, the form of the standard. The new standard affects both the primary and secondary standards; as such, the new standards can potentially bring an added measure of protection to human health and the environment, but added protection may be quite costly, depending, in part, on how the new standards are implemented.

The current primary National Ambient Air Quality Standard (NAAQS) for ozone is a 1-hour 0.12 parts per million (ppm) standard. The test for attainment is whether monitoring data for a particular site exceed the 1-hour average concentration of 0.12 ppm on average no more than once per year, averaged over three years. If the 0.12 ppm concentration is exceeded four times in three years, the site is considered out of attainment.

The EPA promulgated a new NAAQS for ozone in July 1997. The new standard differs from the current standard in averaging time, concentration, and form. Accordingly, the standard for ozone is "0.08 parts per million measured over eight hours, with the average fourth highest concentration over a three-year period determining whether an area is out of compliance" (USEPA, July 1997). This form of standard is expected to be a more stable determination of compliance, less subject to short-term meteorological variations

than the current one-hour standard. The new secondary standard is identical to the new primary standard and is intended to protect the public welfare including effects of ozone on vegetation, crops, animals, materials and visibility.

The new 8-hour ozone standard was challenged in court and remanded in May 1999. Even so, many areas compare their monitoring data against the 8-hour standard, in addition to the 1-hour standard, applying it as an unofficial yardstick in assessing their current and future attainment status.

Ground level ozone can adversely affect children, the elderly, sensitive populations such as asthmatics, and healthy adults through decreased lung function and lung inflammation. It causes reduced crop yields and stunts the growth of ornamental plants and shrubbery. When and if the new, tougher standard is implemented, even more areas will have trouble attaining the ozone NAAQS. In January 1998, there were 57 ozone 1-hour nonattainment areas in the US with an estimated 100 million people living in them (USEPA 1998). In addition to providing healthful air for the public to breathe, areas strive to meet the NAAQSs because federal funds can be lost if they do not. Also, new and expanding businesses in the nonattainment area are forced to install more costly and more efficient controls than are required in an attainment area.

The 1-hour ozone standard has been a difficult standard to attain. Many cities have been unable to meet it despite years of efforts trying to do so. One reason is that ozone is not

emitted directly but is the result of its precursor emissions of volatile organic hydrocarbons (VOCs) and oxides of nitrogen (NO_x) combining in the presence of sunlight. The amount of ozone formed depends on the levels and ratios of VOCs and NO_x to each other and on the quantity and intensity of sunlight. Furthermore, both ozone and its precursor emissions can migrate long, multi-state distances depending on the prevailing wind patterns.

In 1990 the Clean Air Act Amendments (CAAA) were promulgated and focused on reducing VOC emissions to control urban ozone concentrations, largely ignoring NO_x as an ozone precursor. These efforts have not proved successful in solving the ozone problem in the Southeast. Studies of Tennessee air quality involving ozone precursor emissions show that reducing VOC emissions has little effect on ozone concentrations, while on the other hand, reducing NO_x emissions does have a significant effect on ozone (Davis and Miller, 1994; Ahmed, Miller and Davis, 1996). Because of their minor effect on ozone, focusing on reducing VOC emissions in the Southeast misses the point of achieving and maintaining the ozone standard, and consumes resources that could have been expended on reducing NO_x *and* ozone concentrations. For these reasons, NO_x emissions will be the only precursor controlled, varied, and analyzed in this study. No variations in VOC emissions will be made or studied.

In Tennessee, forty counties in the eastern portion of the state comprise the East Tennessee area where the main sources of NO_x emissions are anthropogenic combustion

processes. Examples of combustion include car engines burning gasoline, electricity generating plants burning coal, and backyard hamburger grills burning propane. NO_x is also formed by natural processes in which microorganisms use soil nitrogen compounds to generate NO_x emissions. These emissions fall into four categories: 1) stationary point sources, 2) mobile sources, both on-road and off-road, 3) area sources, those sources too small and numerous to count as point sources and those sources spread over large areas, and 4) biogenic sources.

Typically, the amount of reduction of emissions necessary to attain the standard is determined by computer modeling of emissions to predict ambient concentrations of the pollutant. Once the quantity of emission reductions is determined, then various control technologies and strategies are added together until the required emission reductions are attained. The costs of these control technologies and strategies represent part of the direct costs of attaining the ozone standard. Regulatory oversight and implementation cost are also direct costs. Compliance with standards also involves indirect costs associated with losses in an individual's well-being from changes in consumption of goods and services and changes in lifestyles that result from implementation of the control measures.

Good public policy requires that decision makers have solid information on the incremental benefits and costs of attaining the 1-hour and 8-hour standards. As the recent debate over the form and level of the 8-hour standard indicates, science alone does not provide an adequate basis for selecting one specific standard. Moreover, differing control

methodologies affect the costs of attainment, and differing control methodologies means not simply different technologies, but also regulatory regimes. For example, the costs of attainment may be substantially less under a regional rather than local approach.

The Clean Air Act directs the Administrator of EPA to set the primary standard at a level that protects human health, including sensitive populations, without regard to costs of implementation (42 U.S.C. 7409). However, the methods used to achieve the standard can take into account cost. Episodic controls may enable areas to achieve the ozone standard at a supposedly lower cost than can traditional, permanent controls.

Episodic ozone controls are being used to reduce ambient ozone concentrations in many cities across the nation. Episodic controls are different than traditional, permanent controls in that they are implemented not continuously, but only when needed, for instance, when ozone concentrations are forecasted to exceed the standard on what is called a "high ozone day." In such cases, predetermined controls are activated for a short time to avoid an exceedence. This method has been instituted by more than forty cities around the country as a tool for bringing down ozone concentrations (USEPA, March 1997).

Episodic control methods are not intended to replace permanent, command-and-control regulations; rather, the two methods work in concert to avoid an exceedence. Some

examples of episodic controls include taking mass transit instead of driving, taking lunch to work instead of driving to a restaurant, tele-commuting, rescheduling to another day an industrial process operation with high NO_x emissions, waiting until the next day to mow the lawn or to cook on an outside grill, load-switching between electric utilities, and gas reburn or selective catalytic reduction in fossil fuel-fired boilers.

Episodic controls may prove to be a cost-effective tool for achieving and maintaining the ozone standard. Many episodic measures are low in capital costs, an appealing aspect for industries and utilities while being high in short-term operating costs. For instance, a coal-fired electricity generating plant, under command-and-control regulations, might have to implement permanent, year-round NO_x controls to reduce emissions that contribute to ozone exceedences only ten days a year. Instituting extraordinary NO_x control measures, for ten days a year, may be more cost-effective for the plant than to use permanent controls for 365 days. This aspect makes episodic controls attractive to industry and utilities.

However, the effectiveness of episodic controls in reducing ozone concentrations has yet to be quantified by any area that is implementing them, and the cost of various control strategies among source categories has yet to be assessed or compared with conventional, permanent regulatory methods.

In this study a variety of episodic controls are examined for their effectiveness at reducing ozone concentrations and whether episodic controls are best suited for "shaving

the peaks" off high ozone concentrations by a few parts per billion on a high ozone day in order to maintain compliance with the ozone NAAQS or if episodic controls can reduce ozone concentrations by an amount that contributes to public health and welfare. The Urban Airshed Model IV (UAM IV) is used to determine how effective episodic controls are at reducing ozone concentrations. Ignoring biogenic sources as too widespread and difficult to control, reductions of NO_x emissions from the three remaining emission categories; point sources, mobile sources and area sources; are simulated in this study to represent the effects of a variety of episodic control methods. Both voluntary and mandatory measures are among the control methods in addition to the traditional, permanent controls. Reliability of each method in achieving ozone reductions is assessed also. Model predictions of 1-hour and 8-hour average ozone concentrations are analyzed and compared with both the current 1-hour NAAQS for ozone and the new, but remanded, 8-hour NAAQS.

Costs are used as an additional measure of the effectiveness of implementing the various emission reduction methods. The direct cost of each method is quantified and analyzed to determine its cost effectiveness. Societal costs of having to alter lifestyles to participate in episodic controls are examined to the extent possible given the limited available cost data. Costs of control measures are calculated for comparison across point, mobile and area source categories and for voluntary and mandatory controls.

The episodes of high ozone are assumed to last for periods of one day and for three consecutive days. These simulate meteorological conditions of stagnant air and high ozone conditions for a single high ozone day and for three consecutive days.

Two sets of NO_x emissions changes are investigated for their influence on ozone concentrations and for cost effectiveness:

1. NO_x emission reductions from elevated point sources - NO_x emission controls of individual point sources and of combinations of point sources are examined for their effect on ozone concentrations in the East Tennessee Modeling Domain (ETMD). Effects of reducing NO_x emissions are examined using EPA's UAM IV to predict ozone concentrations. The point source emission scenarios for UAM IV are developed from a 1993 emission inventory of the modeling domain that was compiled by the Tennessee Department of Air Pollution Control with assistance from the University of Tennessee's Department of Civil and Environmental Engineering.
2. NO_x reductions from area and mobile sources - NO_x emissions reductions from area and mobile sources focus on the typical control methods targeted in an episodic control program. Reduction methods include measures requiring voluntary actions from the public such as driving less and involuntary methods that use mechanical controls such as reformulated gasoline. A series of increasing NO_x emission reductions from area and mobile sources are simulated in UAM IV to demonstrate

how cost varies with increasing reductions of NO_x emissions and with increasing impacts on ozone concentrations.

These strategies are used to determine the effect of episodic controls on ozone concentration and the cost effectiveness of episodic controls. The results of the study quantify the impact that episodic controls can have on ambient ozone concentrations and identify the control measures that result in the most cost effective means of reducing ozone concentrations. These results illustrate whether or not episodic controls are a viable tool for decision makers to rely on for reducing ozone or if resources and efforts consumed in implementing episodic controls are better spent on other methods of reducing ozone concentrations.

2. LITERATURE REVIEW

Several cities across the United States have endured persistent, high seasonal ozone concentrations through the 1980's and 90's and, despite their efforts, have been unable to meet the NAAQS for ozone. To make matters worse for these cities, the US Environmental Protection Agency (EPA), in July 1997, promulgated a new, more stringent NAAQS for ozone. In an effort to decrease ozone concentrations and have another technique for use as a control mechanism, cities have instituted episodic control programs for ozone. The programs are implemented exclusively when high air pollution levels are predicted to occur. Emission reductions happen, then, only when needed and when they are needed most.

Episodic Control Programs

Episodic ozone controls differ from traditional air pollution controls in that episodic controls are instituted temporarily, a few hours or days, a month or even the summer season. Conversely, traditional air pollution control techniques are used continuously, 365 days a year, during periods of modest ozone levels and in winter months when ozone levels are lowest and not a health concern.

One of the complicating factors in controlling ozone concentrations is that ozone is not directly emitted into the air. It is formed as a secondary pollutant from precursor emissions of NO_x and VOCs that mix, and in the presence of sunlight, form ozone

through a series of complicated chemical reactions. Lowering ozone concentrations can be realized only by reducing the emissions of its precursor components NO_x and VOCs.

Ground level ozone can adversely affect children, the elderly, sensitive populations such as asthmatics, and healthy adults through decreased lung function and lung inflammation. These effects are negative economic outcomes because of reduced productivity and lost workdays. Ozone causes reduced crop yields and stunts the growth of ornamental plants and shrubbery (Federal Register, 1998). To better protect human health and welfare, EPA revised the NAAQS for ozone in July 1997 to 80 parts per billion (ppb) measured as an 8-hour average, with the average 4^{th} highest concentration over a 3-year period determining whether an area is out of compliance (USEPA, 1997a). This form of standard is expected to be a more stable determination of compliance and less subject to short-term meteorological variations than the previous 1-hour, 120 ppb standard. After being challenged in the courts, the 8-hour standard was remanded in May 1999 and is still being argued in the courts at this writing (USEPA, 1999a). As of January 1998, for the 1-hour standard, 57 ozone nonattainment areas exist in the US with an estimated 100 million people living in them (USEPA, 1998). When the new, 8-hour standard takes effect, if ever, even more cities will have trouble attaining the ozone NAAQS.

Areas strive to meet the NAAQSs because federal funds for transportation projects can be lost if they do not comply (Public Law 101-549, 1990a). More commonly, new and expanding businesses in a nonattainment area are forced to install more costly and more

efficient controls than required in an attainment area, and any new emissions must be offset from existing emissions at a ratio of greater than one for one. The ratio depends on just how much higher the area's ambient concentrations are than the NAAQS.

In an attempt to maintain attainment status or to achieve attainment, more than forty episodic control programs are currently in use in US cities. These cities are shown in Figure 2-1 (USEPA, May 1997). The three pollutants they target are ozone, carbon monoxide, and particulate matter. Ozone and carbon monoxide programs focus mainly on mobile source emissions, while wood smoke from home heating is the focus of particulate matter programs. Table 2-1 lists the cities with episodic control programs and their target pollutants.

A potential benefit of an episodic control program is less costly control measures to reduce emissions of ozone precursors. A thorough cost analysis has yet to be conducted that analyzes the costs and benefits of an episodic control program. It is possible that a comparison of episodic versus traditional controls will show that episodic controls are cheaper than traditional, year-round controls. Other benefits of implementing episodic controls are public education, attaining or maintaining an area's attainment status of the ozone NAAQS and health benefits to the local population. Table 2-2 ranks the goals of programs from around the country. Topping most program lists is public education at 53 percent. Second among the programs is the goal of attaining or maintaining the NAAQS (30 percent), and third is health benefits to the local population (13 percent) (USEPA,

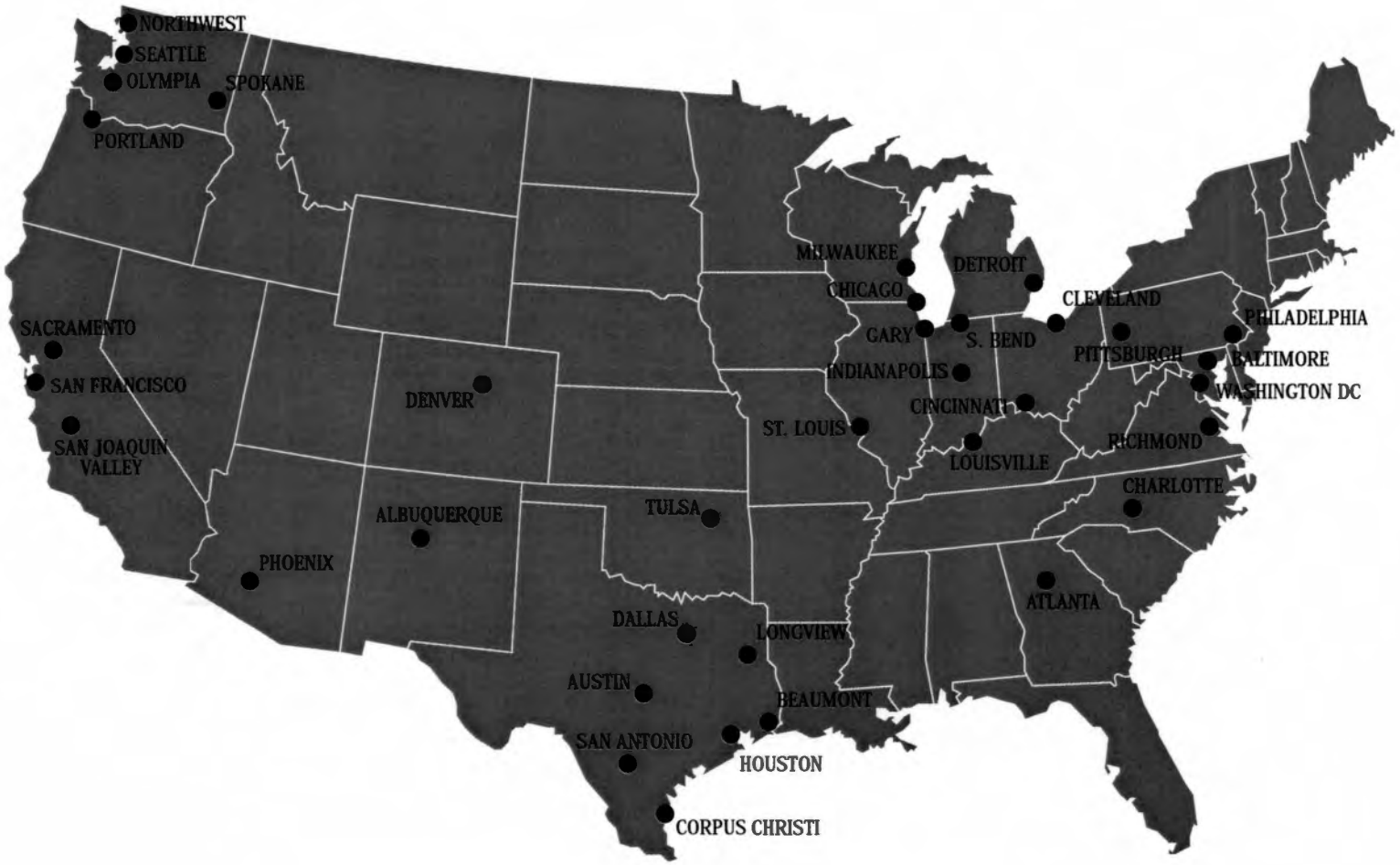


Figure 2-1. U.S. Cities with Episodic Control Programs.

Table 2-1. Target Pollutants of Cities with Episodic Control Programs.

Area	Name	Target	Attainment Status[1]
Albuquerque, NM	Winter Pollution Advisory	CO	Nonattainment (moderate)
Atlanta, GA	Ozone Advisory	Ozone	Nonattainment (serious)
Austin, TX	Clean Air Force	Ozone	Attainment
Baltimore, MD	Ozone Action Days	Ozone	Nonattainment (severe)
Baton Rouge, LA[2]	Ozone Action	Ozone	Nonattainment (serious)
Beaumont/Port Arthur, TX	Ozone Action Days	Ozone	Nonattainment (moderate)
Charlotte, NC	Ozone Awareness	Ozone	Attainment
Chicago, IL	Ozone Action Days	Ozone	Nonattainment (severe)
Cincinnati, OH	Smog Alert	Ozone	Nonattainment(moderate)
Cleveland, OH	Ozone Action Day	Ozone	Attainment (maintenance)
Corpus Christi, TX	Ozone Action Days	Ozone	Attainment
Dallas/Ft. Worth, TX	Ozone Alert	Oz one	Nonattainment (moderate)
Denver, CO	High Pollution Advisory	PM	Nonattainment (moderate)
Detroit, MI	Ozone Action Days	Ozone	Attainment
Gary, IN	Partners for Clean Air	Ozone	Nonattainment (severe)
Houston/Galveston, TX	Clean Air Action	Ozone	Nonattainment (severe)
Indianapolis, IN	Partners for Clean Air	Ozone	Nonattainment (moderate)
Longview/Marshall/Tyler, TX	Northeast Texas Air Care	Ozone	Attainment
Louisville, KY[2]	Partners for Clean Air	Ozone	Nonattainment (moderate)
Milwaukee, WI	Ozone Action	Ozone	Nonattainment (severe)
Northwest (Mt. Vernon), WA	Woodsmoke Curtailment	PM	Attainment
Olympia, WA	Woodsmoke Curtailment	PM	Nonattainment (moderate)
Philadelphia, PA	Ozone Action	Ozone	Nonattainment (severe)
Phoenix, AZ	Ozone High Air Pollution Advisory	Ozone	Nonattainment (moderate)
Phoenix, AZ	Residential Woodburning Restriction	CO	Nonattainment (serious)
Pittsburgh, PA	Ozone Action	Ozone	Nonattainment (moderate)
Portland, OR	Clean Air Action Days	Ozone	Nonattainment (marginal)
Puget Sound (Seattle), WA	Woodsmoke Curtailment	PM	Nonattainment (moderate)
Puget Sound (Seattle), WA	Smog Watch	Ozone	Nonattainment (marginal)
Richmond/Col. Heights, VA	Ozone Advisory	Ozone	Nonattainment (moderate)
Sacramento, CA	Spare the Air	Ozone	Nonattainment (severe)
San Antonio, TX	Ozone Action Days	Ozone	Attainment
San Francisco, CA	Spare the Air	Ozone	Attainment
San Joaquin Valley, CA	Spare the Air	Ozone	Nonattainment (serious)
South Bend, IN	Partners for Clean Air	Ozone	Attainment
Spokane, WA	Wood Stove Curtailment	PM	Nonattainment (moderate)
St. Louis, MO	Regional Clean Air Partnership	Ozone	Nonattainment (moderate)
Toledo, OH	Ozone Action Day	Ozone	Attainment
Tulsa, OK	Ozone Alert	Ozone	Attainment
Washington, D.C.	Ozone Action Days	Ozone	Nonattainment (serious)

1. Attainment status as of July 1996.
2. Program was not reviewed in detail because only limited data were available at the time of this study. (USEPA, March 1997)

Table 2-2. Goals of Episodic Control Programs.

Area	Program	Program Goals, Ranked		
		#1	#2	#3
Albuquerque, NM	Winter Pollution Advisory	Maintain AQ Std	Public Education, Health Benefits	Congestion Mngmt
Atlanta, GA	Ozone Advisory	Public Education	Health Benefits	Congestion Mngmt
Austin, TX	Clean Air Force	Public Education	Maintain AQ Stds	Health Benefits
Baltimore, MD	Ozone Action Days	Public Education	Health Benefits	Attain AQ Stds
Beaumont, TX	Ozone Action Days	Public Education	Attain AQ Stds	Economic Benefits
Charlotte, NC	Ozone Awareness	Public Education	Economic Benefits	Health Benefits
Chicago, IL	Ozone Action Days	Health Benefits	Public Education	Attain AQ Stds
Cincinnati, OH	Smog Alert	Attain AQ Stds	Public Participation	Health Benefits
Cleveland, OH	Ozone Action Day	Public Education	Health Benefits	Economic Benefits
Corpus Christi	Ozone Action Days	Maintain AQ Std	Public Education	Economic Benefits
Dallas/Ft. W.	Ozone Alert	Public Education	Attain AQ Stds	Emission Reduction
Denver, CO	High Pollution Advisory	Attain AQ Stds	Emission Reduction	Health Benefits
Detroit, MI	Ozone Action Days	Attain AQ Stds	Public Education	Health Benefits
Gary, IN	Partners for Clean Air	Public Education	Health Benefits	Maintain AQ Stds
Houston/Galv	Clean Air Action	Public Education, Health Benefits	Attain AQ Stds	
Indianapolis, IN	Partners for Clean Air	Public Education	Health Benefits	Maintain AQ Stds
Longview, TX	Northeast TX Air Care		Economic Benefits	Public Education
Louisville, KY	Partners for Clean Air	Public Education	Health Benefits	Maintain AQ Stds
Milwaukee, WI	Ozone Action	Maintain AQ Std	Attain AQ Stds	Public Education
Northwest, WA	Woodsmoke Curtailment	Health Benefits	Public Education	Economic Benefits
Olympia, WA	Woodsmoke Curtailment	Attain AQ Stds	Maintain AQ Stds	Health Benefits
Philadelphia	Ozone Action	Public Education	Health Benefits	Attain AQ Stds
Phoenix, AZ	Ozone High Air Poll. Advisory	Public Education	Emission Reductions	Health Benefits
Phoenix, AZ	Residential Wood-burning Restriction	Public Education	Emission Reduction	Health Benefits
Pittsburgh, PA	Ozone Action	Public Education	Attain AQ Stds	Economic Benefits
Portland, OR	Clean Air Action Days	Attain AQ Stds	Health Benefits	Public Education
Puget Sound, WA	Woodsmoke Curtailment	Attain AQ Stds	Health Benefits	Maintain AQ Stds
Puget Sound, WA	Smog Watch	Maintain AQ Std	Economic Benefits	Public Education
Richmond, VA	Ozone Advisory	Maintain AQ Std	Economic Benefits	Health Benefits
Sacramento, CA	Spare the Air	Attain AQ Stds	Health Benefits	Public Education
San Antonio, TX	Ozone Action Days	Public Education	Maintain AQ Stds	Health Benefits
San Francisco	Spare the Air	Health Benefits	Attain AQ Stds	Public Education
San Joaquin, CA	Spare the Air	Public Education	Attain AQ Stds	Health Benefits
South Bend, IN	Partners for Clean Air	Public Education	Health Benefits	Maintain AQ Stds
Spokane, WA	Wood Stove Curtailment	Public Education	Attain AQ Stds	Health Benefits
St. Louis, MO	Clean Air Partnership	Public Education	Attain AQ Stds	Health Benefits
Toledo, OH	Ozone Action Day	Maintain AQ Std	Economic Benefits	Public Education
Tulsa, OK	Ozone Alert	Health Benefits	Maintain AQ Stds	Economic Benefits
Washington, DC	Ozone Action Days	Public Education	Health Benefits	Attain AQ Stds

(USEPA, March 1997)

May 1997). The goal of ozone reductions in this study was to attain and maintain the ozone standard.

Typical control measures used nationwide for episodic programs (USEPA, March 1997) vary with the pollutant of concern. Controls for ozone are focused on the precursor compounds, NO_x and VOCs. Common travel-related control measures for ozone and its precursors include:

- avoid driving at lunch time, NO_x and VOCs,
- use alternative modes of transportation instead of driving alone, NO_x and VOCs,
- keep vehicles tuned up, NO_x and VOCs,
- combine multiple auto trips or errands, NO_x and VOCs,
- work or telecommute from home, NO_x and VOCs,
- refuel vehicles in the evening, VOCs,
- maintain travel speeds at the speed limit and steady, NO_x and VOCs, and
- change work schedules to avoid rush-hour traffic, NO_x and VOCs.

Area source emission reduction suggestions include:

- avoid use of wood stoves and fireplaces, particulate matter,
- avoid using gasoline-powered equipment, NO_x and VOCs,
- avoid using charcoal lighter fluid, VOCs, and
- avoid household maintenance activities that produce emissions such as painting, cleaning, etc., VOCs.

Point source strategies for reducing emissions involve:

- reschedule batch operations to late afternoon or night times, NO_x and VOCs,
- implement Selective Catalytic Reduction, Selective Non-Catalytic Reduction or other control technique during periods of high ozone, NO_x.

Corporate and industrial policy changes could involve:

- postpone fleet refueling until evening, VOCs,
- use fleet vehicles to attend lunch and meetings, NO_x and VOCs, and
- use conferencing technology instead of face-to-face meetings, NO_x and VOCs.

The usefulness of these emission control measures in reducing ozone concentrations depends partly on the region of the country in which the program is located. Some regions are VOC-limited meaning that reducing VOC emissions will reduce ozone concentrations. Other regions, including East Tennessee, are NO_x-limited; reducing NO_x emissions will reduce ozone concentrations. Data collected and analyzed in Tennessee show that, in the southeastern United States, anthropogenic VOC emissions have little influence on ozone formation compared with NO_x. In East Tennessee, biogenic VOC emissions are large in quantity and make up 90 percent of the total VOC emission inventory. This leaves a mere 10 percent of VOCs available for control; therefore, efforts to control anthropogenic VOC emissions in Tennessee will have little influence on ozone formation (Davis and Miller, 1994). The NO_x emission inventory is the opposite. Only 5 percent are biogenic; 95 percent are anthropogenic and available for control. Reducing NO_x emissions will have a more immediate effect on ozone concentrations.

A study of the Nashville/Middle Tennessee area shows that reducing anthropogenic VOC emissions has little effect on ozone concentrations but reducing anthropogenic NO_x emissions has a large effect (Davis and Miller, 1994). Eliminating VOC emissions from mobile sources made a 4 part per billion difference in the ozone concentration as predicted by UAM IV. On the other hand, eliminating NO_x emissions from mobile sources lowered the ozone concentration by 20 to 25 parts per billion - almost six times more effective than VOC reductions. The study also examined emissions from coal-fired power plants. When three large power plants were removed from the emission inventory,

they made a difference of about 30 parts per billion less ozone in modeling results. This effect is attributed to reduced NO_x emissions since power plant emissions of NO_x are typically 100 times higher than VOC emissions. Figure 2-2 graphically shows the relationships among VOC emissions, NO_x emissions and ozone concentrations. The upper left portion of the graph is VOC-limited and has VOC to NO_x ratios typically around 4:1. Tennessee is NO_x-limited, and its ozone formation is best illustrated in the lower right portion of the graph where VOC to NO_x ratios may be 15:1 or higher. Elbow-shaped isopleths of ozone concentration, horizontal to the x-axis in the lower right, show that in order to lower ozone concentrations, a relatively small decrease in NO_x ambient concentration is required, but a large reduction in ambient VOC concentrations is required. This reinforces the findings of the Tennessee study described previously. In the Southeast, ozone concentrations are influenced more by reducing NO_x emissions than by reducing VOC emissions. Cutting NO_x emissions is the key to lower ozone concentrations in Tennessee, and this study will focus exclusively on NO_x emission reductions.

For cities with episodic control programs, tracking how many people and industries participate in episodic controls is difficult. Direct measurements of participants are usually done via surveys that are difficult and expensive to conduct. When conducted the same day or day after an episodic ozone alert, the most accurate data can be obtained.

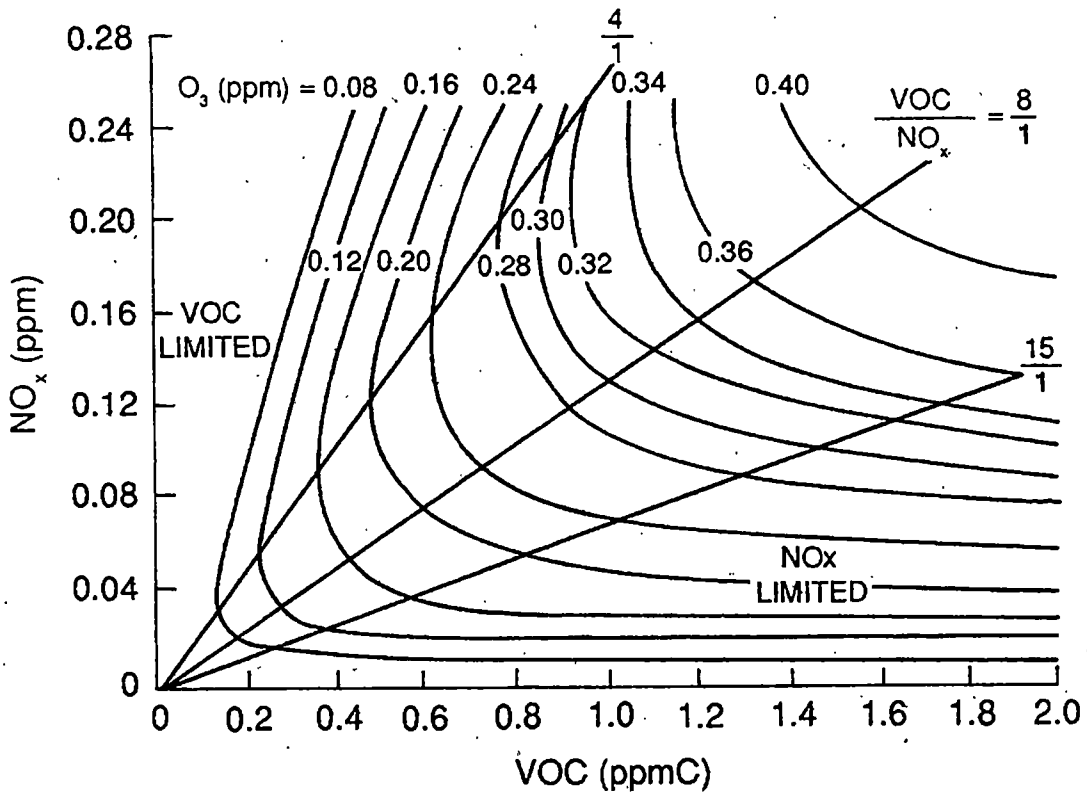


Figure 2-2. Concentration Isopleths of NO_x and VOCs. (National Research Council, 1991 and Dodge, 1977)

Surveys that are conducted at the end of the ozone season have a large potential for error because people may not remember if and how they participated. Survey techniques have other inherent errors too. Some respondents may answer the survey in the way they think they are supposed to instead of accurately, others may not remember correctly, and others may intentionally lie. Results collected by personal interviews may be biased if the respondent tries to please the interviewer with "correct" answers. Surveys may not be the most accurate or reliable method of quantifying these data even if they are a direct measurement of participation.

Indirect measurements of actions taken to reduce ozone precursor emissions can be obtained from traffic counts, mass transit ridership, mass transit ticket sales and gasoline sales. These indirect measurements most often have shown no difference, though, from measurements taken on days with no ozone alert (USEPA, 20 May 1998) and have failed to yield reliable data quantifying emission reductions from public participation in episodic control programs. However, two air quality agencies have attempted to quantify emission reductions from their episodic control programs, Bay Area Air Quality Management District (BAAQMD) and the Metropolitan Washington Council of Governments. The BAAQMD, quantifying emission reductions through various survey techniques, reported that less than 2 tons per day of NO_x emissions and less than 2 tons per day of reactive organic gases (also called VOCs) were reduced on a day when the use of episodic controls was requested (Personal communication with Ms. Teresa Galvin Lee, June 2000). The Metropolitan Washington Council of Governments reported more

successful reductions in emissions of 2.13 tons of NO_x per day and 1.24 tons of VOCs per day (Rohlfs, 2000).

Episodic control programs consist of three main ingredients: forecasting of ozone concentrations, notification of the public and industries, and public and industry participation. Participation can be either voluntary or mandatory. In voluntary programs, the person or industry decides if she or he will participate, and then decides in what way to participate. Mandatory programs decide ahead of time who will participate and by what means they will participate (Jorquera, 1997). Most US episodic control programs allow voluntary-voluntary responses. For instance, if a person does decide to participate, she or he still has the opportunity to choose in what way to participate whether by foregoing driving or mowing the lawn or using less air conditioning or other measure(s). Companies can voluntarily choose to participate and have a variety of ozone reducing measures to choose from such as implementing a carpooling arrangement, allowing telecommuting, postponing landscaping activities for a day or two, and using less air conditioning among other measures.

During the 1996 Summer Olympic Games, Atlanta, Georgia implemented major voluntary transportation changes to avoid intolerable traffic delays that had been predicted by travel demand models. At the same time, Atlanta experienced ozone concentrations 10 to 20 percent lower than the summer 1996 average. Initially this was thought to be the result of reduced mobile source emissions from the extensive

transportation control measures that were carried out (GA EPD 1996). While traffic patterns and volumes did change during the Olympics, a later, more comprehensive study by Cambridge Systematics, Inc. (1997) concluded that no relationship could be established between transportation control measures implemented during the Olympics and lower ozone concentrations. Even though traffic volumes were reduced 10 to 19 percent at some locations in Atlanta, not enough data were collected, for a variety of reasons, to correlate emission reductions with ozone concentrations. Cambridge Systematics also concluded that meteorology was the more likely cause of low ozone concentrations. Most of the southeastern United States experienced lower than normal ozone concentrations during that time, and Atlanta's local reduction of ozone precursors would not have affected ozone concentrations across the entire southeast. Especially in the city of Birmingham, located west of Atlanta, ozone concentrations were 20 to 25 percent lower than normal. Atlanta's winds were out of the west for most of that period, indicating that Atlanta's emissions could not have impacted Birmingham's ozone concentrations and that meteorology was the cause of Atlanta's reduced ozone concentrations as well as those of the rest of the southeast. Cambridge Systematics reported:

> *"While the transportation strategies implemented during the Olympics were successful at reducing traffic from expected levels and pollutant levels were lower than normal during the Olympics, available air quality monitoring data are insufficient to identify a relationship between these changes with any certainty. In fact, meteorological factors affecting much of the southeast region of the United States appear to be the primary determinant of the reduced levels of ozone experienced in the Atlanta metropolitan area during the period of the Olympics."*

In mandatory participation programs, specific measures are usually required for the individual and for industries. The city of Santiago in Chile enforces an episodic control program for PM-10, particulate matter less than 10 micrometers in aerodynamic diameter (CONAMA, 1998). As PM-10 concentration levels rise in Santiago, environmental officials of the Comision Nacional del Medio Ambiente (CONAMA), the Chilean version of EPA, can call three increasingly stringent levels of episodic controls in to effect. The first level is an 'alert.' If PM-10 levels continue to rise, CONAMA calls a 'pre-emergency', and if levels rise even higher, CONAMA calls an 'emergency.' In the cold winter season of high PM-10 levels in Santiago, typically March through September in the southern hemisphere, PM-10 pollution is caused by mobile sources and by fuels burned for heating. In the winter, mobile sources are restricted every day in driving by two license plate digits. For instance on Monday, license plates ending in 1 and 2 can be on the road only if the vehicle has a catalytic converter. On Tuesday, vehicles with license plates ending in 3 and 4 are restricted unless they have a catalytic converter. Restrictions for the rest of the work week follow accordingly. Both private and public vehicles (i.e., city buses) without catalytic converters are subject to the restriction. When Santiago calls an 'alert', the normal two plus two more digits, for a total of four, are restricted from use. A 'pre-emergency' status dictates that six license plate digits stay off the road, and a full-fledged 'emergency' due to PM-10 concentrations requires eight license plate digit restrictions.

As a way to get around the regulation, some residents have two or more license plates and switch them according to the day of the week. In spite of the mandatory control measures that affect 20 percent of the driving population on any given day, some residents disobey the law and knowingly refuse to participate in the episodic control program. Their refusal indicates that voluntary episodic control programs will have trouble persuading people to participate, and that voluntary controls will be less reliable than mandatory controls for reducing ozone concentrations.

Industries in Santiago are subject to episodic controls also. Industries are ranked from highest to lowest in emissions with the highest emitter first. The three episodic levels require varying percent reductions in total citywide PM-10 emissions. Every time an 'alert' is called, the several largest emitters must completely shut down operations. In a 'pre-emergency,' the next several industries on the list must shut down too until a sufficient amount of emissions are reduced. Santiago vigorously enforces this episodic control program for industries. Emission reductions have yet to be quantified for the episodic control program. While Santiago's focus is PM-10, a similar episodic control program could be instituted for ozone precursors as well.

One problem with mandatory controls for mobile source emissions during a high ozone episode is the lack of public transportation in East Tennessee where public transit systems are minimal, at best. East Tennessee urban population centers are relatively small and located 120 to 150 kilometers apart, making it difficult for public transit systems to be

self-supporting. Knoxville, Tennessee, the most populous urban center in East Tennessee, spent $5.1 million in 1997 providing a bus system for the city. Buses transport 8,000 people per day in Knoxville, and ridership averages three percent of the population served (Knoxville Area Transit, 1998). In comparison, the city of Atlanta has a more extensive public transportation system in its Metropolitan Atlanta Rapid Transit Authority (MARTA). The 'city' of Atlanta covers Fulton and De Kalb Counties in this example, about 1,241,000 people and 804 square miles (MARTA, 1998). Average weekday total boarding runs 480,000 passengers on the MARTA bus/rail system. About 15 percent of Atlanta city residents claim to use MARTA every week, and 67 percent of area residents use MARTA sometime during the year (Haas Associates, 1998). With such an extensive public transit system in place, mandatory participation in an episodic control program is easier to require than in an area like East Tennessee where there are few alternative sources of transportation.

Types of Regulatory Programs

Command and control regulations typically require permanent, year-round control technologies. Most regulatory structures were designed for command-and-control style emission regulation and do not allow credit to be given to an area for emission reductions from voluntary actions like telecommuting or foregoing a trip or postponing lawn mowing. Without credit for their voluntary emission reductions, most areas do not bother to initiate them. However, one city has found a way to get credit for voluntary reductions that are implemented through a traditional command-and-control regulation. Tulsa,

Oklahoma has a Flexible Attainment Region (FAR) agreement with EPA. In the FAR, Tulsa has developed a series of response measures to be implemented if and when Tulsa experiences an exceedence of the ozone standard. Rather than lose its attainment designation, Tulsa implements a previously-agreed-upon list of control measures (command-and-control) to reduce ozone concentrations. If exceedences continue to occur, more stringent control measures are implemented. Some of the control measures are of the command and control style and are quantifiable and enforceable and can be given credit in the State's Implementation Plan (Oklahoma DEQ, 1995). An excerpt from the Memorandum of Agreement of the FAR states that agencies signing the agreement are committed to:

1. *The continued development, expansion and improvement of the highly successful voluntary Ozone Alert! Program as a control approach to maintaining National Ambient Air Quality Standards (NAAQS).*

2. *The development, implementation and refinement of RESPONSE (Real Environmental Strategies for Partners in Ozone Negation Systems) measures as quantifiable, enforceable revisions to the SIP (State Implementation Plan), illustrating a flexible, collaborative community response to maintaining the NAAQS.*

3. *The creation of the Tulsa Ozone Prevention Strategy to develop and evaluate methods which accurately identify sources and levels of pollution and predict its impact on the urban plume with an emphasis on formulating effective common sense control strategies within a specified airshed.*

Some of the RESPONSE measures of Tulsa's FAR include:

Substantially increase the number of businesses notified on Ozone Alert! Days.
Initiate phased implementation of the Regional Mobility Plan.
Implement a local Clean Fuel Fleets program (command and control).
Implement an employee commute options awareness program for businesses with twenty-five or more employees.
Expand access to ozone information through computer network systems.
Further reduce vehicle miles traveled on Ozone Alert! Days.

Create a smoking vehicle hotline.
Increase the number of public announcements about ozone.
Set up an ozone hotline.
Create mandated maximum 8.2 RVP gasoline and initiate the fuel pressure test (command and control).

In addition to command and control regulations, another method of controlling emissions is trading and banking of emission permits or allowances in a market-based program. Similar to the sulfur dioxide emissions trading scheme currently in place, a NO_x Budget Plan, using a cap-and-trade emission allowance program has been conceived as a method to reduce NO_x emissions in the Ozone Transport Region (OTR). The OTR includes 12 Northeastern states: Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York Pennsylvania, New Jersey, Maryland, Delaware, and Virginia. The NO_x Budget Plan sets an emission cap in the OTR for fossil fuel-fired boilers and indirect heat exchangers of 250 Million BTUs and greater, and electric generating units of 15 megawatts and greater (Farrell, Carter and Raufer, 1999). One problem of a cap-and-trade program is that it does not respond to episodic ozone events – when high ambient temperatures and high NO_x emissions from increased electricity demand for air conditioning occur simultaneously, creating the highest potential for ozone formation. Cap-and-trade does not guarantee healthful ozone levels because it cannot change its cap or allowable level of emissions quickly enough to reduce NO_x emissions and subsequent ozone levels. Long-term standards such as annual averages are better addressed by cap-and-trade programs than are short-term 1-hour and 8-hour standards.

Urban Airshed Model, Carbon Bond IV

The Urban Airshed Model is used to simulate photochemical processes in the atmosphere and predict concentrations of ozone and other compounds. UAM employs the continuity equation to handle emissions, transport, diffusion, chemical reactions, and removal processes. Temporal and spatial variability as well as varying reactivities of emissions are addressed in the model. General inputs to the model include meteorological data, emissions data and ambient air quality. These data are supplied via thirteen separate input files to UAM for a single simulation. Output from the model are 1-hour average concentrations of ozone in addition to several selected chemical species (USEPA June 1990).

Since the version of the model used in this study, UAM IV, was developed, another version has been created, UAM V. The earlier version, UAM IV, had been compiled by researchers at the University of Tennessee and was readily available for use. Rather than spend time and resources on preparing the newer version for use, UAM IV was used in this investigation. A study conducted by the South Coast Air Quality Management District (Mitsutomi, Zhang, Hogo, Morris and Myers, 1993) of UAM IV and UAM V compares results of the two models. A series of simulations were designed to display the effects of UAM V's enhancements which include deposition velocity, 3-dimensionally varying photolysis rates and a Plume-in-Grid option. The conclusions of the SCAQMD study are:

- *UAM-V is roughly equivalent to UAM-IV when the same modeling parameters are employed.*

- *The deposition velocities predicted by UAM-V were generally lower than UAM-IV deposition velocities. The NO deposition velocity was significantly lower than the UAM-IV estimation. Consequently, the regional ozone peak location moved further downwind.*

- *The utilization of three-dimensionally varying photolysis rates did not significantly affect surface ozone production; however, ozone production at higher altitude could increase.*

- *The Plume-in-Grid option did not affect regional peak ozone concentrations. Its effects were localized but apparent near the major NO_x point sources.*

Based on the conclusions of SCAQMD, the UAM IV results presented in this study are representative of the best computer simulation abilities available today. The results of using either model will be essentially the same under the conditions of this research.

Cost Analysis

Several measures are available to quantify the desirability of episodic controls as a policy tool in reducing ozone concentrations; among them are assessments of political, equity, technical and cost objectives. A cost analysis is employed in this research to determine the feasibility of various control methods specific to the East Tennessee Modeling Domain. In a simplified example, the costs of emission cuts from point sources that lead to achieving the ozone standard might be higher than costs of cutting emissions from mobile sources. Then again, mobile source emission cuts might be more costly than point source emission cuts. A cost analysis allows NO_x emission control methods with equivalent impact on ozone to be ranked by cost effectiveness in dollars ppb of ozone lowered.

COSTS OF NO_x CONTROL METHODS

Costs of Point Source NO_x Emission Controls

For point source controls, only mechanical removal technologies were considered while for mobile and area sources, behavior based voluntary emission reductions, or foregoing emissions, were also considered for reducing emissions. A removal technology has little effect on an industry's technical ability to produce its product, but foregoing emissions by foregoing production could affect an industry significantly, and costs of foregoing emissions could vary a great deal across industries. For instance, one production facility could forego emissions (i.e., production) on a high ozone day and make up the lost production during the night shift or on a weekend day. At another facility, production may be tied to contractual obligations, and the facility is already operating three shifts per day with no time to recoup lost production. In the latter case, foregoing emissions and production would cause more disruption and have a higher cost than would be incurred by the former facility.

Electricity generating plants, some of the largest emitters of NO_x in the ETMD, are unlikely to reduce power generation and forego NO_x emissions during a high ozone event, because high ambient temperatures go hand-in-hand with high ozone levels. An electricity generator would be operating at maximum production to meet public demand for electricity during a high ozone event and would be unable to meet power demand if it reduced production. Another control method, load switching, is also unlikely to occur in

the ETMD during a high ozone event. If one area experiences high ozone and high temperatures, the neighboring areas will too. Their power plants would be operating at capacity and have no power to spare for other areas. Neighboring electricity generators would be struggling to meet their own demand, and power would have to be transmitted in, possibly over several hundred miles, to meet east Tennessee demand. Load switching is not considered to be a workable option for reducing NO_x emissions while maintaining enough electrical power to meet public demand. For this reason, mechanical controls were chosen as the only method of reducing emissions from point sources.

NO_x removal efficiencies and cost effectiveness vary for each type of control technology, and some technologies are limited to certain types of boilers. Combustion controls reduce NO_x formation during the combustion process and include Gas-Switching, Low NO_x Burners, Overfire Air, Burners Out Of Service, Low Excess Air, and Biased Firing (USEPA, 1994). Low NO_x Burners with Overfire Air, in concert, can achieve as high as 40 to 50 percent reduction in NO_x emissions. Post-combustion controls reduce already-formed NO_x in the flue gas. Selective Non-Catalytic Reduction (SNCR) is a post-combustion control as is Selective Catalytic Reduction (SCR).

For point sources, the goal of NO_x emission reductions in this study was set at 70 percent. This level was chosen to reflect the recent SIP Call regulations promulgated by EPA that suggest reductions from electric utilities at this level in several eastern states (Federal Register, October 1998). The goal of 70 percent NO_x emission reductions is readily

achievable with SCR, a retrofit control technology. SCR is one of the few commercially available and reliable technologies today that can achieve 70 percent removal. It uses a bed of catalyst at a location downstream of the boiler to remove NO_x formed during combustion. Removal efficiencies range from 60 to 90 percent (NESCAUM/MARAMA, June 1998). SCR can be implemented on a seasonal basis or a shorter time period if bypass ductwork is part of the system. With bypass ductwork, boiler combustion gases can be routed through either the catalyst beds, or around the beds if desired. Extra ductwork is expensive however, and for retrofit systems, may require more space than is available. If bypass ductwork were available, SCR could be used on a daily or hourly basis, but if SCR is installed, it is unlikely to be used for only a few hours or days at a time.

Gas switching can also achieve 70 percent NO_x removal, depending on a boiler's firing system and system load. The retrofit costs per ton of NO_x removed are two to four times more than SCR. Switching a boiler's capability from burning coal to burning natural gas has the added benefits of lower sulfur dioxide (SO_2) emissions, particulate emissions and carbon dioxide (CO_2) emissions (OTAG, June 1996). On the down side, natural gas produces less heat per volume of combustion product and in some boiler configurations, the derate penalty is five to fifteen percent of maximum capacity. The derate penalty is highest in the summer time and ozone season. The penalty can be compensated for, though, by reduced need for auxiliary power to pulverize coal, blow soot and remove particulate matter (OTAG, June 1996).

Costs of Mobile and Area Source NO_x Emission Controls

Mobile and area sources are typically pursued by episodic control programs for voluntary emission reductions in addition to mandatory reductions. In this manner an episodic control program spreads the burden of attaining and maintaining the ozone standard from not only point sources but to mobile and area sources as well. Many cities promote voluntary emission reductions by encouraging less driving and other NO_x emitting activities. It may be less disruptive to society for individuals to forego driving for a day or forego mowing the lawn than it is to change a manufacturer's production schedule. Even though the cost to an individual of participating in voluntary reductions is unique, an approximation of the cost can be made.

Opportunity cost of time spent in activities to reduce NO_x emissions is regarded in this study in the same manner as time spent in recreation and, as such, has a dollar value assigned to it. Travel cost models have long been used by economists as a means to find the value of the opportunity cost of time spent in recreational activities or at a recreational site. Time spent traveling to and from the recreational site or activity is included as part of the opportunity cost of doing that activity. Travel time is used in the cost calculations of this study to estimate the opportunity cost of a person's time spent in activities intended to reduce NO_x emissions and ozone concentrations as opposed to spending that time in another manner.

Conflicting opinions exist about the proper value of the opportunity cost of time in travel models. A typical approximation of opportunity cost of recreational time is some fraction of the wage rate; one-third is a commonly used value (Shaw and Feather, November 1999). Shaw and Feather present a short history of the one-third wage rate fraction. It may have been introduced by Beesley (1965) in relation to commuting time. Cesario (1976) claimed it was "an ad hoc approach." Yet another theory is that one-third represents a correction for not using the after tax wage rate (McConnell and Strand, 1982). The 1983 Principles and Guidelines of the U.S. Water Resources Council continues to use one-third of the wage rate for opportunity cost of time.

According to McKean, Johnson and Walsh, (1995) it is earned income, not the wage rate, that is the measuring stick for opportunity cost of time. Yet they acknowledge that for students, who are investing in the future but have little present income, earned income can underestimate opportunity costs, and for wealthy people, whose income may require little of their time, it can overestimate opportunity costs.

Other researchers claim that "the wage does not necessarily reveal anything about the shadow value of discretionary leisure time, either as an upper or lower bound" (Larson, Shaikh, Loomis, 1997). As in the case of a person who must work fixed hours and enjoys an activity that, to engage in, requires a time block of several hours, the value of the person's time may be unrelated to her wage rate (Shaw, 1992). For instance, white water kayaking necessitates that the kayaker travel to the river, kayak, and travel home, a

minimum time block of four hours for the average east Tennessean and preferably longer for many kayak enthusiasts. The stereotypical kayaker is in her twenties and not yet at the height of her earning potential. In such a case, the kayaker places high value on free time, but the opportunity cost of her time, if set equal to her wage rate or a fraction thereof, is much less. In a contrasting example, an individual with no market income does not always have low opportunity cost of time. An unemployed individual may be vigorously looking for a job, may be involved in volunteer work in the community, or may be on sabbatical. At first glance, the opportunity cost of time of these individuals appears to be low because the wage rate is low but, upon closer study, is very different. So for a variety of reasons, the wage rate may be higher or lower than the actual opportunity cost of time.

The timing of activities to reduce NO_x emissions has an effect on opportunity cost, and as such, opportunity cost can be a nonlinear function of the wage rate (Smith, Desvouges, McGiveney, 1983). A pleasure trip to the library could be easily put off until the next day for an individual. Similarly, cooking inside instead of grilling outside that day could have a low opportunity cost of time. Contradicting those examples is the single parent with an 8:00 meeting at work, who must take his child to day care, allocating forty extra minutes in the morning and in the evening to take public transportation from home to day care to work and back. The opportunity cost of time for the parent is higher in this instance because of time constraints on when he is allowed, or required, to participate in episodic controls. If the foregone driving could be moved to a weekend day that had no

fixed working hours, the opportunity cost would be lower. Timing of the NO_x reduction activity can affect its opportunity cost.

Participation in episodic controls via mobile and area source emission reductions may have a negative opportunity cost, in other words, people may want to participate; they may be willing to pay to participate. In a study of the costs of recycling household waste, Jakus, Tiller and Park (1996) present an economic model "in which recycling is observed even in the absence of monetary incentives, a common occurrence in many communities." This theory of voluntary public participation in environmental measures, fueled by altruistic motives, is the same as that of episodic controls. Contrary to an individual bearing a cost to implement mobile and area source NO_x controls, he may gain utility from participating, earning a 'warm and fuzzy feeling' by engaging in NO_x emission reduction activities.

An array of opportunity costs and, conversely, utility enhancing outcomes are possible for an individual or a company from participating in an episodic control program. This study quantifies and estimates some of these opportunity costs and uses the estimates in analyzing the cost effectiveness of episodic control programs.

Acid Deposition

Episodic controls endeavor to reduce emissions for a short time, beneficial especially when an area is trying to meet a short term standard such as the 1-hour average ozone

NAAQS. In the longer term, NO_x emissions contribute to acid deposition, a serious and continuing problem in the ETMD, especially in the centrally located Great Smoky Mountains National Park. Short-term, temporary NO_x controls do not alleviate acid deposition problems and can provide a false sense of environmental security by allowing the public to believe their actions in episodic control programs fully solve the problems caused by deposition of ozone and its precursors.

3. METHODOLOGY

A method of evaluating episodic controls was necessary to determine if they were effective and cost-effective tools for reducing ozone concentrations. A cost analysis was performed for several control technologies and methods to gage their cost effectiveness. The effectiveness of episodic controls on ozone concentrations was predicted using the Urban Airshed Model (UAM) with Version IV of the Carbon-Bond Chemical Mechanism (CB-IV). EPA accepts this model for predicting urban ozone concentrations. In fact, EPA states in the UAM User's Guide, "Because the UAM accounts for spatial and temporal variations as well as differences in the reactivity (speciation) of emissions, it is ideally suited for evaluating the effects of emission control scenarios on urban air quality...That is, the model will calculate hourly ozone patterns likely to occur under the same meteorological conditions as the base case" (USEPA, June 1990).

UAM requires extensive data input files to generate the ozone predictions. The necessary data are arranged into thirteen final input files:

AIRQUALITY
BOUNDARY
CHEMPARAM
DIFFBREAK
EMISSIONS
METSCALARS
PTSOURCE
REGIONTOP
SIMCONTROL
TEMPERATUR
TERRAIN
TOPCONC, and
WIND

Each of these files is discussed in the following pages. The four output files generated by UAM for this analysis were:

TRACE
AIRQUALOUT
OUTPUT, and
AVERAGE.

UAM was run on a Digital Equipment Corporation (DEC) alpha box, DEC 3000 with a VAX/VMS 6.1 operating system. Data were stored on magnetic tapes.

Matrix of Modeling Scenarios

A matrix of modeling scenarios was developed to represent possible NO_x emission reductions due to an episodic control program for point, area and mobile sources, and is shown in Table 3-1. One scenario was designed to simulate normal conditions with all sources operating at normal capacity. This was the base case, run for each day, and it established the baseline ozone levels in the ETMD. For the elevated point sources and TVA power plants, NO_x reduction targets were set at 70 percent to emulate EPA's SIP Call ruling (Federal Register, October 1998) that suggest NO_x reductions of 60 to 70 percent for electricity generating units. The SCR control technology can consistently achieve 70 percent reduction; 90 percent is claimed for some boilers but is not as consistent a removal efficiency as is the 70 percent level. To reflect the new regulation and increasingly common SCR control technology, the point source removal level for NO_x was fixed at 70 percent. NO_x emission reductions from the three TVA power plants:

Table 3-1. Matrix of UAM Scenarios of NO_x Reductions for Episodic Controls.

	NO_x Emission Reductions			
All Sources	Base Case, All Sources Operating at Normal Levels			
Elevated Point Sources	70% at 3 TVA Utilities	70% at Kingston Power Plant	70% at Bull Run Power Plant	70% at All Elevated Point Sources
Area and Mobile Sources	10% of Area and Mobile Sources in Knox County and Seven Contiguous Counties*	30% of Area and Mobile Sources in Knox County and Seven Contiguous Counties*	50% of Area and Mobile Sources in Knox County and Seven Contiguous Counties*	

* Seven contiguous counties are: Anderson, Union, Grainger, Jefferson, Sevier, Blount and Loudon.

Kingston, Bull Run, and John Sevier Power Plants, were reproduced in one scenario, 70% at all 3 TVA Utilities, to establish their impact on ozone concentrations. VOC emissions were not changed in this scenario, or any other scenario. Next, two TVA power plants, Kingston and Bull Run Power Plants, had their NO_x emissions reduced in separate scenarios to determine their individual impacts on ozone concentrations. The third TVA plant, John Sevier Power Plant, did not have its emission reductions modeled individually. It is located close to the edge of the modeling domain, and its plume blows out of the modeling domain, literally off the map, because of the meteorological conditions chosen for the study. To assess the impact of other point sources in addition to TVA power plants, a fourth scenario was modeled, 70% of All Elevated Point Sources. In this scenario, all elevated point sources in the ETMD with plume heights above the first level (50 meters) had their NO_x emissions cut 70 percent in order to predict their effect on ozone.

Area and mobile source NO_x emission reductions were simulated at three levels, 10%, 30% and 50% of Area and Mobile Sources in Knox County and Seven Contiguous Counties. These percentages were selected to cover the full range of emission reductions likely to occur in an episodic control program. A hundred percent reduction in NO_x emissions is theoretically possible for mobile sources, but is an unrealistic value. A media outreach program, despite a large effort, may not reach every person. Even if the outreach program were successful in contacting every individual, a few vehicles might be on the road anyway as evidenced by behavior in the worst snow and ice storms; a few

vehicles are on the road in spite of the physical barriers to safe driving. People are less likely to stay off the roads in the summertime, when tempting travel and recreational pleasures like hiking, fishing and skiing are available. The region of area and mobile source NO_x emission reductions was set to represent Knox County and its surrounding counties that could, some day, be declared nonattainment and have to work together to attain the ozone standard.

Selection of Modeled Days

Choosing the days for modeling involved several steps. Meteorology from days with recorded high ozone concentrations was desired in order to show the possible effects of episodic controls. To find which days had highest ozone, raw monitoring data from 1993, 1994 and 1995 were requested of EPA through the Freedom of Information Act and were supplied by EPA Region IV for the thirteen monitoring stations located in east Tennessee. The thirteen stations are listed in Table 3-2.

The raw data computer files from EPA of high ozone concentrations were transformed from horizontal listings of concentrations (one row for a season of concentrations) to vertical listings, one column for each monitor. These raw data files had many missing data, for instance, the Anderson County file lacked every 11:00 to 12:00 PM hour (hour 2300) on every day. EPA had flagged the missing value by insertion of 9999 or other similar numbers (i.e., 9995, 9996, 9997 and 9998).

Table 3-2. Ozone Monitors in East Tennessee.

State	County	Site	County Name	Monitor Owner	Location
47	001	0101	Anderson	Tennessee	Freels Bend Study Area Melton Lake
47	009	0101	Blount	NPS	Look Rock
47	009	0102	Blount	NPS	Cades Cove
47	0011	0004	Bradley	TVA	1815 Pine Road, Georgetown, TN
47	025	8001	Claiborne	Tennessee	Route 1, Box 52, Speedwell, TN
47	065	0028	Hamilton	Hamilton Co.	Volunteer Army Ammunition Plant
47	065	1011	Hamilton	Hamilton Co.	Ridgetrail Road
47	089	0001	Jefferson	Tennessee	Nances Grove, Nances Ferry Road
47	093	0021	Knox	Knox Co.	9315 Rutledge Pike, Mascot, TN
47	093	1020	Knox	Knox Co.	4625 Mildred Drive
47	155	0101	Sevier	NPS	Cove Mountain
47	155	0102	Sevier	NPS	Clingman's Dome
47	163	2002	Sullivan	Tennessee	Hill Road, SLAMS Ozone Site

When calculating the 8-hour rolling average, the numeric flag 9999 was read as 9999 parts per billion (ppb) which created false, high concentrations beginning at 5:00 PM each day. To account for this idiosyncrasy of the data files, a Matlab program was written that interpolated values for missing data. Up to three consecutive missing hours were interpolated. Four or more hours of missing data were left as missing.

Eight-hour rolling averages were then calculated from the monitoring data. If, with the interpolated values, 8 hours of consecutive data were not available, those fewer-than-8 hours were not included in the 8-hour average analysis of monitoring data. This may have left out a few high concentrations, but it was better to leave them out than interpolate half or more of the hourly values of an 8-hour average. The calculated 8-hour averages were then sorted from highest to lowest, and the highest values were analyzed for each monitor.

Meteorological data for that day were also analyzed. Surface meteorological data from the National Weather Service station at McGhee-Tyson Airport (station 13891) in Alcoa, Tennessee and close to Knoxville, Tennessee were considered most representative of the Knoxville and East Tennessee area. Upper air meteorological data collected at the Nashville International Airport (station 13897) were used. Analysis included the magnitude of the highest value for each monitor, month of occurrence, location of monitor, high temperature for the day, and wind direction and speed.

The Jefferson County monitor was chosen as representative of metropolitan Knoxville emissions since the monitor was located specifically to capture summertime, afternoon, 20 kilometers downwind-of-the-Central-Business-District ozone concentrations. The monitor location was required by EPA regulations. Not surprisingly, the Jefferson County monitor recorded the highest 8-hour average ozone concentration during the 1993-95 ozone seasons in East Tennessee, 117 ppb at 1900 hours on July 20, 1995.

This day was chosen for modeling as a one-day ozone event. Not only is the concentration high as shown in Table 3-3, but the temperature is 95° F, wind speeds are low, and wind directions are out of the southwest which is the prevailing, afternoon, summertime wind direction. Tables 3-3 and 3-4 display the 1-hour monitored average, 8-hour calculated average and meteorological conditions for the selected days.

The Jefferson County monitor also recorded a series of high ozone days in July 1993. The 24th, 25th, and 26th of July were chosen for modeling because of their high ozone concentrations and for their meteorological characteristics listed in Table 3-4. These 3 days had a total of 23 calm hours which contributed to the high ozone concentrations. Also contributing were winds blowing generally out of the southwest during the day at low speeds, and high temperatures of 97° and 98° F. The wind trajectories for the selected days were drawn on clear mylar overlaying United States Geological Survey 7.5 minute topographic quadrangle maps. Winds on July 26, day 3 of the 3-day event, began close to Lenoir City in the southwest with 9 calm hours and slowly moved northeast, passing over

Table 3-3. July 20, 1995, McGhee-Tyson Airport Meteorological Data and Jefferson County Monitor Concentrations.

1-Day Event

Weather Station Number	Year	Month	Day	Hour	Temp (°F)	Compass Direction (x10)	Wind Speed (m/s)	Wind Speed (m/hr)	1-Hour Average Conc. (ppb)	8-Hour Average Conc. (ppb)
13891	95	7	19	0	71	36	1.5	5561	55	63
13891	95	7	19	1	69	0	Calm	Calm	46	60
13891	95	7	19	2	67	0	Calm	Calm	33	56
13891	95	7	19	3	66	36	2.1	7415	27	51
13891	95	7	19	4	64	36	2.1	7415	17	45
13891	95	7	19	5	66	2	2.1	7415	16	40
13891	95	7	19	6	65	3	2.1	7415	16	34
13891	95	7	19	7	69	3	1.5	5561	27	30
13891	95	7	19	8	73	5	2.1	7415	49	29
13891	95	7	19	9	77	4	3.6	12976	64	31
13891	95	7	19	10	82	3	3.1	11123	79	37
13891	95	7	19	11	84	9	3.6	12976	82	44
13891	95	7	19	12	86	5	3.1	11123	85	52
13891	95	7	19	13	87	4	3.1	11123	90	62
13891	95	7	19	14	89	9	3.1	11123	94	71
13891	95	7	19	15	89	4	4.1	14830	97	80
13891	95	7	19	16	89	2	2.1	7415	88	85
13891	95	7	19	17	90	1	2.6	9269	88	88
13891	95	7	19	18	88	33	2.1	7415	84	88
13891	95	7	19	19	85	36	2.1	7415	83	89
13891	95	7	19	20	80	0	Calm	Calm	74	87
13891	95	7	19	21	78	0	Calm	Calm	64	84
13891	95	7	19	22	75	0	Calm	Calm	56	79
13891	95	7	19	23	71	0	Calm	Calm	*9996	73
13891	95	7	20	0	73	0	Calm	Calm	45	68
13891	95	7	20	1	71	36	1.5	5561	34	61
13891	95	7	20	2	69	32	1.5	5561	32	55
13891	95	7	20	3	67	0	Calm	Calm	30	48
13891	95	7	20	4	68	2	1.5	5561	24	42
13891	95	7	20	5	67	32	1.5	5561	21	37
13891	95	7	20	6	68	1	1.5	5561	21	32

Table 3-3. Continued.

1-Day Event										
Weather Station Number	Year	Month	Day	Hour	Temp (°F)	Compass Direction (x10)	Wind Speed (m/s)	Wind Speed (m/hr)	1-Hour Average Conc. (ppb)	8-Hour Average Conc. (ppb)
13891	95	7	20	7	69	6	1.5	5561	*9995	30
13891	95	7	20	8	73	3	2.1	7415	*9995	29
13891	95	7	20	9	78	6	2.6	9269	48	31
13891	95	7	20	10	84	28	2.1	7415	71	36
13891	95	7	20	11	87	24	2.6	9269	85	42
13891	95	7	20	12	91	27	2.6	9269	105	53
13891	95	7	20	13	93	23	3.6	12976	122	65
13891	95	7	20	14	93	22	4.6	16684	120	78
13891	95	7	20	15	95	23	3.1	11123	127	90
13891	95	7	20	16	95	18	4.1	14830	132	101
13891	95	7	20	17	94	24	4.1	14830	122	110
13891	95	7	20	18	94	23	3.1	11123	106	115
13891	95	7	20	19	90	31	2.1	7415	99	117
13891	95	7	20	20	83	0	Calm	Calm	96	116
13891	95	7	20	21	79	0	Calm	Calm	81	110
13891	95	7	20	22	79	0	Calm	Calm	63	103
13891	95	7	20	23	78	20	2.1	7415	*9996	95

- EPA flagged a missing value by insertion of 9999 or other similar numbers (i.e., 9995, 9996, 9997 and 9998).

Table 3-4. July 24, 25 and 26, 1993, M'Ghee-Tyson Airport Meteorological Data and Jefferson County Monitor Concentrations.

3-Day Event

Weather Station Number	Year	Month	Day	Hour	Temp (°F)	Compass Wind Direction (x10)	Wind Speed (m/s)	Wind Speed (m/hr)	1-Hour Average Conc. (ppb)	8-Hour Average Conc. (ppb)
13891	93	7	23	0	81	4	2.6	9268.8	55	63
13891	93	7	23	1	80	34	1.5	5561.3	48	60
13891	93	7	23	2	78	36	2.1	7415.0	47	58
13891	93	7	23	3	77	2	3.1	11122.6	51	57
13891	93	7	23	4	76	5	2.1	7415.0	48	55
13891	93	7	23	5	75	3	2.1	7415.0	43	52
13891	93	7	23	6	74	1	2.1	7415.0	37	49
13891	93	7	23	7	76	1	2.1	7415.0	38	46
13891	93	7	23	8	78	6	1.5	5561.3	50	45
13891	93	7	23	9	83	0	Calm	Calm	63	47
13891	93	7	23	10	87	32	1.5	5561.3	84	52
13891	93	7	23	11	90	4	2.6	9268.8	95	57
13891	93	7	23	12	93	32	2.1	7415.0	86	62
13891	93	7	23	13	94	30	2.6	9268.8	90	68
13891	93	7	23	14	95	26	3.1	11122.6	106	76
13891	93	7	23	15	95	27	2.1	7415.0	104	85
13891	93	7	23	16	96	29	3.1	11122.6	94	90
13891	93	7	23	17	94	27	3.1	11122.6	80	92
13891	93	7	23	18	93	27	2.1	7415.0	73	91
13891	93	7	23	19	91	32	2.1	7415.0	68	88
13891	93	7	23	20	86	32	1.5	5561.3	62	85
13891	93	7	23	21	84	3	1.5	5561.3	61	81
13891	93	7	23	22	83	1	2.6	9268.8	62	76
13891	93	7	23	23	81	0	Calm	Calm	*9996	69
13891	93	7	24	0	81	36	2.1	7415.0	45	63
13891	93	7	24	1	77	0	Calm	Calm	44	59
13891	93	7	24	2	77	2	2.1	7415.0	41	55
13891	93	7	24	3	76	0	Calm	Calm	42	51
13891	93	7	24	4	75	0	Calm	Calm	35	48
13891	93	7	24	5	73	0	Calm	Calm	33	44

Table 3-4. Continued.

3-Day Event										
Weather Station Number	Year	Month	Day	Hour	Temp (°F)	Compass Wind Direction (x10)	Wind Speed (m/s)	Wind Speed (m/hr)	1-Hour Average Conc. (ppb)	8-Hour Average Conc. (ppb)
13891	93	7	24	6	74	0	Calm	Calm	29	40
13891	93	7	24	7	76	7	1.5	5561.3	36	38
13891	93	7	24	8	81	14	2.1	7415.0	55	39
13891	93	7	24	9	84	21	3.1	11122.6	76	43
13891	93	7	24	10	87	24	3.1	11122.6	89	49
13891	93	7	24	11	91	32	2.6	9268.8	97	56
13891	93	7	24	12	93	23	3.1	11122.6	93	64
13891	93	7	24	13	95	32	2.1	7415.0	95	71
13891	93	7	24	14	97	27	2.1	7415.0	96	80
13891	93	7	24	15	93	30	2.6	9268.8	102	88
13891	93	7	24	16	94	29	2.6	9268.8	112	95
13891	93	7	24	17	93	27	1.5	5561.3	80	96
13891	93	7	24	18	91	29	1.5	5561.3	76	94
13891	93	7	24	19	89	0	Calm	Calm	73	91
13891	93	7	24	20	87	25	2.1	7415.0	69	88
13891	93	7	24	21	83	0	Calm	Calm	70	85
13891	93	7	24	22	80	11	1.5	5561.3	64	81
13891	93	7	24	23	79	0	Calm	Calm	*9996	75
13891	93	7	25	0	78	7	3.1	11122.6	48	67
13891	93	7	25	1	77	0	Calm	Calm	43	62
13891	93	7	25	2	76	36	1.5	5561.3	38	58
13891	93	7	25	3	75	0	Calm	Calm	35	53
13891	93	7	25	4	74	0	Calm	Calm	31	48
13891	93	7	25	5	75	0	Calm	Calm	20	42
13891	93	7	25	6	73	0	Calm	Calm	22	37
13891	93	7	25	7	77	30	1.5	5561.3	24	33
13891	93	7	25	8	80	23	2.1	7415.0	47	33
13891	93	7	25	9	83	33	2.1	7415.0	75	37
13891	93	7	25	10	87	24	3.1	11122.6	96	44
13891	93	7	25	11	89	32	2.1	7415.0	105	53
13891	93	7	25	12	92	27	3.1	11122.6	107	62

Table 3-4. Continued.

3-Day Event										
Weather Station Number	Year	Month	Day	Hour	Temp (°F)	Compass Wind Direction (x10)	Wind Speed (m/s)	Wind Speed (m/hr)	1-Hour Average Conc. (ppb)	8-Hour Average Conc. (ppb)
13891	93	7	25	13	94	31	3.6	12976.3	111	73
13891	93	7	25	14	95	25	2.1	7415.0	121	86
13891	93	7	25	15	97	25	3.1	11122.6	106	96
13891	93	7	25	16	86	29	2.1	7415.0	67	98
13891	93	7	25	17	86	3	2.6	9268.8	64	97
13891	93	7	25	18	87	9	3.6	12976.3	69	94
13891	93	7	25	19	87	18	2.6	9268.8	75	90
13891	93	7	25	20	84	12	2.6	9268.8	70	85
13891	93	7	25	21	83	23	3.1	11122.6	66	80
13891	93	7	25	22	80	25	2.1	7415.0	58	72
13891	93	7	25	23	79	31	2.1	7415.0	*9996	65
13891	93	7	26	0	76	0	Calm	Calm	45	62
13891	93	7	26	1	77	0	Calm	Calm	31	58
13891	93	7	26	2	75	0	Calm	Calm	24	53
13891	93	7	26	3	74	0	Calm	Calm	28	47
13891	93	7	26	4	73	0	Calm	Calm	15	40
13891	93	7	26	5	72	0	Calm	Calm	16	34
13891	93	7	26	6	72	0	Calm	Calm	15	28
13891	93	7	26	7	74	0	Calm	Calm	34	26
13891	93	7	26	8	79	0	Calm	Calm	47	26
13891	93	7	26	9	82	23	2.6	9268.8	60	30
13891	93	7	26	10	86	23	2.1	7415.0	79	37
13891	93	7	26	11	90	16	2.6	9268.8	93	45
13891	93	7	26	12	94	13	2.1	7415.0	92	54
13891	93	7	26	13	95	30	2.6	9268.8	102	65
13891	93	7	26	14	97	32	2.1	7415.0	111	77
13891	93	7	26	15	98	24	3.1	11122.6	96	85
13891	93	7	26	16	98	24	2.6	9268.8	109	93
13891	93	7	26	17	98	24	2.6	9268.8	108	99
13891	93	7	26	18	97	25	2.6	9268.8	100	101
13891	93	7	26	19	93	30	2.6	9268.8	92	101
13891	93	7	26	20	90	27	2.6	9268.8	66	98

Table 3-4. Continued.

3-Day Event										
Weather Station Number	Year	Month	Day	Hour	Temp (°F)	Compass Wind Direction (x10)	Wind Speed (m/s)	Wind Speed (m/hr)	1-Hour Average Conc. (ppb)	8-Hour Average Conc. (ppb)
13891	93	7	26	21	88	31	1.5	5561.3	54	92
13891	93	7	26	22	85	0	Calm	Calm	48	84
13891	93	7	26	23	82	2	2.6	9268.8	*9996	78

- EPA flagged a missing value by insertion of 9999 or other similar numbers (i.e., 9995, 9996, 9997 and 9998).

the downtown Knoxville area about 2:00 to 3:00 PM. The 20 hours preceding the maximum concentration (101 ppb as an 8-hour average at 1800 hours) include 9 calm hours. The trajectory tracks along the interstate, beginning southwest of Knoxville at the split of the combined roadways of Interstates 40/75, and moves northeast to the Jefferson County monitor. Days 1 and 2 of the 3-day event (July 24 and July 25) also have meteorological conditions favorable to ozone formation: high temperature, low wind speed and winds out of the southwest.

These days have prime high-ozone meteorological conditions and were chosen for modeling purposes because if any changes in ozone concentrations due to local episodic controls were to be seen, they would occur on days with low wind speeds and many calm hours causing emissions to remain nearby and within the modeling domain.

The days of the 3-day event fall, respectively, on Saturday, Sunday and Monday. The days of the week on which the event occurs are irrelevant, however. These days were chosen because they have meteorological conditions favorable to ozone formation (i.e., high temperatures, low wind speeds, winds out of the Southwest, and several calm hours.) The emissions used in the modeling were representative of a weekday when high ozone concentrations are more likely to occur. While emissions are linked to a specific day of the week, variations in meteorology are not and can occur on any day of the week. Use of these meteorological conditions did not link the modeling results to any specific day of the week. This research premise does not seek to calibrate UAM or compare modeled

concentrations with measured data. The premise is to perform a sensitivity analysis of the Urban Airshed Model, to show what changes in ozone concentrations are possible with episodic controls. Therefore, it is acceptable to use weekday emissions with meteorology of either a weekday or weekend.

Preparation of UAM Input Data

AIRQUALITY

The AIRQUALITY file established the initial concentration in the modeling domain of all chemical species at the beginning of a model run for each cell. EPA default concentrations were used for the 1-day event, July 20, 1995, and for the first day of the 3-day event, July 24, 1993. For days 2 and 3 of the 3-day event, the output file from the previous day was used to set the initial concentration in the domain. For instance, to run a scenario for July 25, 1993, the AIRQUALOUT file, generated as an UAM output file and also discussed in this chapter, was substituted for the AIRQUALITY binary input file to UAM. The July 24, 1993 AIRQUALOUT binary file contained cell-by-cell, calculated concentrations for each specie at the end of the day on July 24, making it more appropriate than EPA default valued for setting current concentrations for the next day July 25, 1993.

To create the binary input file for UAM, a control file was prepared that set the initial concentrations in the domain. One file name was AQ_DEF_JUL2493_BASE.CTL. A command file was created that called in the control file, assigned names to the output

binary and ASCII files and executed the program AIRQUL.EXE. The binary output file AQ_DEF_JUL2493_BASE.BIN was an input file to UAM. A sample file is shown in Appendix A.

BOUNDARY

The BOUNDARY file was adapted from a previous modeling study. This file set the concentration of each specie blowing into the modeling domain. Concentrations for each specie were set for each cell along the edge of the domain. Concentrations can vary hour by hour. The concentration of each specie was set at the EPA default value, the same value as used in the TOPCONC file. A control file was prepared of the concentration of each specie for each hour. A command file was then run that called in the control file, assigned file names to the output binary and ASCII files and executed the BNDARY.EXE program. The binary file was input to UAM. Appendix A contains a sample control file.

CHEMPARAM

The CHEMPARAM file passes chemical parameters to UAM. It contains the number of species, number of reactions, reactivities, activation energy and reference temperature. These values were all set to EPA default values. A control file of parameters was prepared. A command file then called in the control file, assigned names to the output binary and ASCII files and executed the CHEMPARAM program. The binary file CPREP_JUL2493.BIN was input to UAM. Appendix A has a sample file.

DIFFBREAK

DIFFBREAK data define the thickness of the layers of the domain for UAM. The diffusion break is the level in the atmosphere below which air is well mixed and has similar diffusion characteristics (USEPA, June 1990, Volume II). The following procedure was used to determine the heights of the diffusion breaks for each day.

Upper air meteorological data from the National Weather Service station 13897 in Nashville, Tennessee were obtained and the sounding elevation profile (Y axis) was plotted against temperature (X axis). This was done twice a day, in the morning and evening. From surface meteorological data, the maximum temperature of the day and the minimum temperature between 0200 and 0600 hours local time were recorded. From the minimum temperature mark on the on the x-axis, the adiabatic lapse rate (-1° C per 100 meters) was plotted. The same was plotted for the maximum temperature. The elevations where the two lines of adiabatic lapse rates crossed the sounding profile were recorded as the morning and afternoon mixing heights or diffusion breaks.

To set the height of the diffusion break at each hour of the day, the profile given in the DIFFBREAK chapter of EPA's user's manual was followed (USEPA, June 1990, Volume II, page 159). This profile is a schematic illustration of the original RAMMET interpolation procedures. The RAMMET profile divides a day into four periods: midnight to sunrise, sunrise to 1400 hours, 1400 hours to sunset, and sunset to sunrise

with the lowest diffusion break during midnight to sunrise and the highest diffusion break 1400 hours to sunset. Other hourly values were interpolated.

These diffusion break heights were typed into a file named, as an example, DBDATA_JUL2593_5LAYER.IN. A control file was prepared for DIFFBREAK. In this example, it was called PDFSNBK.CTL. Also a command file was prepared that called in the DBDATA_JUL2593_5LAYER.IN file, the PDFSNBK.CTL file, assigned the name of the output file DBPACK.DAT, and executed PDFSNBK.EXE. The output file DBPACK.DAT was renamed DIFFBREAK.IN. The executable file DFSNBK.EXE was run. Next typed in were the filenames:

DIFFBREAK.IN
DIFFBREAK.ASC
DIFFBREAK.BIN

The executable program generated the binary output file called DIFFBREAK.BIN, ready for input to UAM. Appendix A contains an example file.

EMISSIONS

Creating the emissions file of area, mobile, biogenic and low-level point sources required several steps. The initial collection and processing of emissions data for UAM is an intensive effort requiring thousands of hours of labor. Emissions files are prepared through a series of pre-processing steps called modules. The emissions files that had been prepared for a previous study were used and modified for this study. Modifications were made to emissions files using the TMPRL, GRDEM and MRGUAM modules.

The matrix of modeling scenarios included a 50, 30 and 10 percent cut in area and mobile source emissions. To change area and mobile source emissions, emissions files had to be modified 3 modules before the final file. The MRGUAM module generated the final file. The file before that was generated by the GRDEM module and the file before that by the TMPRL module. The GRDEM mobile emissions file was found to have no emissions after 10:00 A.M. The cause was found to be in the MADJIN file of the TMPRL module, which contains hourly temperature adjustment factors for on-road motor vehicle emissions. The packet MVTMPRL had values only for 10 hours, not 24 hours. This packet was eliminated, forcing TMPRL to use default diurnal profiles to allocate emissions from on-road motor vehicles. The TMPRL binary file then had 24 hours of emissions. An input file example sequence to the TMPRL module was:

TPL_25J93_USERIN.IN
CHMSPL_JUL25_MOBILE.EMBR
MOBSCCTP.UXR
MOBTMPRF.UDT
M5A_RMADJIN.OUT

Twenty spaces preceded each input and output filename. The output files generated were:

TMPRL_25J93_MOBILE.EMBR
TMPRL_25J93_MOBILE.ERR
TMPRL_25J93_MOBILE.MS

The GRDEM module was run using the revised TMPRL_25J93_MOBILE.EMBR file to create a GRDEM_25J93_MOBILE.EMBR file. The GRDEM module input file sequence was:

GRDEM_JUL25_USERIN.IN

TMPRL_25J93_MOBILE.EMBR
SCCSRG_ETN.XRF
SURROGAT_ETN.XRF
LNKBLK.DAT

Again, 20 spaces preceded each input and output filename. The output files were:

GRDEM_25J593_MOBILE.EMBR
GRDEM_25J593_MOBILE.ERR
GRDEM_25J593_MOBILE.MSG.

Within a specified grid, emissions were reduced by 50, 30 and 10 percent. This was done by a FORTRAN program written specifically for this purpose and called ADJ_GRDEMIS_CAROL.EXE. The grid of reduced emissions is shown in Figure 3-1. The grid coordinates were selected to cover the seven counties contiguous to Knox County. Mobile and area source emissions inside the grid were reduced. Emissions outside the grid were not reduced because the media outreach of an episodic control program would likely not be effective outside the metropolitan area of Knoxville. Mobile and area source emissions were reduced while the file was in ASCII format. The GRDEM files for mobile and area sources were converted back to binary and input to the MRGUAM module. The MRGUAM module combines the temporally and spatially allocated GRDEM files of biogenic, area, mobile and elevated point sources.

The biogenic file simulated a sunny day with no cloud cover at all. This simulation was done by running the UAM-BEIS2 module with zero cloud cover in the SURMET file. Ahmed presents a discussion of this in "Impacts of Hypothetical NO_x Sources on Ozone Formation in East Tennessee," (Ahmed, 1996). The input files to the MRGUAM module were:

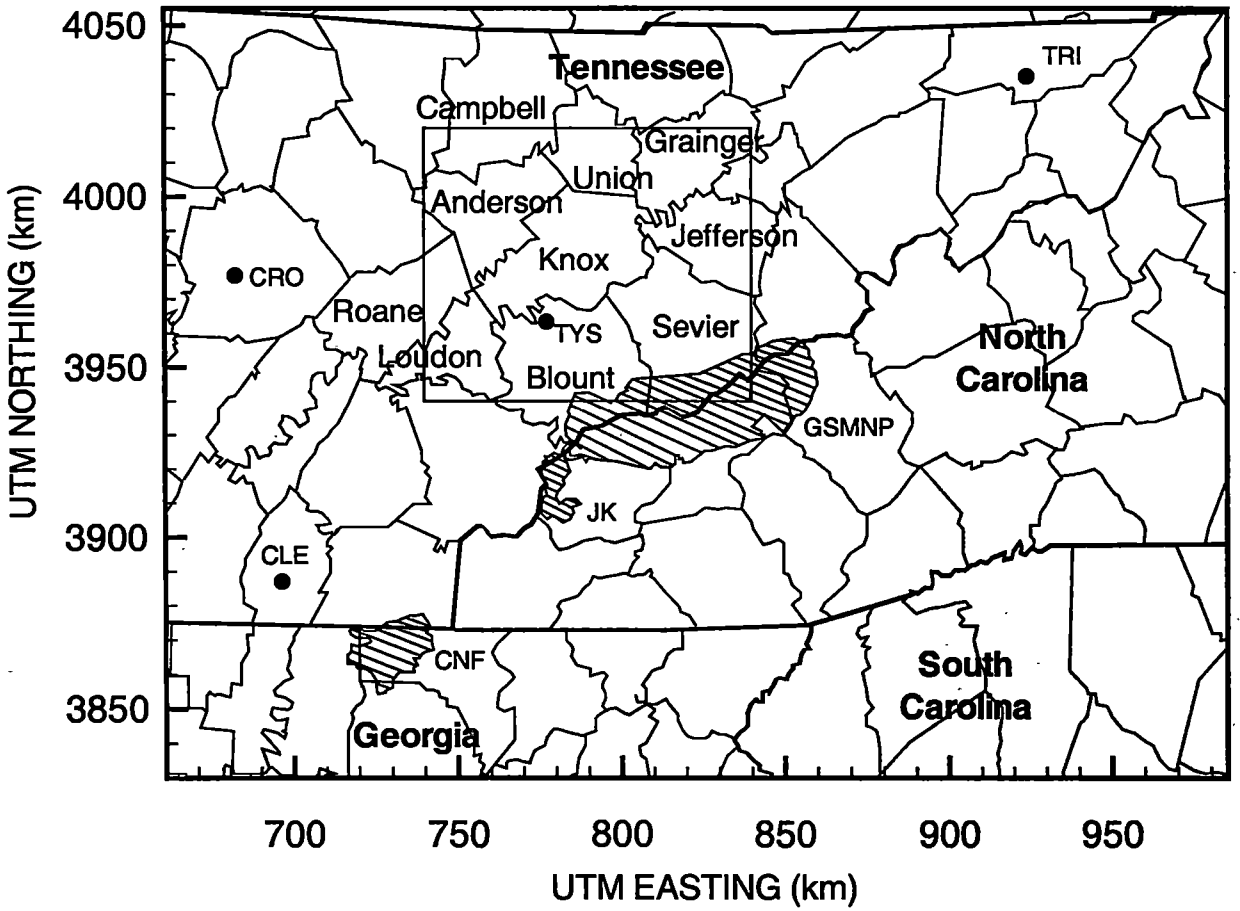


Figure 3-1. Grid of Reduced Area and Mobile Source Emissions.

MRGUAM_25J93_USERIN.IN
BIOEMISS_JUL25_SUNNY.BIN
GRDEM_25J93_POINT.BIN
GRDEM_25J93_AREA.BIN
GRDEM_25J93_MOBILE.BIN

Twenty spaces preceded each input and output filename. The output files generated were:

MRG_25J93_SUN_50ARMO.BIN
MRG_25J93_SUN_50ARMO.MSG
MRG_25J93_SUN_50ARMO.ERR.

The file MRG_25J93_SUN_50ARMO.BIN was an input file to UAM.

METSCALARS

The METSCALARS file includes information of the temperature gradient above and below the diffusion break, exposure class, radfactor or NO_2 photolysis rate, water vapor concentration and atmospheric pressure. These values varied hour by hour but were spatially constant across the domain.

Water vapor concentration was determined from meteorological data, specifically relative humidity and dry bulb temperature. Wet bulb temperature was calculated using the relative humidity and dry bulb temperature as per the procedure in the CRC Handbook of Chemistry and Physics (CRC Handbook of Chemistry and Physics, 1980-81). With wet bulb and dry bulb, ambient moisture in parts per million by volume was calculated from a psychrometric chart. Atmospheric pressure was recorded as 1.0 atmosphere of pressure throughout the modeling domain. Temperature gradient above and below the diffusion break was determined from relationships given by the Nuclear Regulatory Commission

(NRC Guide 1.23, 1972). Wind speed in meters per second from the meteorological data was used to determine the temperature change with height in degrees Celsius per meter. Table 3-5 shows these relationships.

Radfactors were taken from a previous study of the East Tennessee Modeling Domain. Exposure class was determined using Table 6-9 "Exposure class (CE) classification based on cloud cover and solar zenith angle" from EPA (USEPA, June 1990, Volume II). Zenith angle was obtained from Exhibit 6-13 of the same reference. Atlanta is the example city of Exhibit 6-13 and is located within 100 miles of the modeling domain, making it a good choice for zenith angle data. The zenith angle, together with the assumption of less than 50 percent cloud cover at all times during the modeled days, were used to determine exposure class.

A control file was prepared of temperature gradients, exposure class, radfactors, moisture concentrations, and atmospheric pressure. A command file was run that called in the control data file, assigned file names to the ASCII and binary files generated by METSCL.EXE. METSCL_JUL25.BIN was the binary file input to UAM. A sample METSCALARS file is included in Appendix A.

PTSOURCE

The PTSOURCE file was modified from a file created for previous research studies. It provides data about the elevated point sources in the domain: location, emission rate,

Table 3-5. Relationship of Wind Speed to Vertical Temperature Gradient.

Pasquill Stability Category	Wind Speed (m/s)	Temperature Change with Height* (°C/100m)
A	1	<-1.9
B	2	-1.9 to -1.7
C	5	-1.7 to -1.5
D	5	-1.5 to -0.5
E	3	-0.5 to 1.5
F	2	1.5 to 4.0
	-	> 4.0

* These values are per 100 meters; 1.9°C/100m = -0.019°C/m.

species emitted, and exit gas characteristics for each hour of the day. The point source file was modified to simulate scenarios of the modeling matrix. Emissions of NO and NO_2 were reduced by 70 percent to simulate removal of NO_x by Selective Catalytic Reduction (SCR) at all three coal-fired power plants - Kingston Steam Plant, Bull Run Steam Plant, and John Sevier Steam Plant; at Kingston alone; at Bull Run alone; and at all elevated point sources in the modeling domain. Emissions were reduced 70 percent for each hour of the day. At Kingston Steam Plant, emissions of NO and NO_2 were simulated by two stacks - three actually, but the third had no emissions. The stacks were source numbers 22, 23, and 24 in the PTSOURCE file. Source 24 had no emissions. Table 3-6 shows the emissions reductions for the three coal-fired steam plants. John Sevier Steam Plant was simulated using two stacks, sources 11 and 12 in the PTSOURCE file, and Bull Run was simulated with one stack, source 4 in the PTSOURCE file. A sample file is in Appendix A.

REGIONTOP

Region top files were prepared containing the Julian dates and region top heights that vary with location and time. Constant region top values can be set by adding 50 meters to the maximum height of the diffusion break for that day (USEPA, June 1990, Volume II). An extra hour was added to the end of the file for UAM to run correctly. In other words, for July 20, 1995, or Julian day 95201, the first hour 0100 from the next day, 95202, was added to the end of the file. The steps to generate the binary file included first preparing the REGIONTOP.IN file of Julian dates and region top heights. Next the

Table 3-6. Emission Reductions at Coal-Fired Power Plants in the PTSOURCE File.

Chemical Species	Scenario	Emission Rate (moles/hour)	Source Number
Bull Run Steam Plant, source number 4 in ptsource file			
NO	base	0.316804355E+05	4
	70% reduced	0.950413065E+04	4
NO_2	base	0.351375195E+04	4
	70% reduced	0.105412558E+04	4
Kingston Steam Plant, source numbers 22, 23 in ptsource file			
NO	base	0.263450156E+05	22
	70% reduced	0.790350468E+04	22
	base	0.322261289E+05	23
	70% reduced	0.966783867E+04	23
NO_2	base	0.292198706E+04	22
	70% reduced	0.876596118E+03	22
	base	0.357427490E+04	23
	70% reduced	0.107228247E+04	23
John Sevier Steam Plant, source numbers 11, 12 in ptsource file			
NO	base	0.171502051E+05	11
	70% reduced	0.514506153E+04	11
	base	0.131890068E+05	12
	70% reduced	0.395670204E+04	12
NO_2	base	0.190216895E+04	11
	70% reduced	0.570650685E+03	11
	base	0.146282397E+04	12
	70% reduced	0.438847191E+03	12

DIFFBREAK.BIN file (preparation is described in this chapter) was copied to the filename FOR011.DAT. The executable file for region top was run and generated the binary output file by typing the following commands:

REGNTP.EXE
REGIONTOP.IN
REGIONTOP.ASC
REGIONTOP.BIN

The file REGIONTOP.BIN was the binary input file to UAM. Appendix A shows an example file.

SIMCONTROL

The SIMCONTROL file contains information about the simulation of the model scenario such as Julian date, and start hour. It has a series of True/False switches that tell UAM if the run is a restart, if pollutant uptake effects are to be calculated, if elevated point sources are included or a roadway file, if terrain and temperature files are to be used. SIMCONTROL states the maximum and minimum time steps for the chemistry module, the iterative step size, the vertical diffusivity, pollution uptake capability, and convergence criteria among other things.

For July 20, 1995 and July 24, 1993 the restart switch was set to False for no restart. It was set to True for July 25, and July 26, days 2 and 3 of the 3-day event to restart from the previous day's AIRQUALOUT file. The binary file for UAM input was created by simply changing an ASCII version to binary. A sample file is shown in Appendix A.

TEMPERATUR[E]

The TEMPERATUR[E] file provided ground level, hourly temperatures to UAM. To create the binary input file for UAM, first a control file of temperature was prepared for each day. Temperature data were taken directly from the meteorological data, transformed from degrees Fahrenheit to Kelvin and input to the control file. Then a command file was prepared and run that called in the control file of temperatures, assigned names to the binary and ASCII output files, and executed the TMPRTR.EXE program. The temperature binary file was named, for July 25, JUL25_TMPRTR.BIN and was the binary input file to UAM. An example file is shown in Appendix A.

TERRAIN

Terrain files contain spatially varying data of surface roughness lengths and deposition factors. Files taken from previous modeling studies of East Tennessee were used, and their settings were not changed. The only changes made to these existing files were of the Julian days selected for this study. For example, an existing file was renamed ICRETER_JUL2095.CTL and the Julian date changed. Then the command file - used to call in the data file, surface roughness file, gridded land use file, and executable file and to assign the output binary file name - was modified to call in the newly named data file. The output binary file, named TERRAIN_JUL2095.BIN, was an input to UAM. An example is shown in Appendix A.

TOPCONC

The TOPCONC file established the concentrations of various chemical species at the top of the modeling domain. These concentrations were set to EPA default values. The only difference in files for the various modeled days was the Julian date. To create the binary input file for UAM, a control file was prepared that listed, hour by hour, chemical species and their concentration at the top of the modeling domain. A command file was prepared and run that called in the control file of data, assigned filenames to the binary and ASCII output files, and executed the TOPCONC program. The binary file generated by the command file was the input file to UAM. Appendix A contains an example file.

WIND

Several pre-processing steps were necessary to generate the input files of wind speed and direction for UAM. Tables 3-3 and 3-4 list the wind directions and speeds. A sample input file is shown in Appendix A. Wind direction is input in X and Y Cartesian coordinates to UAM which meant that the compass direction given in the meteorological data had to be transformed. Wind speed, given in meters per second, was changed to meters per hour, and calm hours were changed from 0 meters per hour to 10 meters per hour in the X direction and 10 meters per hour in the Y direction. A wind speed of non-zero magnitude is necessary for UAM to run, but low enough to not affect the plume movement or modeling results. This data file was renamed DATA.IN and input to an executable file called DATA.EXE that expanded the wind speed and direction to each cell, hour and level for the model to use. The output file, DATA.OUT was renamed to

reflect the day, for instance WINDJ20.OUT, and edited. DATA.EXE placed some of the header information in incorrect columns and these data were placed in correct columns manually. In the third row of the header, the UTM zone, 16, was in the wrong columns as were all of the following data in that row. These were moved to correct columns. In the fifth row, the beginning hour, 0., was in the wrong column and was moved. The sixth row contained only partial information and had to be supplemented manually. The hourly headings had to each be edited for complete information and column placement. When all data were complete and properly placed, UAMWIND.EXE was run to generate the binary file of wind speed and direction. This binary file was an input file to UAM. Appendix A contains an example file.

Processing UAM Output Data

UAM generated 4 output files of data:

TRACE
AIRQUALOUT

OUTPUT
AVERAGE.

TRACE

The TRACE file reiterated information read from the 13 input files and was used as a debugging tool to show what UAM read in as data and what computations it carried out while running. If a file was misnamed and not read, the TRACE file would state "File not found," or if a parameter were set incorrectly, TRACE would many times state that in an error message. If UAM was unable to complete a run, TRACE would show at what

hour computations stopped, facilitating the modeler to look there first. The TRACE file tracked what the model was doing and provided a record of the computations.

AIRQUALOUT

AIRQUALOUT contained records of instantaneous concentrations that UAM was using in the modeling domain. AIRQUALOUT recorded concentrations of each specie in each cell in all 5 layers. Its concentrations were used to restart UAM in the middle of a run and to start the second and third day of modeling.

AVERAGE

AVERAGE contained 1-hour average concentrations of each specie in each cell, in all 5 layers for 24 hours. From this file 1-hour average ozone concentrations were extracted for the first or lowest layer for each cell for 24 hours. Data from the other 4 layers were stored and not used in this study.

OUTPUT

OUTPUT files were not used in this study.

POST-PROCESSING

Post-processing steps were performed on the UAM output file AVERAGE. Level 1 concentrations of ozone were extracted from AVERAGE. Level 2, 3, 4 and 5 concentrations were not used, neither were concentrations of any other species. From the

extracted 1-hour average ozone concentrations, 8-hour average concentrations were calculated using a FORTRAN program written for that purpose. Several operations were then performed on these files of 1-hour average and 8-hour average concentrations. Colored concentration isopleths were plotted hour-by-hour for each day and each scenario to show how the ozone plumes developed and moved through the domain that day. Isopleths were plotted for both the 1-hour and 8-hour averages.

The maximum ozone concentration in the modeling domain was extracted from the level 1 files for each hour of each scenario for both the 1-hour and 8-hour averages. The maximum difference in the domain between 2 scenarios was calculated, hour-by-hour, and cell-by-cell for both averaging times. Difference files were created which showed the differences in concentrations between 2 scenarios, cell-by-cell and hour-by-hour. The difference files were plotted for 1-hour and 8-hour average concentrations.
Results of the post-processing analyses are shown in the Results chapter.

Cost Analysis

The cost analysis was performed to determine the feasibility of various control options and emission reduction scenarios. NO_x control costs for elevated point sources, mobile sources and area sources were calculated, and the cost effectiveness of each was compared along with the effect on ozone concentrations.

POINT SOURCE NO_x EMISSION REDUCTIONS

The costs of Selective Catalytic Reduction (SCR) were analyzed for elevated point sources. Three references provided cost effectiveness data for SCR controls for point sources: the Ozone Transport Assessment Group (OTAG, 1996), the Northeast States for Coordinated Air Use Management/Mid-Atlantic Regional Air Management Association (NESCAUM/MARAMA, 1998) and the State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officers (STAPPA/ALAPCO, 1994). The NESCAUM/MARAMA data were presented in 1998 dollars, the OTAG data in 1996 dollars and STAPPA/ALAPCO in 1993 dollars. Using the Consumer Price Index (CPI), the OTAG and STAPPA/ALAPCO data were brought forward to 1998 dollars. These data are presented in Table 3-7. The change in the CPI for 1993 to 1998 was 1.1283 and for 1996 to 1998 was 1.0393 (U.S. Bureau of Labor Statistics, 2000). The CPI was chosen because it includes many different goods and services in its computation and is a good indicator of the inflation rate for SCR cost factors.

OTAG had a committee study the control options for electric utilities - the OTAG Control Technologies & Options Workgroup. This workgroup prepared a document listing several utility boiler control techniques of which SCR was one (OTAG, 1996). The cost factors are $1352 to $2598 per ton of NO_x removed for SCR retrofitted on an electric utility boiler that is tangentially-fired, burns coal, has baseloaded duty, a 55 to 65 percent capacity factor and Low NO_x Burners with Overfire Air already installed.

Table 3-7. Cost Factors for Elevated Point Sources Using SCR for NO_x Control.

Cost Reference	Range of Costs for SCR in 1998 Dollars[a]			
	Annual Control Costs ($ / ton of NO_x removed)		Seasonal Control Costs[b] ($ / ton of NO_x removed)	
	low	high	low	high
OTAG[c]	1351	2598	N/A	N/A
NESCAUM/MARAMA[d]	825	1525	1750	3430
STAPPA/ALAPCO[e]	880	1207	N/A	N/A

a. OTAG cost data were originally in 1996 dollars. STAPPA/ALAPCO cost data were in 1993 dollars. Using the Consumer Price Index (CPI), dollars were brought to a reference year of 1998 to make cost comparisons easy. The CPI for 1993 to 1998 was 1.1283, and for 1996 to 1998 was 1.0393. <http://www.dismal.com/toolbox/cpi_index.stm>

b. NESCAUM/MARAMA is the only reference to provide cost data specifically for seasonal controls. Data for other ozone season costs (OTAG and STAPPA/ALAPCO) were calculated using annual cost factors and multiplying the tons of NO_x removed in 153 days or the ozone "season." The ozone season extends from May 1 through September 30 and is 153 days long.

c. OTAG - Ozone Transport Assessment Group (OTAG, 1996). Costs are on a current dollar basis that accounts for inflation. OTAG cost values are for retrofitted, tangentially-fired, baseload duty utility boilers with 55 to 65 % capacity factors. The costs assume that Low NO_x Burners with Over-Fire Air are already installed. An annual Capital Recovery Factor (CRF) of 0.17 is used in a current dollar analysis. A 20-year recovery period is assumed with a discount rate of 9.2 %. The CRF in constant dollars would be 0.12 if following EPRI Technical Assessment Guide. Annual operating costs were levelized with a factor of 1.3 based on EPRI TAG, 9.2 % discount rate, 4.1 % inflation rate and zero real escalation rate. Catalyst replacement, on a 4 year cycle, is levelized with a factor of 1.24. Average catalyst life is assumed to be 4-6 years for a retrofit. Catalyst costs are $400 per cubic foot, coal is $1.50 per MBtu, and anhydrous ammonia is $250 per ton.

d. NESCAUM/MARAMA - Northeast States for Coordinated Air Use Management/Mid-Atlantic Regional Air Management Association (NESCAUM/MARAMA, 1998). This is retrofit cost. Costs are on a constant dollar basis, disregarding inflation. A capacity factor of 65 % is assumed. Typical boiler size is 330 MW. The CRF is 0.1067 and based on a 15-year life. Nominal cost of money is 9.75 %, inflation is 3 % and real cost of money is 6.55 %. Effects of depreciation and debt service on corporate income tax are ignored. For seasonal controls, extended life is ignored for capital equipment. Catalyst volume is assumed as 300 cubic meters in two layers. Layers are replaced after 24,000 operating hours. Catalyst disposal costs, from German data, are $1200 per cubic meter. Fixed operating and maintenance costs are $100,000 per year.

e. STAPPA/ALAPCO - State and Territorial Air Pollution Program Administrators / Association of Local Air Pollution Control Officers (STAPPA/ALAPCO, 1994). These costs assume a 500 MW utility boiler with a 65 % capacity factor. Catalyst life is 5 years at a cost of $400 per cubic foot, catalyst volume is defined by 4000 per hour space velocity. Annual costs of 5 % of total capital are assumed to pay for operation and maintenance, taxes, insurance and administration.

The factors are on an annual basis. OTAG states that SCR can attain a NO_x removal efficiency of 60 to 80 percent. These cost factors assume annual operating schedules.

OTAG presents its cost data in current dollars, taking into account inflation. An annual Capital Recovery Factor of 0.17 was assumed, with a 20 year recovery period and 9.2 percent discount rate. If the cost analysis were in constant dollars, OTAG states the Capital Recovery Factor would be 0.12 instead of 0.17. A levelizing factor of 1.3 was used for annual operating costs, the inflation rate was 4.1 percent and escalation rate was zero.

Catalyst is replaced, according to OTAG, on a 4 year cycle and this cost was levelized using a factor of 1.24. For a retrofit, average catalyst life is 4 to 6 years. Cost of catalyst was $400 per cubic foot, of coal was $1.50 per MBtu, and anhydrous ammonia was $250 per ton.

NESCAUM/MARAMA provided SCR cost data for the boilers in the NESCAUM area and for boilers in the Ozone Transport Region (OTR) (NESCAUM/MARAMA, 1998). NESCAUM includes Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island and Vermont. Other states in the OTR include Delaware, District of Columbia, Maryland, Pennsylvania and northern Virginia. These cost data were in 1998 dollars and needed no adjustment for comparison with the other cost references. NESCAUM/MARAMA cost factors were for retrofit systems on utility

boilers. Costs were presented on a constant dollar basis disregarding inflation. Typical boiler size in the OTR was 330 MW with a capacity factor of 0.65. The average age of boilers in the OTR was 33 years so a 15 year life for the SCR system was determined to be more appropriate than the usual 20 year life. The Capital Recovery Factor used was 0.1067. Nominal cost of money was assumed to be 9.75 percent, inflation was 3 percent and the real cost of money 6.55 percent. NESCAUM/MARAMA decided to disregard effects of depreciation and debt service on corporate income tax. Also disregarded was the extended life of capital equipment when controls were used seasonally.

Catalyst volume was assumed to be 300 cubic meters (392 cubic yards) in two layers with layers replaced after 24,000 hours of operation. Catalyst disposal costs, based on German data, were $1200 per cubic meter. Fixed operating and maintenance costs were set at $100,000 per year.

From these assumptions and data, cost factors for SCR were estimated to be between $825 and $1525 per ton of NO_x removed on an annual basis. NESCAUM/MARAMA was the only reference to estimate seasonal cost factors for SCR. These factors are higher than annual because the same capital costs are spread over fewer tons of NO_x removed. Seasonal SCR cost factors range from $1750 to $3430 in 1998 dollars.

STAPPA/ALAPCO presented cost factors for utility boilers with SCR systems operated all year round (STAPPA/ALAPCO, 1994). No seasonal cost factors were estimated. The

range extended from $880 to $1207 per ton of NO_x removed. These costs were estimated for a 500 MW boiler with 65 percent capacity factor.

Catalyst life was assumed to be 5 years, and the cost was $400 per cubic foot. Volume of catalyst was defined by 4000 per hour space velocity. Annual costs of 5 percent of total capital would pay for operation and maintenance, taxes, insurance and administration.

MOBILE SOURCE NO_x EMISSION REDUCTIONS

Costs of mobile source NO_x emission reductions were estimated by three methods: reducing emissions by voluntarily not driving, by lowering interstate highway speed limits, and by using reformulated gasolines.

Voluntary Trip Avoidance

Most cities with "Ozone Action" programs aimed at averting high ozone concentrations ask people to not drive - to avoid making trips to the grocery, to a restaurant for lunch, to work and other non-essential activities. This NO_x control method was analyzed to determine its cost and cost effectiveness. Emission reduction levels were 10 percent, 30 percent and 50 percent of mobile source emissions in the 8-county area shown in Figure 3-1. The tons per day of NO_x reductions simulated in the modeling runs were obtained from MRGUAM.MSG files.

Once the goal for NO_x reductions was calculated, the number of trips necessary to create equivalent NO_x emissions was calculated by dividing the emissions avoided by the average trip length based on national data and the average emissions per trip obtained from Knox County data. Average trip length was 9.1 miles, and the average vehicle occupancy rate in a car was 1.6 (ORNL, 1999). Average emissions per trip were based on Knox County data (Knoxville Urban Area Metropolitan Planning Organization, 1999). One trip was assumed to take thirty minutes. Actual average trip time may be longer or shorter, but thirty minutes was a reasonable assumption.

Cost of a trip was based on per capita money income in Tennessee. Per capita money income includes income of an 80 year old person and a 3 year old. These people were included in the cost analysis, because often there is more than one person making a trip. Based on these assumptions, the cost of voluntary trip avoidance was calculated. Cost effectiveness, in dollars per ton of NO_x removed, was calculated from the cost of trips avoided to achieve a level of NO_x reduction and divided by the tons of NO_x reduced.

Per capita money income may not be the correct measure for opportunity cost of time. If an individual chooses to make a trip, then the trip itself must be at least if not more valuable to the individual than the cost incurred by making the trip or he would not undertake the trip in the first place. As such, an hourly income or wage rate may be too low an estimate of the true value of the trip. Vehicle operating costs such as gasoline and wear and tear on the tires and engine were not considered in this analysis when assigning

the hourly income rate to the value of a trip. If these savings - for the trip not made - were taken into account, hourly per capita income might then be too high an estimate for foregoing a trip. The value of a trip may be completely unrelated to per capita money income or the hourly wage rate. Whether or not it is the best measure of the opportunity cost of time of participating in voluntary mobile source controls, per capita money income is a realistic value to use as a surrogate for estimation purposes and is used in this study in this capacity.

Lower Interstate Highway Speeds

Changes in NO_x emissions from lowered interstate speeds were calculated for the 8-county area. Vehicle speeds ranging from about 25 miles per hour (mph) to 45 mph have the lowest NO_x emission rates, lower than very slow speeds and lower than fast speeds, 55 - 75 mph. Lowering interstate allowable speeds would decrease NO_x emissions and possibly ozone concentrations. Interstate highways were the only roads in east Tennessee with average speeds significantly higher than 45 mph so they were selected for speed reductions to determine what effect lower speeds would have on ozone concentrations and what the cost would be.

Rural and urban interstate vehicle miles traveled (VMT) in 1998 in the 8-county area were obtained from *Growth of VMT in Tennessee 1990-1998* (Davis, et. al., 1999). Total rural VMT per day were 3,623,294 and urban VMT per day were 4,200,248 in 1998. NO_x emission factors for rural and urban interstate speeds from 5 mph to 75 mph were

predicted using EPA's mobile source emission factor model MOBILE5b, version dated September 1997. Model inputs for vehicle mix, temperature, operating mode and other input data were taken from the *Long Range Transportation Plan Update* prepared by the Knoxville Urban Area Metropolitan Planning Organization (1999). The predicted MOBILE5b emission rates are tabulated in Table 3-8. Vehicle speeds greater than 65 mph are assigned the same emission rate as 65 mph by MOBILE5b even though actual emission rates are greater. Figure 3-2 illustrates the predicted emission rates and how NO_x emission factors vary with vehicle speed. Rural interstates are less congested in general and vehicles can travel at higher speeds than they can on more heavily traveled urban interstates.

In the 8-county area, 45 mph was chosen as the speed limit on a high ozone day because emissions were close to the minimum for interstate roads, yet it was the highest of the speeds with low emission factors and least disruptive to travelers. Emission factors for normal speeds were multiplied by VMT for the appropriate road type and factors for lowered speeds were also multiplied by appropriate VMT. The difference in the two, normal minus lowered, equaled NO_x emissions avoided.

Costs of lower interstate speeds were from VMT per day, 1.6 occupants per vehicle and the speed limit. The opportunity cost of time was estimated as per capita money income in Tennessee. Additional time required for travel on interstate roads with lower speed limits was calculated from the difference between the normal speed to the lowered speed.

Table 3-8. NO_x Emissions Predicted by Mobile5b for Rural and Urban Mobile Sources.

1998 Emission Factors		
	Urban	**Rural**
Vehicle Speed (miles/hour)	**Composite NO_x Emissions (grams/mile)**	**Composite NO_x Emissions (grams/mile)**
5	3.98	4.96
15	3.10	3.81
25	2.83	3.42
35	2.81	3.38
45	2.97	3.59
55	3.70	4.46
65	5.00	6.09
75	5.00	6.09

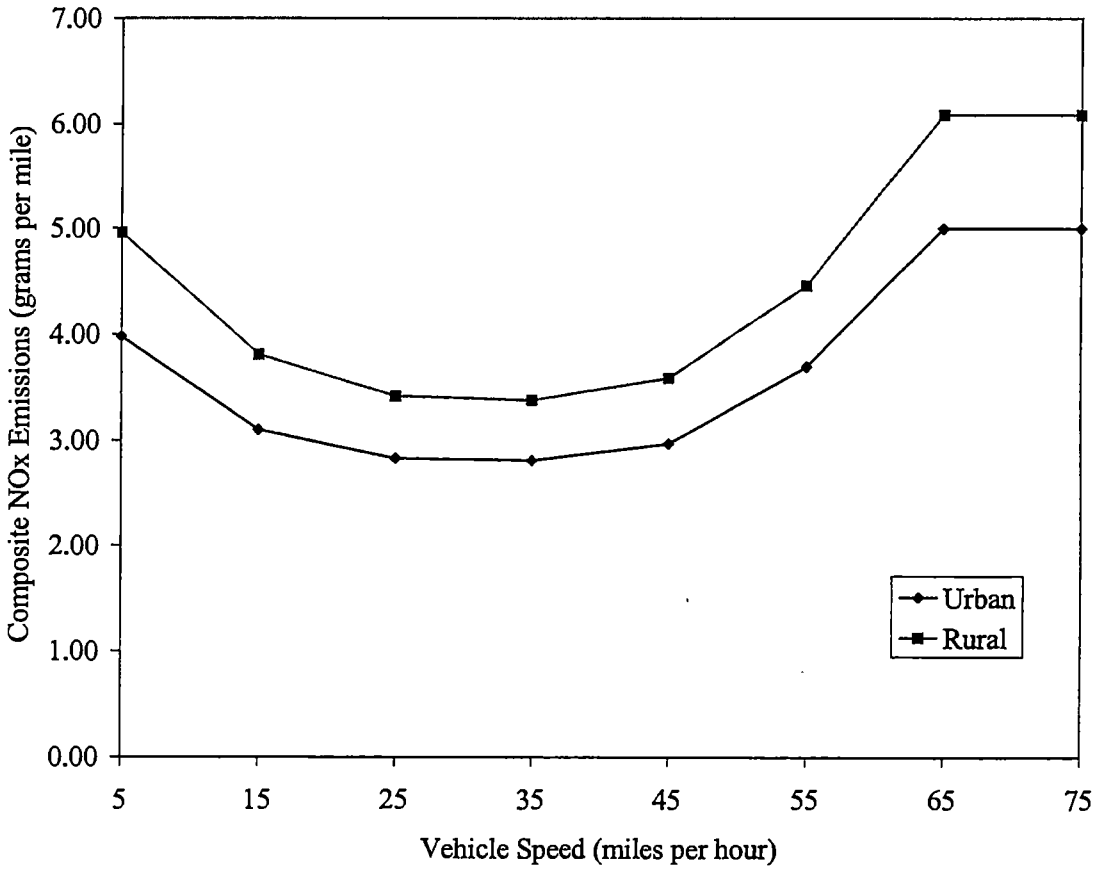


Figure 3-2. NO_x Emissions and Vehicle Speed Predicted by Mobile5b for Interstate Highways in 1998.

Reformulated Fuels

Reductions in NO_x emissions by burning reformulated fuels in on-road, light duty vehicles were calculated for the 8-county area. Several fuel types were considered (Cummings, Osborne, Terrebonne, 1997):

- California Reformulated gasoline,
- OTAG Reformulated gasoline,
- EPA Phase I gasoline,
- EPA Phase II gasoline, and
- Reformulated Diesel.

The new low-sulfur gasoline required by EPA's recently promulgated rule, *Control of Air Pollution from New Motor Vehicles: Tier 2 Motor Vehicle Emissions Standards and Gasoline Sulfur Control Requirements* (Federal Register, February 10, 2000), (USEPA, December 1999) was not included in the list, because it is intended to be a permanent control technology, used year round, not an episodic control.

The percentages of NO_x emissions reduced by burning reformulated fuels vary from fuel to fuel. NO_x emission reductions in tons per day were calculated from the percentages and total NO_x emissions from mobile sources in the 8-county area. By doubling the difference in NO_x emissions between the base case and 50 percent mobile source reductions listed in the MRGUAM.MSG file, mobile source NO_x emissions were calculated as 77.68 tons per day in the 8-county area. The ratio of NO_x emissions from gasoline fuel and from diesel fuel was assumed to be the same as the ratio in the Atlanta 13-county nonattainment area, 63 percent due to gasoline fuels and 37 percent due to diesel fuels (Cummings, et.al., 1997). Mobile source NO_x emissions multiplied by the

percentage in NO_x reductions due to burning that fuel gave tons per day of NO_x reductions. Assuming that the fuels were sold throughout the ozone season, NO_x reductions in tons per season were calculated.

To estimate cost, price increase per gallon of fuel, taken from a study of the Atlanta region (Cummings, et. al., 1997), and volume of gasoline sold in the 8-county area were necessary. Gallons of gasoline sold in the entire state of Tennessee was recorded in the Tennessee Statistical Abstract (University of Tennessee, 1996), but was not broken out into counties. However, another document listed total VMT by county and for the entire state (Davis, et. al., 1999). Knox County and all of the seven surrounding counties; Anderson, Blount, Grainger, Jefferson, Loudon, Sevier and Union; combined to account for 14 percent of VMT in Tennessee. Gasoline sales were then ratioed by 14 percent to estimate gasoline sold in the 8-county area. The 8-county area and Knox County and seven surrounding counties did not exactly match in boundaries, but were assumed to be close enough to provide a reliable estimate. Diesel fuel was calculated the same way.

Since Interstates 40 and 75 carry many large trucks on long haul routes through the study area, some NO_x emissions due to diesel trucks in the 8-county area come from fuel purchased elsewhere and may not be reformulated. And some fuel sold in the 8-county area may be burned elsewhere. No adjustments were made for variations in gallons sold and gallons burned in the 8-county area; however, this method gave reasonable estimates of NO_x emission reductions from reformulated fuel.

Cost was calculated from gallons of fuel sold and price increase per gallon. Cost per season was based on the 153 days or 5 months that constitute the ozone season. Cost per year was not calculated because all types of reformulated gasoline are not sold in climates with cold winter months. Cars will not start in cold weather with reformulated gasoline in the tank. Cost per day and per season were the applicable time periods for estimates of reformulated fuels. From cost and NO_x reductions, cost effectiveness in dollars per ton of NO_x removed was calculated.

AREA SOURCE NO_x EMISSION REDUCTIONS

Releases of area source emissions are difficult to quantify, and over the years less research effort has been made in estimating them than has been put into mobile source and point source emissions. As a result, the accuracy of area source emission factors is not as good as are other emission source factors. Numerous detailed cost analyses of emission reductions from area sources were not performed since they could not be reliably calculated

Costs of area source emission reductions were calculated for landscaping and horticulture workers forgoing work on a day with predicted high ozone. These costs were only foregone wages. No costs were included for the disutility to clients for whom the labor was to be performed, or of the company that also had to forego income from the workers' labor. The cost was simply foregone wages of the landscapers and horticulture workers.

Knox County area source NO_x emissions from off-highway, gasoline and diesel, lawn and garden equipment in tons per year for 1996 were estimated by Pechan (1999). Gasoline NO_x emissions were 27 tons per year and diesel NO_x emissions were 172 tons for a total of 199 tons per year in Knox County. From EPA (USEPA, 2000a) the number of single and double family homes in 1996 was recorded for each of the 8 counties. The total area of the 8-counties was slightly different than the area used in the UAM modeling, but not much. A ratio of NO_x emissions from lawn and garden equipment in Knox County to number of homes in Knox County was calculated and was used to estimate NO_x emissions in the other seven counties based on the number of homes in each county.

Next the number of employees in landscape and horticulture services was recorded from EPA data (USEPA, 2000b). Employees were assumed to work a 10 hour day at two different wages, $5.50 per hour, approximating the minimum wage, and $8.06 per hour, per capita money income in Tennessee in 1998. Foregone wages for the seven other counties were computed in the same manner. Cost effectiveness in dollars per ton was calculated from foregone income per day and tons of NO_x emissions avoided per day.

4. RESULTS

Results of the Urban Airshed Model, Version IV (UAM IV) for 1-hour and 8-hour average ozone concentrations and eight emission scenarios are analyzed in this chapter. Costs are analyzed and discussed to determine the cost effectiveness of the emission scenarios.

Model Results

NO_x emissions were varied in eight scenarios and modeled on four days to predict the effect on ozone concentration. The four days were July 20, 1995, and July 24, 25 and 26, 1993. July 20, 1995, was a single day, high ozone event, chosen from historical monitoring data. The other three days were consecutive, high ozone days and were also selected using historical monitoring data from East Tennessee. In the eight scenarios for a single day, the only variable in input data was NO_x emissions. In the individual scenario modeled on four different days, the only variable was meteorology.

NO_x emissions and how they vary are shown for each scenario in Table 4-1. Model inputs of NO_x emissions are broken out by source categories: point, area, mobile and biogenic emissions. Point sources are subdivided into elevated and low level sources. Elevated point sources have a plume extending into the second layer, out of five, in the modeled atmosphere. The second layer begins at 50 meters above ground level. Total NO_x emissions for each scenario are also presented. The base case, with all sources

Table 4-1. NO_x and VOC Emissions in the Eight Modeling Scenarios.

Source Category	Domain Wide Base Case NO_x (tpd)	Domain Wide Base Case VOCs (tpd)	70% NO_x Reduction at Kingston (tpd)	70% NO_x Reduction at Bull Run (tpd)	70% NO_x Reduction at 3 TVA Plants (tpd)	70% NO_x Reduction at All Elevated Point Sources (tpd)	10% NO_x Reduction of Area & Mobile Sources Inside Grid* (tpd)	30% NO_x Reduction of Area & Mobile Sources Inside Grid* (tpd)	50% NO_x Reduction of Area & Mobile Sources Inside Grid* (tpd)
Point	444	216	388	411	325	249	444	444	444
elevated	*278*	*5*	*222*	*245*	*159*	*84*	*278*	*278*	*278*
low level	*166*	*211*	*166*	*166*	*166*	*166*	*166*	*166*	*166*
Area*	170	615	170	170	170	170	166	159	153
Mobile*	399	325	399	399	399	399	393	377	361
Biogenic	56	9959	56	56	56	56	56	56	56
Total	1069	11,117	1013	1036	950	874	1059	1036	1014
Percent Reduction of NO_x from Base Case Total			5%	3%	11%	18%	1%	3%	5%

* Area and mobile source reductions are inside grid of 8-county region. See Figure 3-1.

emitting at normal rates, has 1069 tons per day of NO_x emissions. The largest total NO_x reduction was in the scenario 70 percent NO_x reduction at all elevated point sources and was 18 percent smaller in total magnitude than the base case. The smallest total reduction was 1 percent and occurred in the scenario of 10 percent NO_x reduction of area and mobile sources. The scenario for 50 percent NO_x reduction of area and mobile sources, despite cutting half of all mobile and area sources in the 8-county area, accounted for a mere 5 percent of total emissions in the modeling domain.

Table 4-2 shows the modeling results for the various emission scenarios and different days. The first column of Table 4-2 lists the day and abbreviated scenario name. An explanation of the abbreviation names follows:

July 20, 1995 - modeled day, one day event,
July 24, 1993 - modeled day, day one of three day event,
July 25, 1993 - modeled day, day two of three day event,
July 26, 1993 - modeled day, day three of three day event.

BASE - base case, all sources emitting full emissions.
70KING - 70 percent reduction in NO_x emissions from Kingston Power Plant.
70BULLRUN - 70 percent reduction in NO_x emissions from Bull Run Power Plant.
70TVA3 - 70 percent reduction in NO_x emissions from three TVA power plants: Kingston, Bull Run, and John Sevier Power Plants.
70ALLELEV - 70 percent reduction in NO_x emissions from all elevated point sources.
AM50PCT - 50 percent reduction in NO_x emissions from area and mobile sources (in the area shown in Figure 3-1.)
AM30PCT - 30 percent reduction in NO_x emissions from area and mobile sources.
AM10PCT - 10 percent reduction in NO_x emissions from area and mobile sources.

The columns labeled Peak Concentration in Table 4-2 show the maximum ozone concentration predicted by UAM in the East Tennessee Modeling Domain. The 8-hour

Table 4-2. Peak Concentrations and Maximum Differences Predicted by UAM.

	Peak Concentration		Maximum Difference	
	1-Hour Average (ppb)	8-Hour Average (ppb)	1-Hr Average (ppb)	8-Hour Average (ppb)
July 20, 1995				
BASE	117	104		
70KING	99	88	35	28
70BULLRUN	113	96	23	17
70TVA3	99	80	40	35
70ALLELEV	99	79	41	35
AM50PCT	116	102	18	16
AM30PCT	117	103	10	9
AM10PCT	117	104	3	3
July 24, 1993				
BASE	121	108		
70KING	103	96	36	33
70BULLRUN	115	98	22	18
70TVA3	98	83	40	35
70ALLELEV	98	83	40	35
AM50PCT	120	106	20	19
AM30PCT	120	106	11	10
AM10PCT	121	107	3	3
July 25, 1993				
BASE	146	125		
70KING	129	115	50	41
70BULLRUN	146	125	32	25
70TVA3	118	96	49	41
70ALLELEV	118	96	49	41
AM50PCT	141	120	19	15
AM30PCT	143	122	11	9
AM10PCT	145	124	3	3
July 26, 1993				
BASE	161	139		
70KING	148	127	52	38
70BULLRUN	161	138	39	24
70TVA3	142	120	52	39
70ALLELEV	140	119	52	40
AM50PCT	154	129	31	22
AM30PCT	154	132	18	13
AM10PCT	158	136	6	4

average values were calculated from the 1-hour average data files and are 8-hour rolling averages.

1-HOUR AVERAGE OZONE CONCENTRATIONS

The next section covers 1-hour average concentration results. After this section, 8-hour average results are discussed.

Peak Concentrations

The base case scenario predicted the highest 1-hour average ozone concentration on each day. The lowest 1-hour average concentration was predicted from 70ALLELEV - 70 percent NO_x reduction at all elevated point sources.

On July 20, 1995, the lowest 1-hour average concentration of 99 ppb was also achieved in two other scenarios, 70 percent reduction in NO_x at Kingston Power Plant and 70 percent reduction in NO_x at three TVA power plants. On July 24 and 25, 1993, the lowest 1-hour averages of 98 ppb and 118 ppb, respectively, were predicted in two scenarios, 70 percent NO_x reduction at all elevated point sources and 70 percent NO_x reduction at three TVA power plants. July 26, 1993 had only one scenario with a lowest concentration of 140 ppb, and it was from 70 percent NO_x reduction at all elevated point sources. The next lowest concentration was merely 2 ppb higher at 142 ppb predicted from 70 percent NO_x reduction at three TVA power plants. The scenario of 70 percent reduction at Kingston

Power Plant predicted 148 ppb ozone, not much higher than that of three TVA plants or of all elevated point sources.

The 1-hour average scenarios with least effect on ozone concentrations on July 20 and July 24 were area and mobile source NO_x reductions of 10, 30 and 50 percent. This changed for July 25 and 26 to 70 percent reduction in NO_x emissions from Bull Run Power Plant, which had no effect on ozone. On July 25, a 5 ppb ozone reduction was predicted to occur from reducing 50 percent of area and mobile source emissions, though a 10 percent area and mobile source NO_x reduction resulted in just a 1 ppb ozone change. On July 26, area and mobile source NO_x reductions contributed to 3, 7 and 7 ppb ozone concentration change for 10, 30 and 50 percent NO_x reduction, respectively.

Ozone concentrations predicted by reductions at three TVA plants were actually the effect of reductions at two plants, Kingston and Bull Run, located west of Knox County. The ozone plume from John Sevier Power Plant, located northeast of Knox County, did not mix in the modeling domain with the plumes of the other two TVA power plants. The three plumes probably do mix at some greater distance downwind, but not in the East Tennessee Modeling Domain. The plumes of Kingston and Bull Run Power Plants mix in the modeling domain because of their proximity to each other, and simultaneous reductions in the plants' NO_x emissions produced large reductions in ozone concentrations.

Ozone formation and plume movement are illustrated in Figure 4-1 through Figure 4-4 for 1-hour averages on July 20, 1995. These figures show color isopleths of ozone concentrations in the East Tennessee Modeling Domain, hour by hour. The base case with all sources emitting is the scenario of these four figures. The color legend for ozone is in parts per million (ppm) and covers concentrations of 0 ppm in purple to 0.12 ppm, the level of the 1-hour NAAQS, in red.

Figure 4-1 depicts early morning ozone concentrations in the East Tennessee Modeling Domain. Dark blue spots mark the locations of large elevated point sources with NO_x emissions large enough to scavenge nearby ozone and reduce concentrations in localized areas. Ozone concentrations throughout the domain are in the 40 ppb range. Knox County is located just above the TYS label. TYS stands for McGhee-Tyson Airport and is in Blount County. To the west of Knox County are two large plumes. The plume furthest west marks TVA's Kingston Power Plant. The nearer western plume is from Bull Run Power Plant. Northeast of Knox County is the plume of John Sevier Power Plant, close to the Virginia border.

Figure 4-2 shows ozone concentrations at noon for the same day and scenario. Concentrations range from 40 to 80 ppb. Higher ozone concentrations are evident in urban areas of Knox County, the Tri-Cities (Kingsport and Johnson City in Tennessee and Bristol, Virginia), Asheville, North Carolina east of the Great Smoky Mountain National Park (GSMNP) and Greeneville-Spartanburg region of South Carolina in the

Figure 4-1. July 20, 1995, 8 A.M., 1-Hour Average,

Base Case, All Source Simulation.

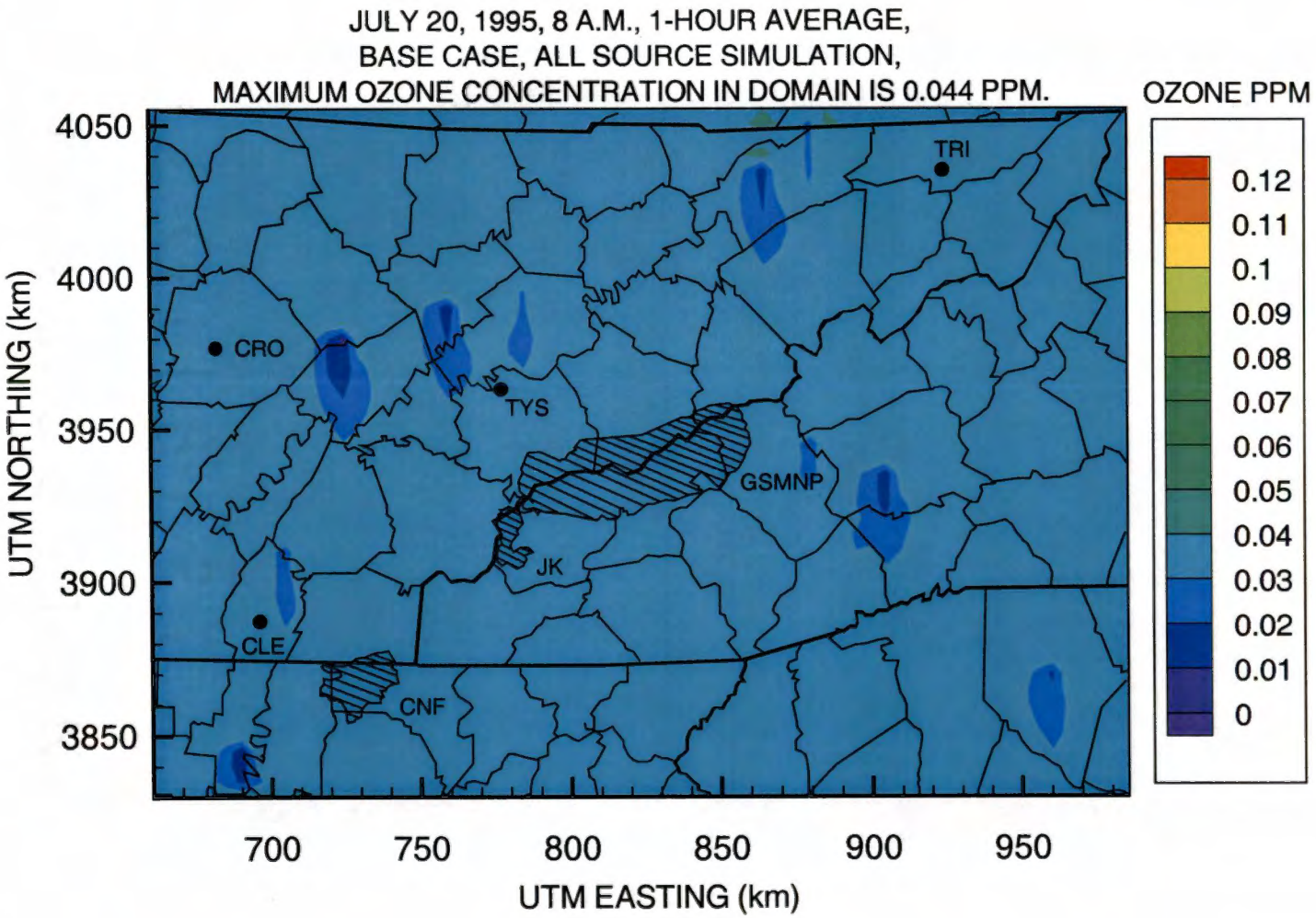

JULY 20, 1995, 8 A.M., 1-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.044 PPM.
OZONE PPM
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)

Figure 4-2. July 20, 1995, Noon, 1-Hour Average,

Base Case, All Source Simulation.

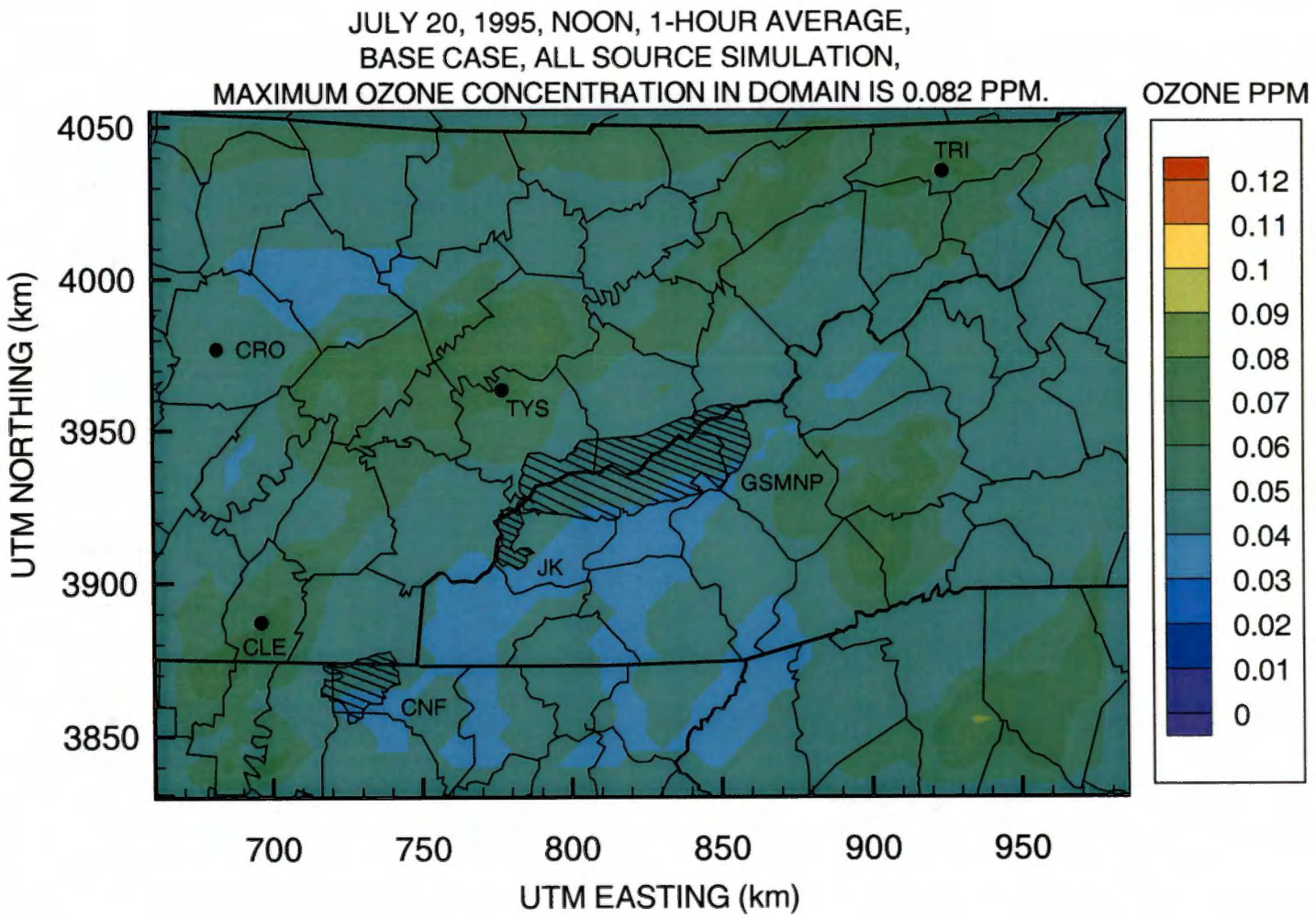

JULY 20, 1995, NOON, 1-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.082 PPM.
OZONE PPM
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)
TRI
CRO
TYS
GSMNP
JK
CLE
CNF

Figure 4-3. July 20, 1995, 4 P.M., 1-Hour Average,

Base Case, All Source Simulation.

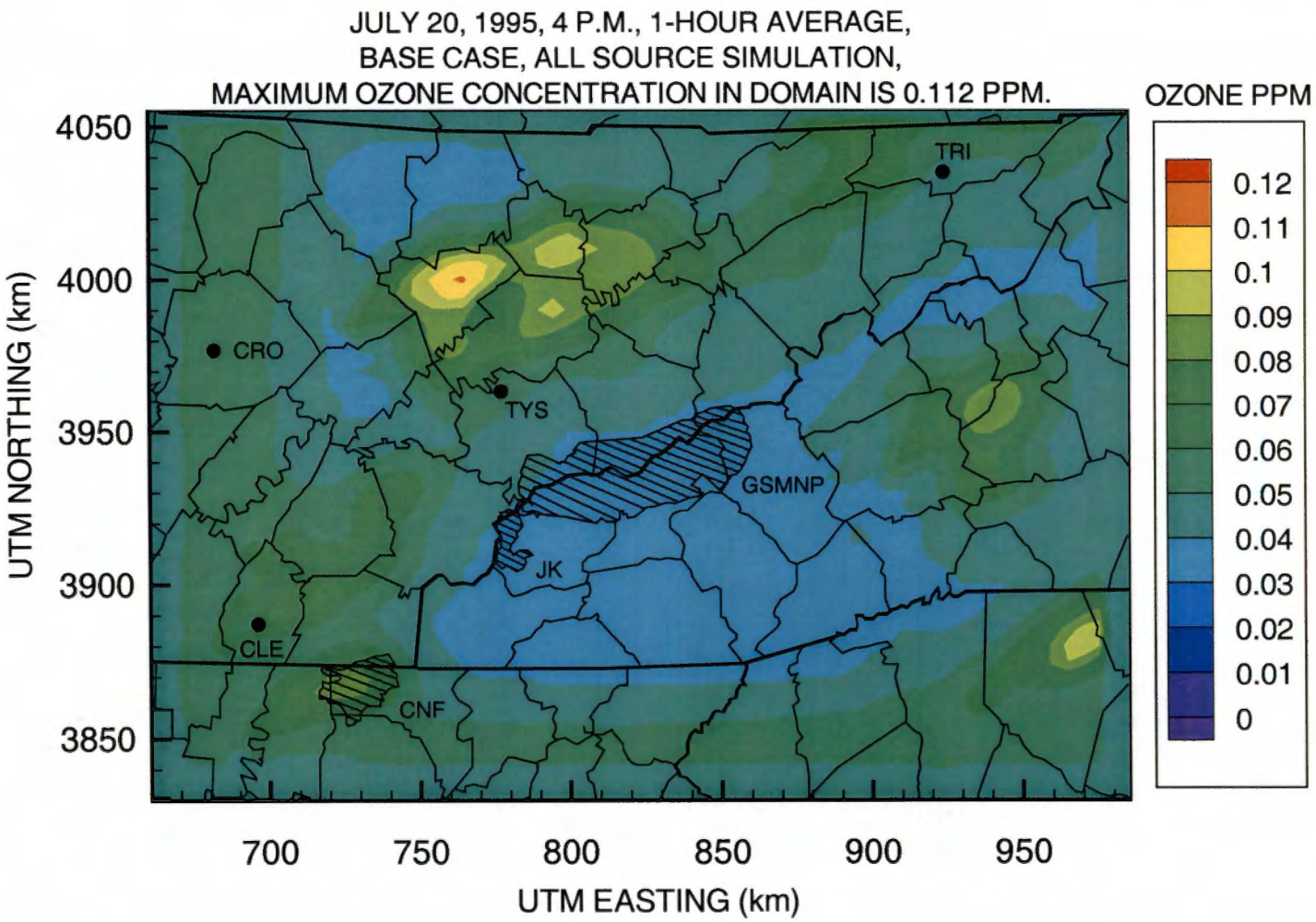
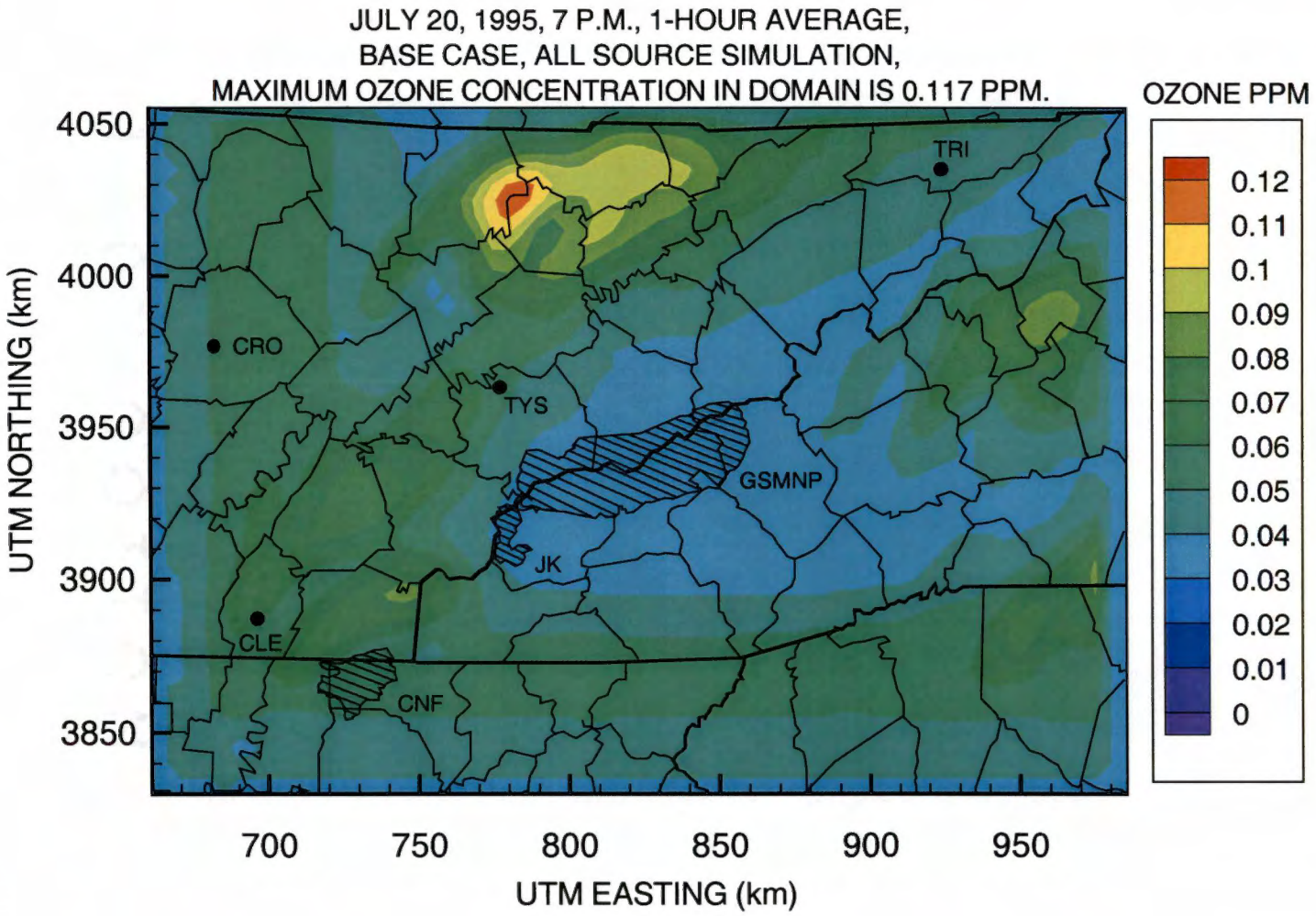

JULY 20, 1995, 4 P.M., 1-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.112 PPM.
OZONE PPM
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
UTM NORTHING (km)
4050
4000
3950
3900
3850
UTM EASTING (km)
700
750
800
850
900
950
TRI
CRO
TYS
GSMNP
JK
CLE
CNF

Figure 4-4. July 20, 1995, 7 P.M., 1-Hour Average,

Base Case, All Source Simulation.


JULY 20, 1995, 7 P.M., 1-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.117 PPM.
OZONE PPM
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)

southeast corner of the domain. Ozone caused by NO_x emissions along the corridor of Interstates 40 and 75 is visible from the northeastern Tri-Cities southwest to Knox County and again southwest towards Cleveland, Tennessee. The western toe of North Carolina, south of the Smoky Mountains, is sparsely populated with little industrial base, and ozone concentrations there are lower than in the more populous areas of the domain.

By 4 P.M. in the afternoon, ozone concentrations rose to 112 ppb as shown in Figure 4-3. The ozone plume moved almost due north to center on Anderson and Union Counties and still had a tail in Knox County. Ozone formation from the interstate highway corridor remained visible from northeast to southwest. Concentrations of ozone in the Great Smokey Mountains National Park are in the 30 to 40 ppb range, much lower than are typically measured, especially in the higher elevations. This may be due to low model input concentrations for initial air quality conditions which were set at 40 ppb of ozone, the EPA recommended level.

Maximum Differences

The peak ozone concentration of the day was predicted to occur at 7:00 P.M., and is shown in Figure 4-4. Lower concentrations are evident along the southern borders of the domain. At the edges of the domain, boundary ozone concentrations were set to 40 ppb, an EPA recommended level, and these low-concentration, incoming winds caused the low ozone concentrations along the border. The peak concentration was unaffected by

boundary conditions, as evidenced in these four figures. Ozone scavenging is apparent in the blue diamond shapes at the locations of Kingston and Bull Run Power Plants.

The columns in Table 4-2 labeled Max Diff list the largest difference in concentration between the base case scenario and each of the other scenarios. These difference values show simply the largest effect of changing emissions. For instance, with the output from two model runs, July 20, 1995 base case and July 20, 1995 70 percent NO_x reduction at Kingston Power Plant, the results from 70 percent reduction at Kingston were subtracted from the base case, cell by cell and hour by hour. These results were then sorted to find the maximum, in this case 35 ppb. In mathematical terms:

base case concentration - 70 percent NO_x reduction at Kingston concentration = 35 ppb at hour 1600 and in cell 2264.

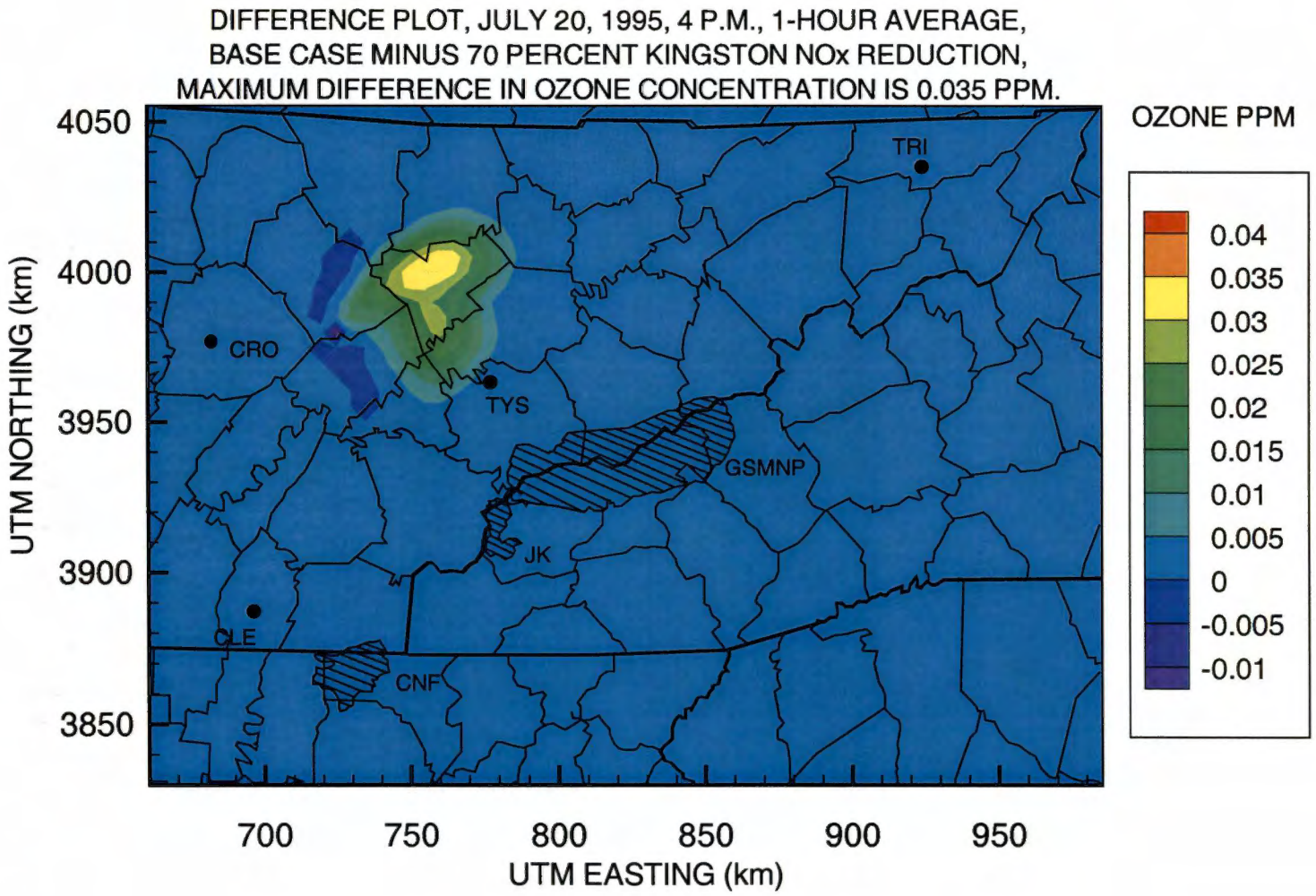
An expanded version of Table 4-2 is contained in Appendix B and lists, besides the peak ozone concentration, the cell and hour of occurrence of the peak ozone concentration. The cell numbering system begins in the lower left corner of the domain and moves upward row by row. The bottom row contains cells 1-66. The next row up contains cells 67-132. The top row contains cells 2971-3036.

No difference value is calculated for the base case since it would be a comparison against itself and would be zero.

A maximum difference value can be greater than the difference in peak concentrations for two scenarios, and it can occur at another time and in another location. As an example, the peak concentration for the July 20 base case was 117 ppb and for 70 percent NO_x reduction at Kingston was 99 ppb. The difference between these peaks is 18 ppb. But the largest difference that occurred anywhere, at any time, for this scenario, in the modeling domain was 35 ppb. The maximum difference can occur in a location and in an hour that does not have the peak concentration in the domain.

Figure 4-5 is a difference plot showing the base case results minus the 70 percent NO_x reduction results at Kingston Power Plant. The plot depicts how much ozone concentrations were lowered by reducing 70 percent of the NO_x emissions at Kingston Power Plant. The color legend ranges from -0.01 ppm to 0.04 ppm or -10 ppb to 40 ppb. A maximum difference of 35 ppb means that ozone concentrations were lowered 35 ppb. The purple areas on the edge show where ozone actually increased in concentration as a result of lowering NO_x emissions and are small compared to the size of the area that experienced a decrease in ozone. The purple indicates a negative reduction or an increase in ozone concentration when NO_x emissions were reduced. This is explained by higher NO_x emissions from elevated point sources in the base case where the high NO_x emissions react to scavenge nearby ozone and artificially lower localized ozone concentrations. When NO_x emissions are reduced, ozone scavenging does not occur, and it appears that ozone concentrations increase, but that is not the case. The base case

Figure 4-5. Difference Plot, July 20, 1995, 4 P.M., 1-Hour Average, Base Case Minus 70 Percent Kingston NO_x Reduction.


DIFFERENCE PLOT, JULY 20, 1995, 4 P.M., 1-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT KINGSTON NOx REDUCTION,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.035 PPM.
OZONE PPM
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
UTM NORTHING (km)
4050
4000
3950
3900
3850
UTM EASTING (km)
700
750
800
850
900
950
TRI
CRO
TYS
GSMNP
JK
CLE
CNF

ozone concentrations were merely scavenged in a small, localized area near large NO_x sources.

On July 20, 1995, the maximum 1-hour difference for all scenarios was 41 ppb between the base case and 70 percent NO_x reduction at all elevated point sources. Figure 4-6 shows the location where the ozone reductions occurred. For 70 percent NO_x reduction at Kingston alone, the maximum difference was 35 ppb. Figure 4-5 presents this difference plot. The second highest difference in ozone concentrations was 40 ppb resulting from comparisons between the base case and 70 percent NO_x reduction at three TVA plants. The difference in ozone concentrations is displayed in Figure 4-7. John Sevier Power Plant's plume, because of its distant location (refer to the discussion of Figure 4-1 for its location), had no effect on the 40 ppb value. This means that combined NO_x reductions at Bull Run and Kingston together accounted for all of the 40 ppb difference and that 70 percent NO_x reductions at the two plants combined resulted in only 5 ppb greater decrease in ozone than NO_x reductions at Kingston alone (35 ppb). NO_x reductions at Bull Run alone made a 23 ppb difference. On this day, July 20, point source NO_x reductions made a greater difference in ozone concentrations than did area and mobile source reductions. The maximum difference from 50 percent area and mobile source NO_x reductions was 18 ppb. Figure 4-8 illustrates the difference in ozone concentration for the area and mobile source scenario.

Figure 4-6. Difference Plot, July 20, 1995, 7 P.M., 1-Hour Average, Base Case Minus 70 Percent NO_x Reduction at All Elevated Point Sources.

DIFFERENCE PLOT, JULY 20, 1995, 7 P.M., 1-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT NOx REDUCTION AT ALL ELEVATED POINT SOURCES,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.041 PPM.

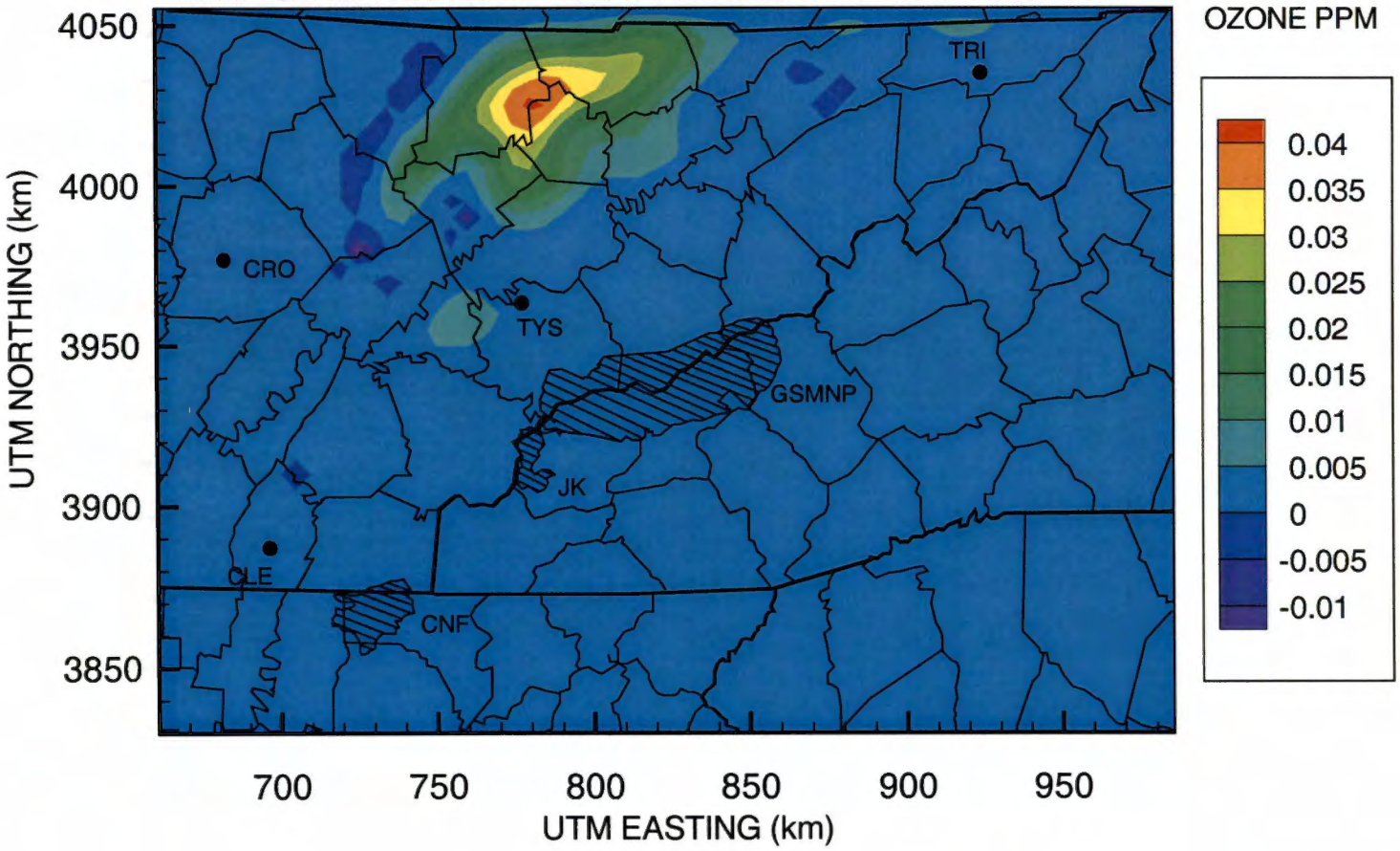


Figure 4-7. Difference Plot, July 20, 1995, 7 P.M., 1-Hour Average, Base Case Minus 70 Percent NO_x Reduction at 3 TVA Power Plants.

DIFFERENCE PLOT, JULY 20, 1995, 7 P.M., 1-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT NOx REDUCTION AT 3 TVA POWER PLANTS,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.040 PPM.

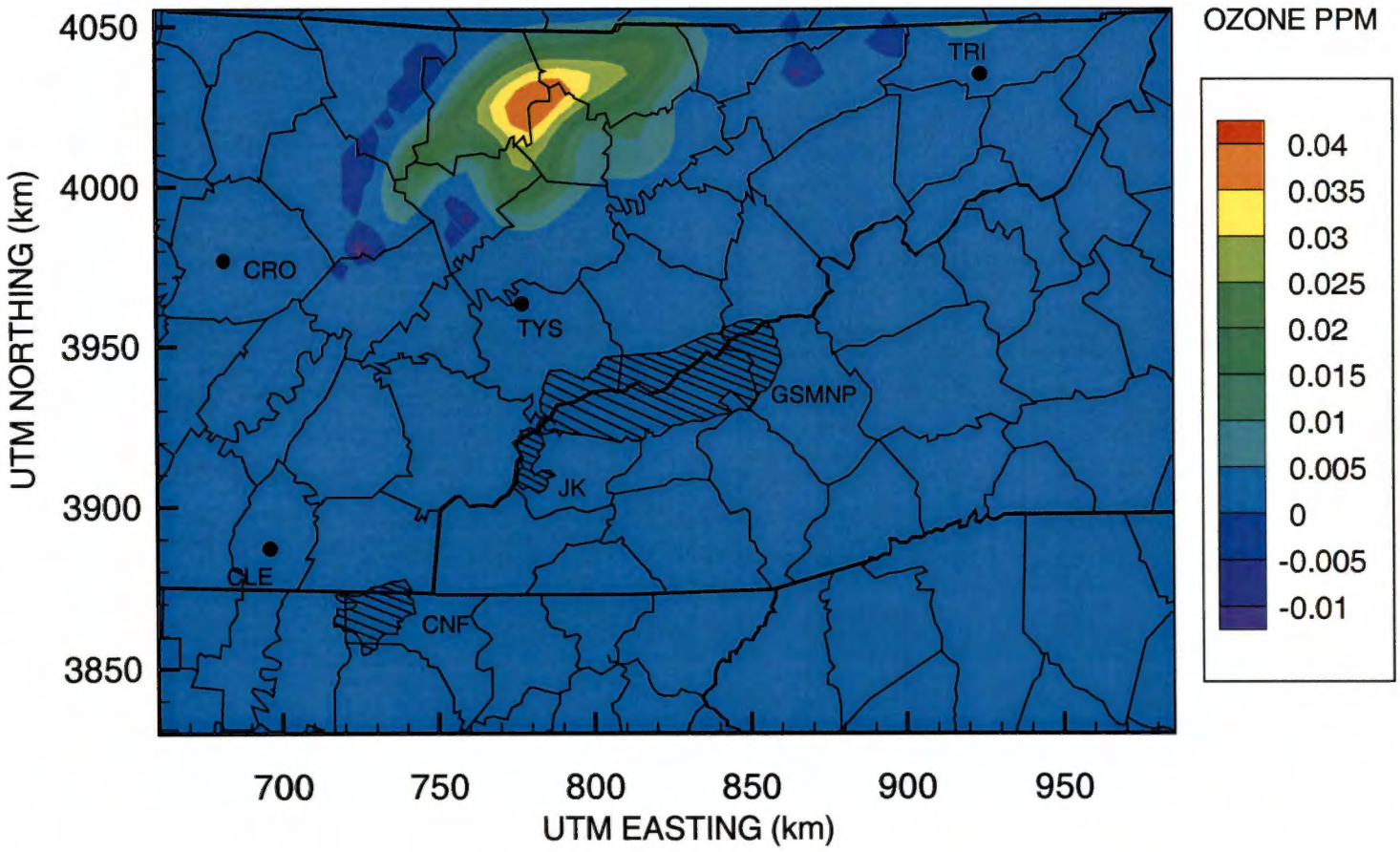
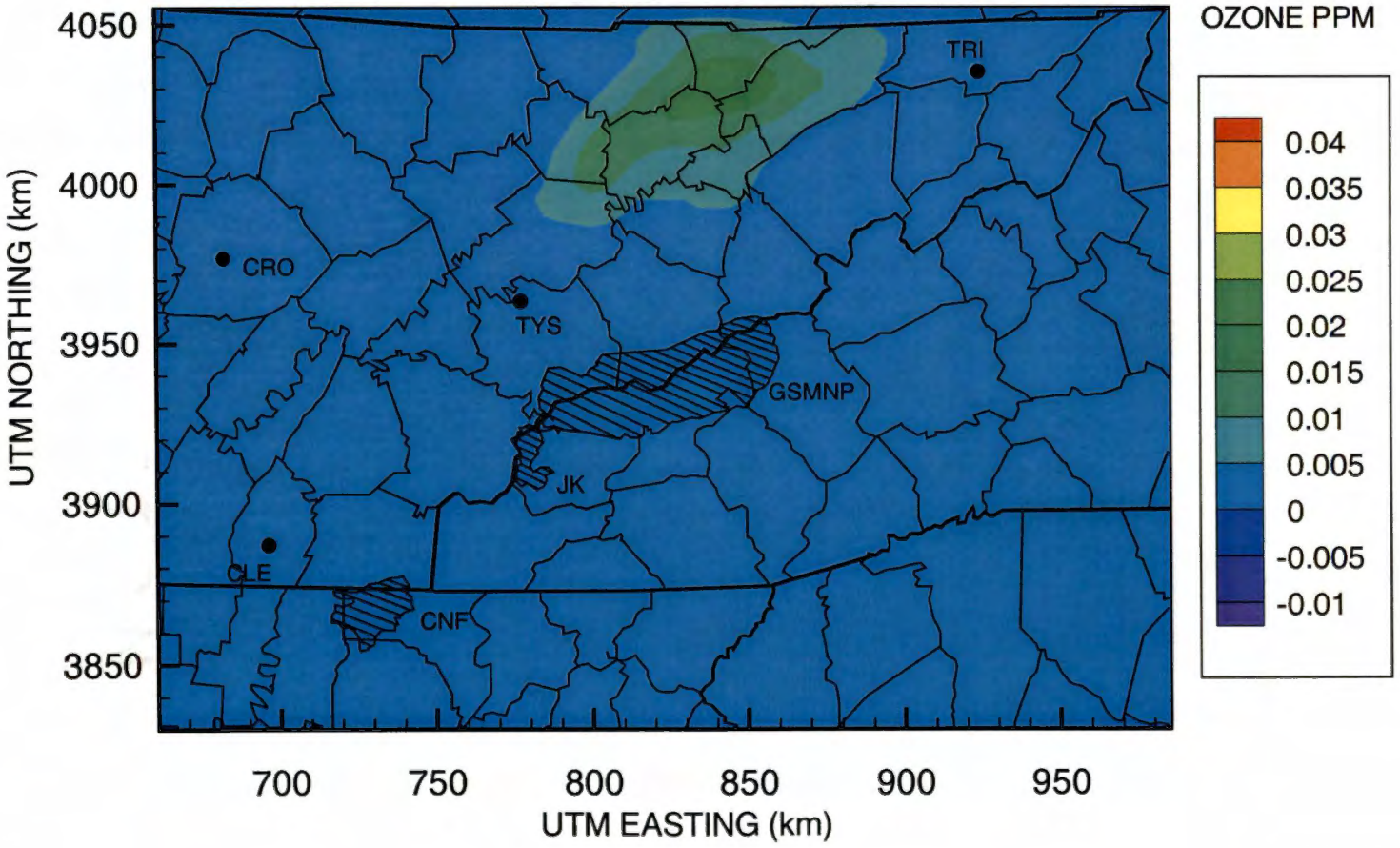


Figure 4-8. Difference Plot, July 20, 1995, 7 P.M., 1-Hour Average, Base Case Minus 50 Percent Area and Mobile Source NO_x Reductions.

DIFFERENCE PLOT, JULY 20, 1995, 7 P.M., 1-HOUR AVERAGE,
BASE CASE MINUS 50 PERCENT AREA & MOBILE SOURCE REDUCTION,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.018 PPM.



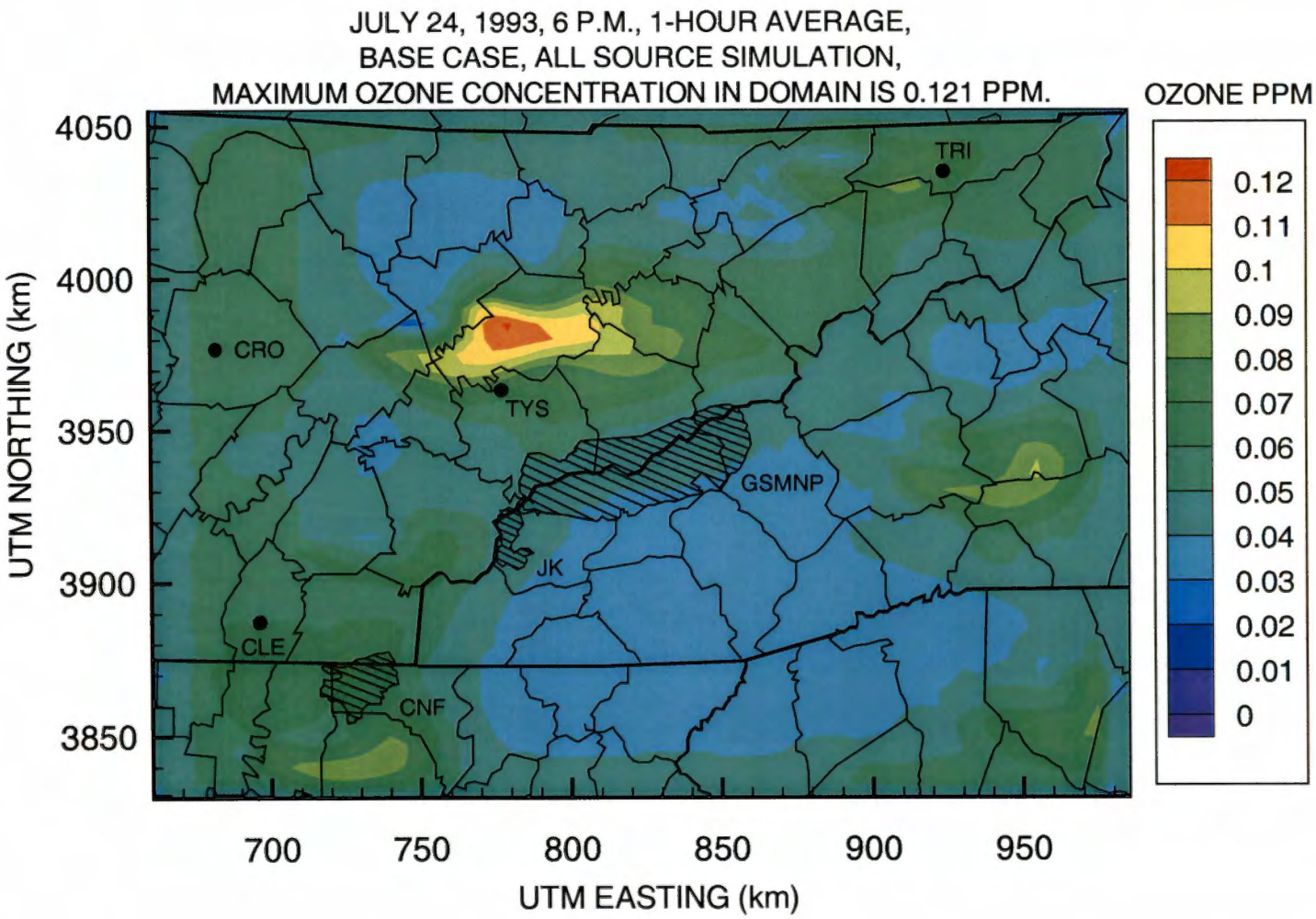
Looking at another day, July 24, 1993, in the base case 1-hour average scenario, 121 ppb was the maximum predicted ozone concentration in the East Tennessee Modeling Domain. The only change in input data from July 20, 1995 to July 24, 1993 modeling scenarios was meteorological data - wind speeds and directions and ambient temperature.

Figure 4-9 displays peak ozone concentrations in the modeling domain for the July 24 base case scenario. The peak occurred at 6 P.M. and was centered on Knox County. By reducing 70 percent NO_x emissions from Kingston Power Plant, the peak ozone concentration dropped 18 ppb to 103 ppb. The most effective NO_x reductions were from three TVA power plants and all elevated point sources. Both of these scenarios predicted 98 ppb ozone in the modeling domain. Less effective in reducing ozone concentrations was the 50 percent area and mobile source NO_x reduction scenario, with a mere 1 ppb reduction in ozone. Reducing 70 percent NO_x from Bull Run Power Plant by itself caused a 6 ppb reduction in peak ozone concentration, not as effective as controlling 70 percent of the NO_x from Kingston Power Plant (18 ppb reduction) and not nearly as effective as reducing 70 percent of NO_x emissions simultaneously from both Kingston and Bull Run Power Plants (23 ppb).

The maximum difference of the 1-hour averages on July 24, 1993 was 40 ppb for two scenarios, both 70 percent NO_x reduction at three TVA power plants and 70 percent NO_x reduction at all elevated point sources. Controlling emissions from three TVA power plants would be less expensive than controlling emissions from all elevated point sources

Figure 4-9. July 24, 1993, 6 P.M., 1-Hour Average,

Base Case, All Source Simulation.


JULY 24, 1993, 6 P.M., 1-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.121 PPM.
OZONE PPM
0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)
TRI
CRO
TYS
GSMNP
JK
CLE
CNF

in the modeling domain. Figure 4-10 shows the isopleths of ozone concentration for the difference plot of base case minus 70 percent NO_x reduction at three TVA power plants. About half as effective was the scenario of 50 percent area and mobile source NO_x reduction, which had a 20 ppb maximum difference in ozone concentration. The maximum difference for 50 percent area and mobile source NO_x reduction is shown in Figure 4-11.

8-HOUR AVERAGE OZONE CONCENTRATIONS

Peak Concentrations

Of the 8-hour average ozone concentrations predicted by UAM, the base case scenario had the highest concentration for all four days. The peak on July 20, 1995 was 104 ppb. On July 24,1993 the peak was 108 ppb; on July 25 it was 125 ppb, and the July 26 peak was 139 ppb. The scenario that predicted the lowest ozone concentration in the modeling domain was 70 percent NO_x reduction at all elevated point sources. Almost identical to those were the low concentrations predicted by the scenario of 70 percent NO_x reduction at three TVA power plants. Two days, July 20 and July 26, had ozone concentrations 1 ppb higher from the scenario 70 percent NO_x reduction at three TVA power plants than were predicted by 70 percent NO_x reduction at all elevated point sources. The results of those two scenarios were very similar, for 8-hour averages and for 1-hour averages, and it would be cheaper to control NO_x emissions from only three plants than from all elevated point sources.

Figure 4-10. Difference Plot, July 24, 1993, 6 P.M., 1-Hour Average, Base Case Minus 70 Percent NO_x Reduction at 3 TVA Power Plants.

DIFFERENCE PLOT, JULY 24, 1993, 6 P.M., 1-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT NOx REDUCTION AT 3 TVA POWER PLANTS,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.040 PPM.

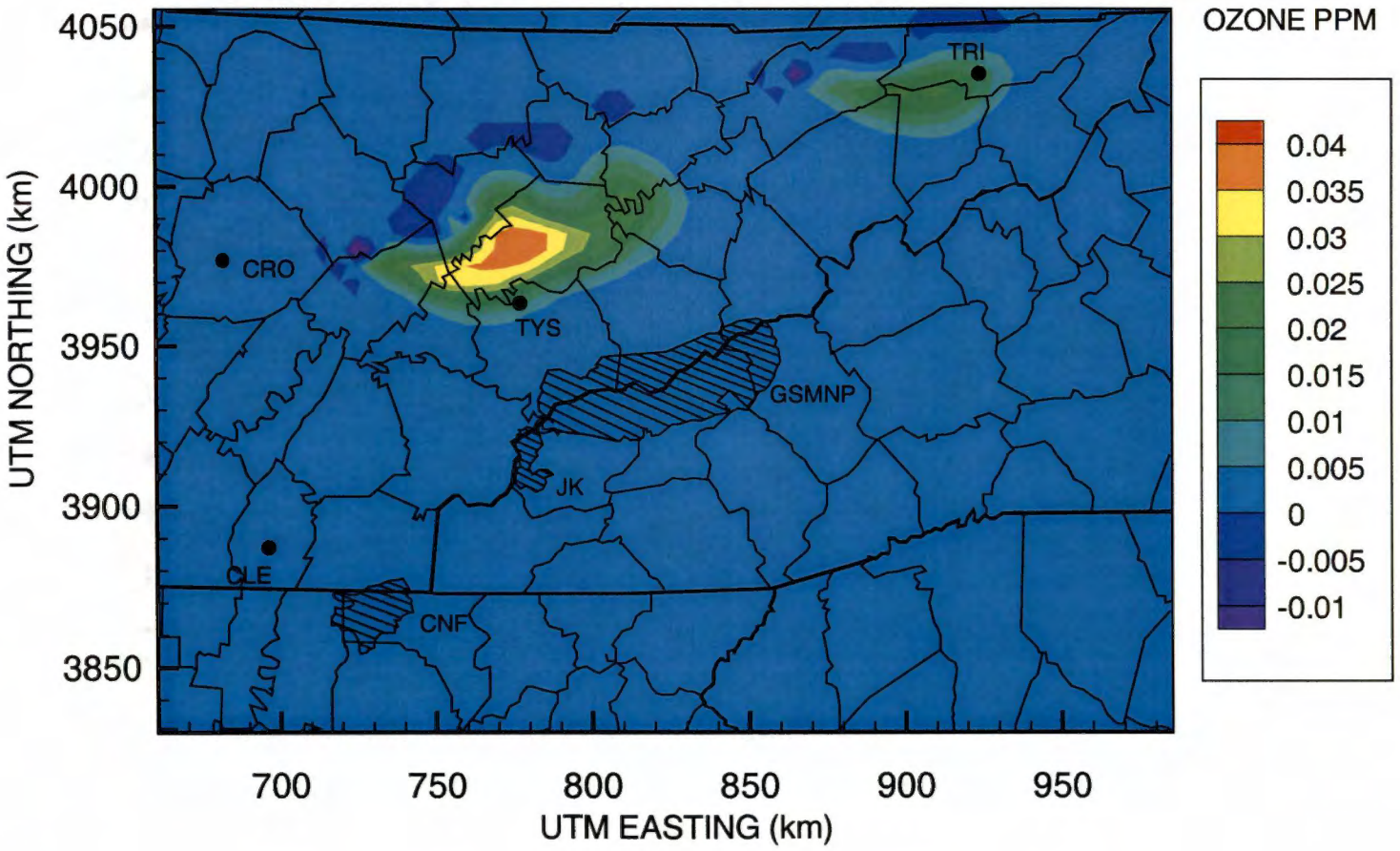
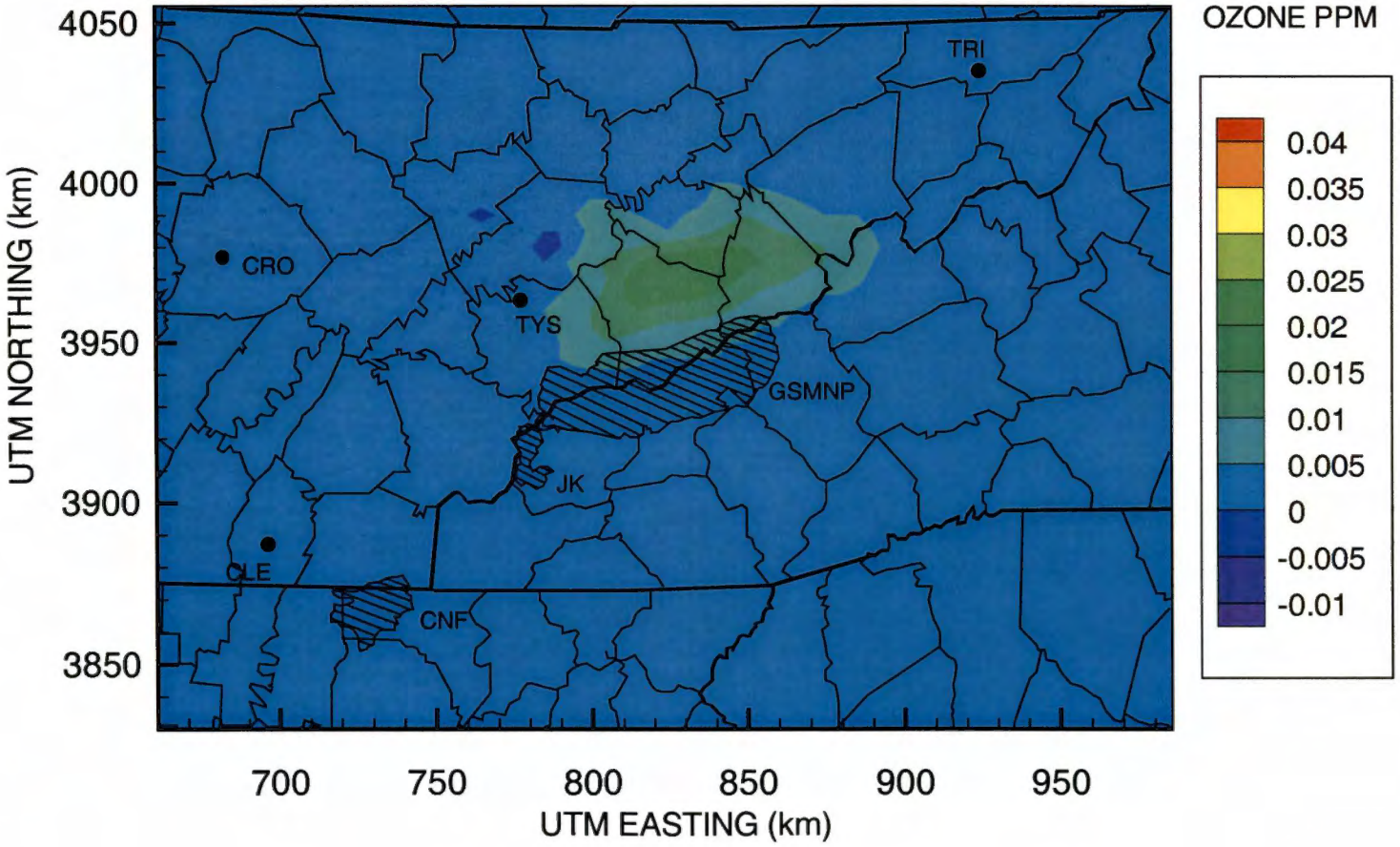


Figure 4-11. Difference Plot, July 24, 1993, 8 P.M., 1-Hour Average, Base Case Minus 50 Percent Area and Mobile Source NO_x Reduction.

DIFFERENCE PLOT, JULY 24, 1993, 8 P.M., 1-HOUR AVERAGE,
BASE CASE MINUS 50 PERCENT AREA & MOBILE SOURCE NOx REDUCTION,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.020 PPM.



In 8-hour average terminology, the leading hour is the identifying hour, meaning that an 8-hour average at 9 A.M. covers the hours 9 A.M. through 5 P.M. In this document, the hour refers to the end of the hour; 8 A.M. to 9 A.M. is called 9 A.M. So for an 8-hour average at 9 A.M., the time period covered is 8 A.M. until 4 P.M.

Development of the ozone plume on July 20, 1995 is shown in Figures 4-12 through 4-15. Figure 4-12 presents 8-hour average concentrations of ozone for the base case scenario at 9 A.M. and represents the time of 8 A.M. up to 4 P.M. The Knoxville urban area is visible in yellow in the center of the domain. Contributing to the western portion of the Knoxville urban plume were Kingston Power Plant and Bull Run Power Plant. The ozone plume of John Sevier Power Plant is visible in the top right of the domain. The Asheville, North Carolina and Greenville-Spartanburg, South Carolina urban areas are also visible in yellow. The interstate highway corridor in light green with ozone concentrations of 50 to 60 ppb extends from the Tri-Cities in the northeast of the domain to Knoxville in the center and southwest on to Cleveland, Tennessee. South of the Smoky Mountains, in western North Carolina, were the lowest ozone concentrations of the domain ranging from 30 to 40 ppb. These concentrations are lower than those typically measured in the higher elevations of the Smoky Mountains and may be the result of model input information that specified 40 ppb of ozone at the top boundary of the modeling domain.

Figure 4-12. July 20, 1995, 9 A.M., 8-Hour Average, Base Case, All Source Simulation.

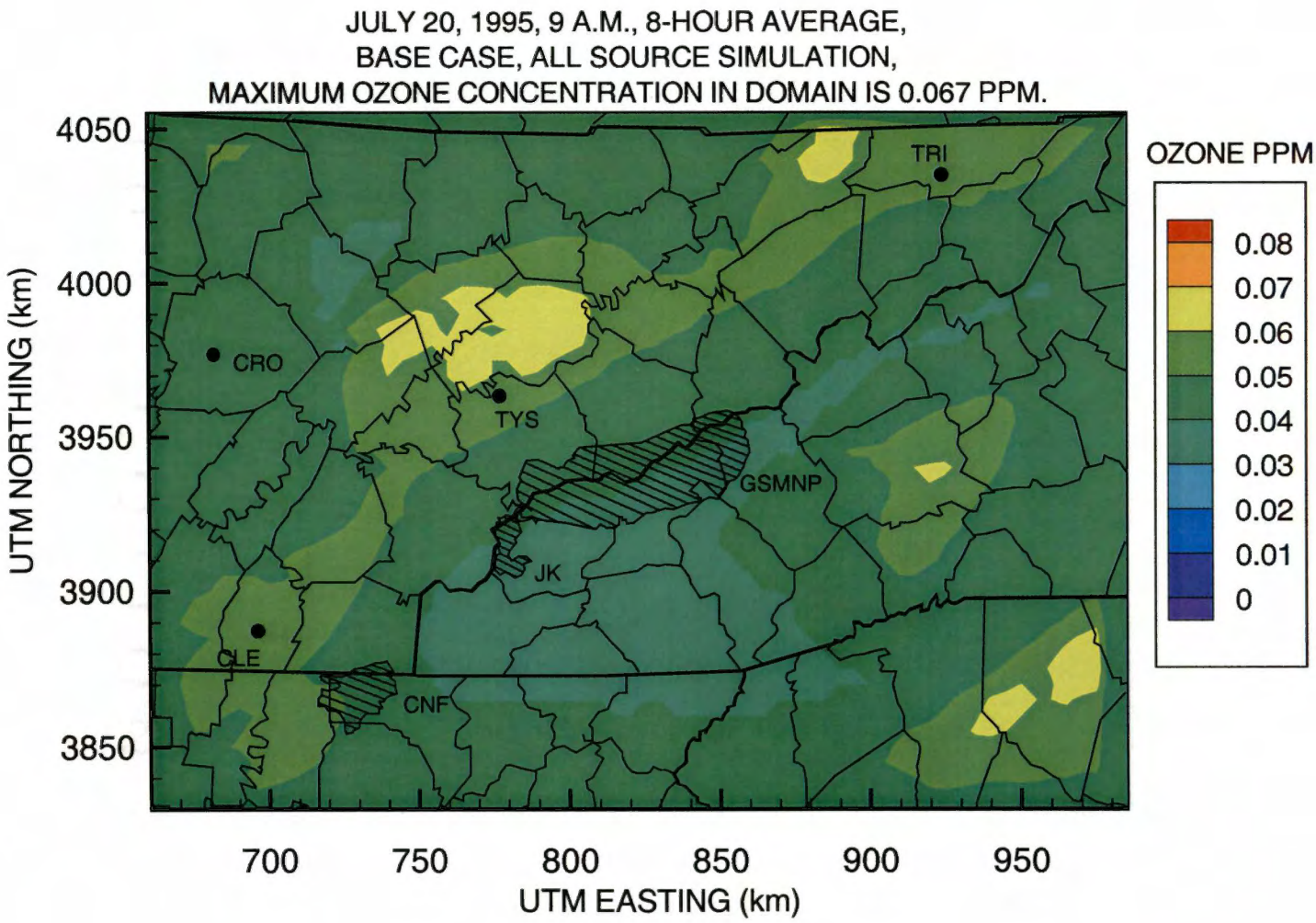

JULY 20, 1995, 9 A.M., 8-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.067 PPM.
OZONE PPM
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)

Figure 4-13. July 20, 1995, 11 A.M., 8-Hour Average, Base Case, All Source Simulation.

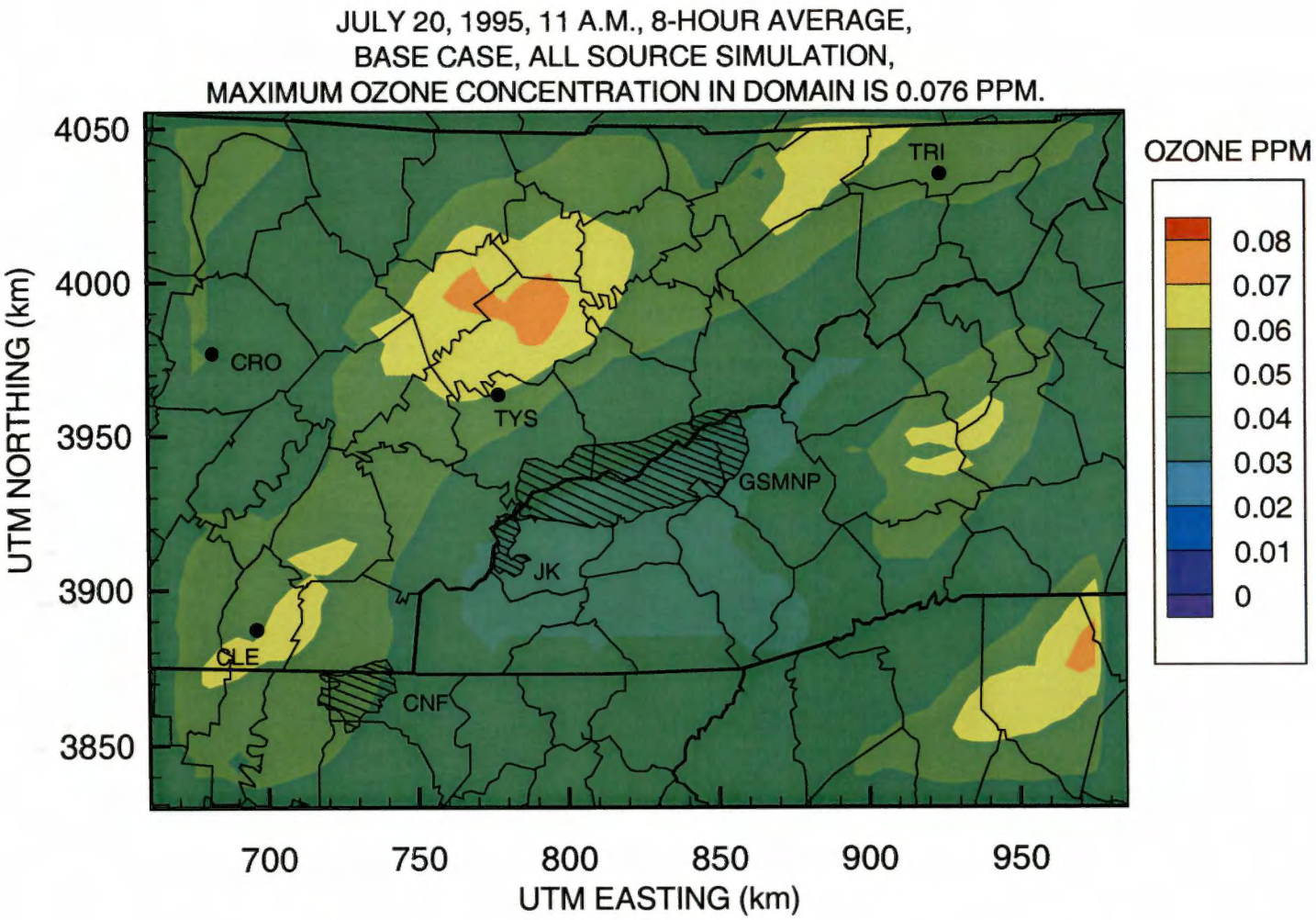

JULY 20, 1995, 11 A.M., 8-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.076 PPM.
OZONE PPM
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)

Figure 4-14. July 20, 1995, 2 P.M., 8-Hour Average, Base Case, All Source Simulation.

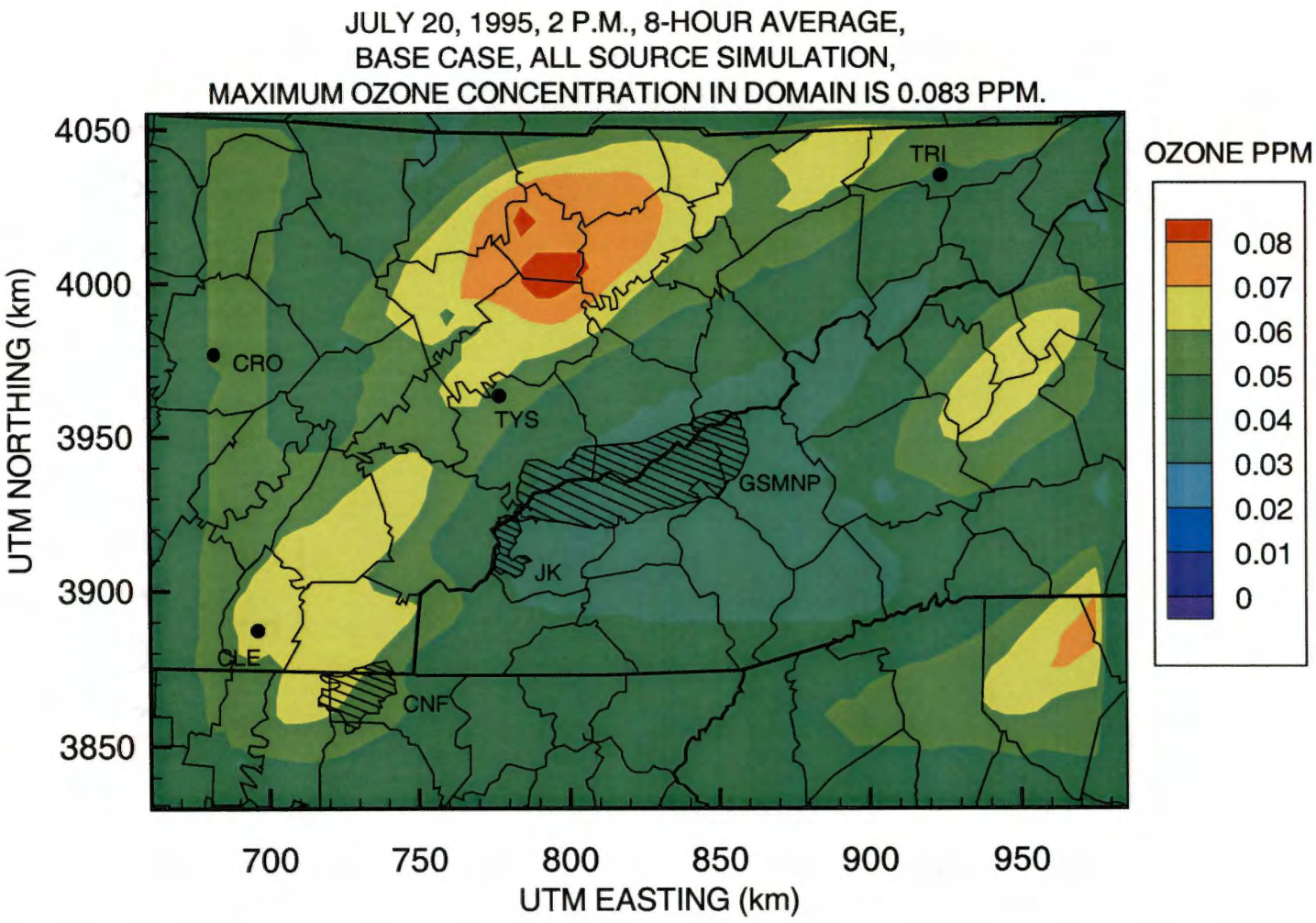
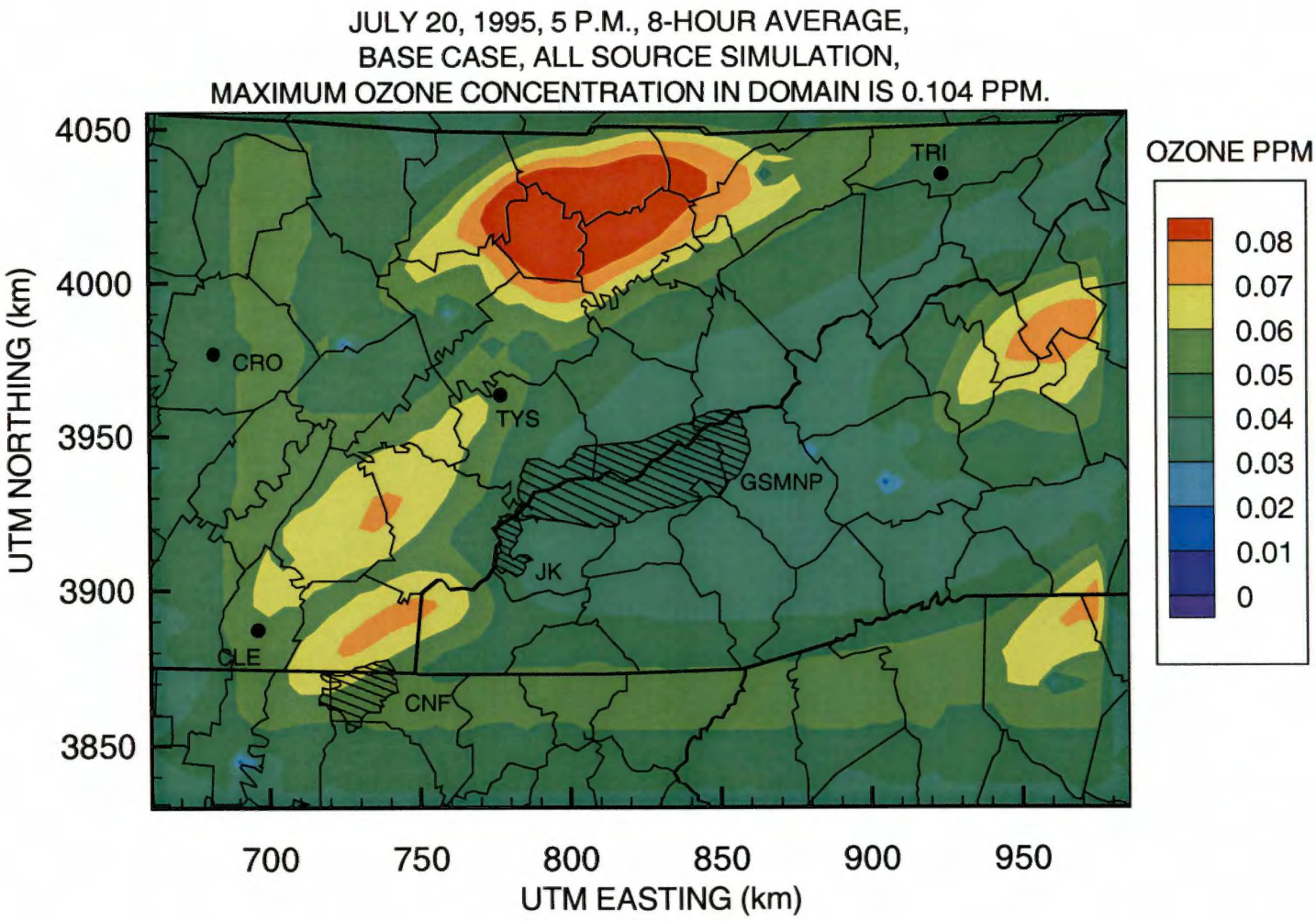

JULY 20, 1995, 2 P.M., 8-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.083 PPM.
UTM NORTHING (km)
4050
4000
3950
3900
3850
700
750
800
850
900
950
UTM EASTING (km)
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
OZONE PPM
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

Figure 4-15. July 20, 1995, 5 P.M., 8-Hour Average,

Base Case, All Source Simulation.


JULY 20, 1995, 5 P.M., 8-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.104 PPM.
OZONE PPM
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)

In Figure 4-13, with 8-hour averages occurring at 11 A.M., ozone concentrations rose to 76 ppb in the Knoxville urban plume. High ozone concentrations were spreading out from the urban areas and interstate corridor across the domain. By 2 P.M. in Figure 4-14, the ozone concentration had passed the 80 ppb proposed NAAQS level to a peak of 83 ppb, again in the Knoxville urban plume. The plume began to move northward in accordance with the wind direction of that day.

The peak concentration on July 20, 1995 was predicted to be 104 ppb at 5 P.M., the last 8-hour average of the day, as portrayed in Figure 4-15. The Knoxville urban plume moved further north and east. A large area of East Tennessee is covered by an ozone plume with concentrations greater than the 8-hour NAAQS (now remanded) of 80 ppb. Scavenging began to occur by 5 P.M. as evidenced by the blue dots at Kingston and Bull Run Power Plants, and at large point sources in North Carolina.

Much larger areas experienced ozone concentrations higher than the standard under the 8-hour average than occurred with the 1-hour average standard, demonstrating that the 8-hour standard is more stringent than the 1-hour standard.

Maximum Differences

Maximum difference values were calculated for the 8-hour average concentrations. On all days but one, the maximum difference resulted from two scenarios, 70 percent NO_x reduction at all elevated point sources and 70 percent NO_x reduction at three TVA power

plants. The one exception was July 26, 1993 when the all elevated point source scenario predicted 1 ppb more reduction in ozone than the scenario of three TVA power plants. Figures 4-16 and 4-17 show difference plots of these two scenarios for July 20, 1995. The plots are almost identical. The difference plot for 70 percent NO_x reduction at all elevated point sources, Figure 4-17, shows a few more purple locations. The explanation is the same as for the 1-hour averages. Purple indicates a negative reduction or an increase in ozone concentration when NO_x emissions were reduced. This is caused by higher NO_x emissions from elevated point sources in the base case where the high NO_x emissions react to scavenge nearby ozone and artificially lower localized ozone concentrations. When NO_x emissions are reduced, ozone scavenging does not occur, and it appears that ozone concentrations increase, but that is not the case. The base case ozone concentrations were merely scavenged in a small, localized area near large NO_x sources.

Figure 4-18 shows concentration differences due to 70 percent NO_x reduction at Kingston Power Plant. Close to the same ozone differences occurred when reducing NO_x emissions from Kingston alone, 28 ppb, as when reducing NO_x emissions from three TVA power plants, 35 ppb. This demonstrates the large effect Kingston had on East Tennessee ozone levels.

The effect of 50 percent NO_x reduction in area and mobile sources is shown in Figure 4-19 for July 20, 1995. The effect was about half that resulting from NO_x reductions at

Figure 4-16. Difference Plot, July 20, 1995, 5 P.M., 8-Hour Average, Base Case Minus 70 Percent NO_x Reduction at 3 TVA Power Plants.

DIFFERENCE PLOT, JULY 20, 1995, 5 P.M., 8-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT NOx REDUCTION AT 3 TVA POWER PLANTS,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.035 PPM.

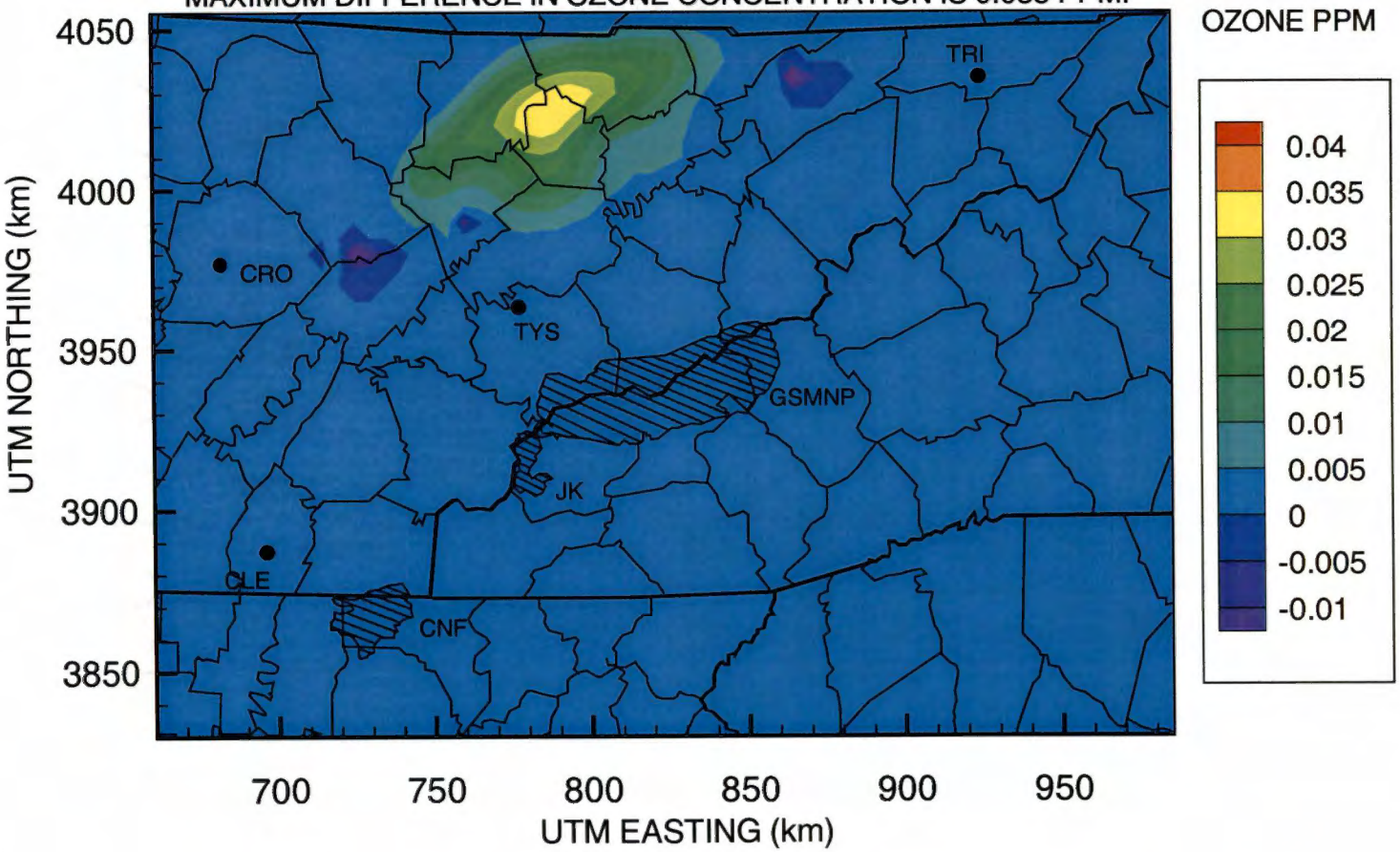


Figure 4-17. Difference Plot, July 20, 1995, 5 P.M., 8-Hour Average, Base Case Minus 70 Percent NO_x Reduction at All Elevated Point Sources.

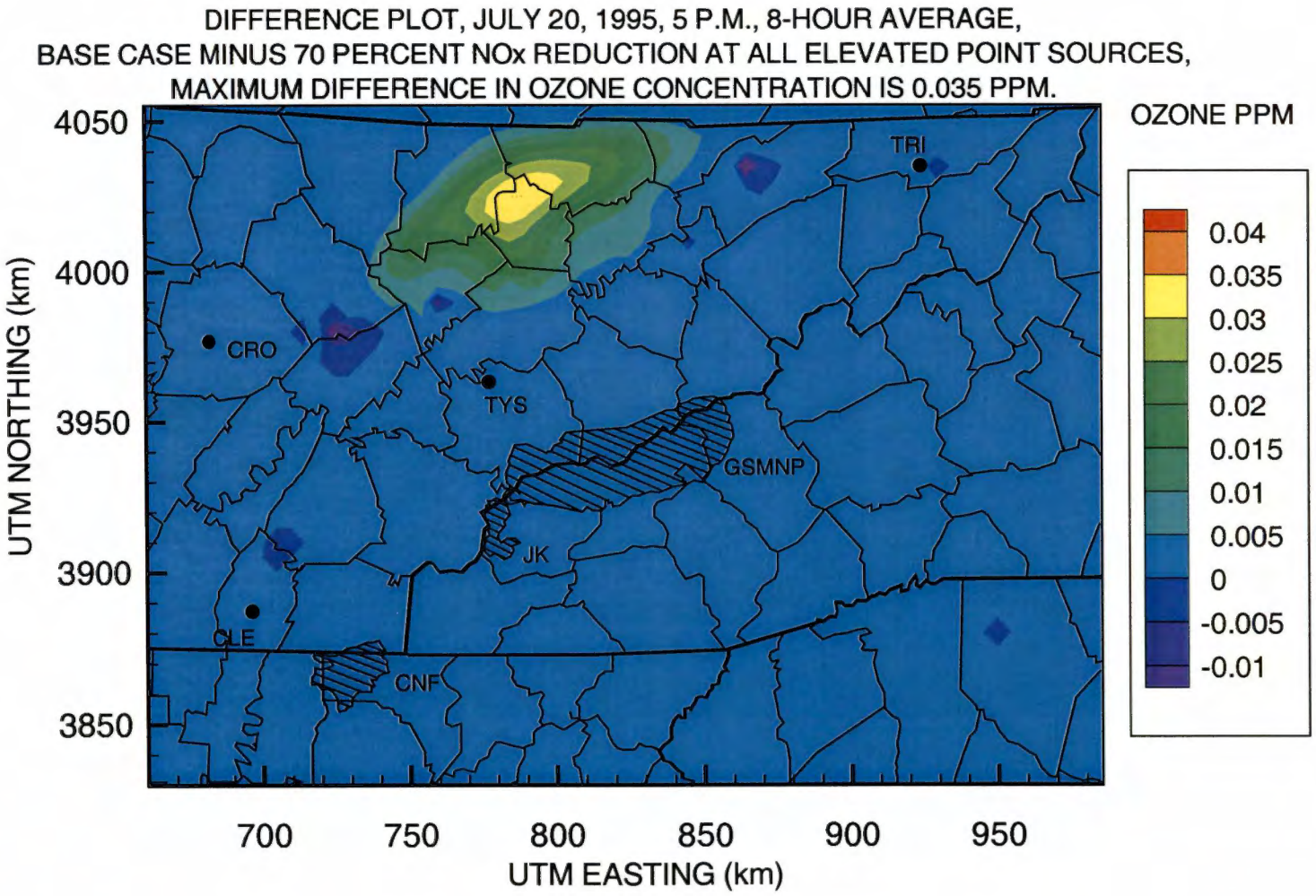

DIFFERENCE PLOT, JULY 20, 1995, 5 P.M., 8-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT NOx REDUCTION AT ALL ELEVATED POINT SOURCES,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.035 PPM.
OZONE PPM
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
UTM NORTHING (km)
4050
4000
3950
3900
3850
UTM EASTING (km)
700
750
800
850
900
950
TRI
CRO
TYS
GSMNP
JK
CLE
CNF

Figure 4-18. Difference Plot, July 20, 1995, 5 P.M., 8-Hour Average, Base Case Minus 70 Percent Kingston NO_x Reduction.

DIFFERENCE PLOT, JULY 20, 1995, 5 P.M., 8-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT KINGSTON NOx REDUCTION,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.028 PPM.

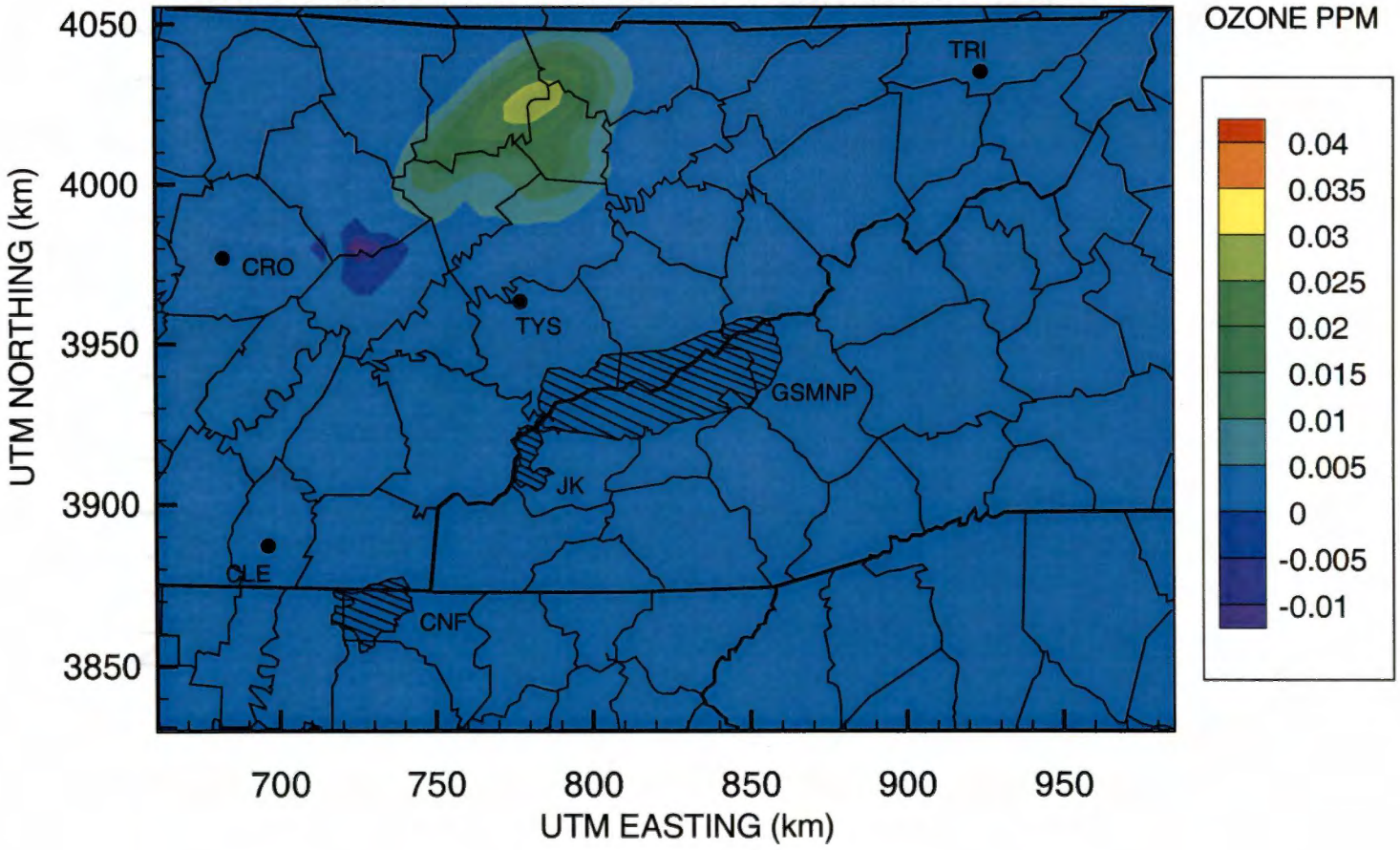
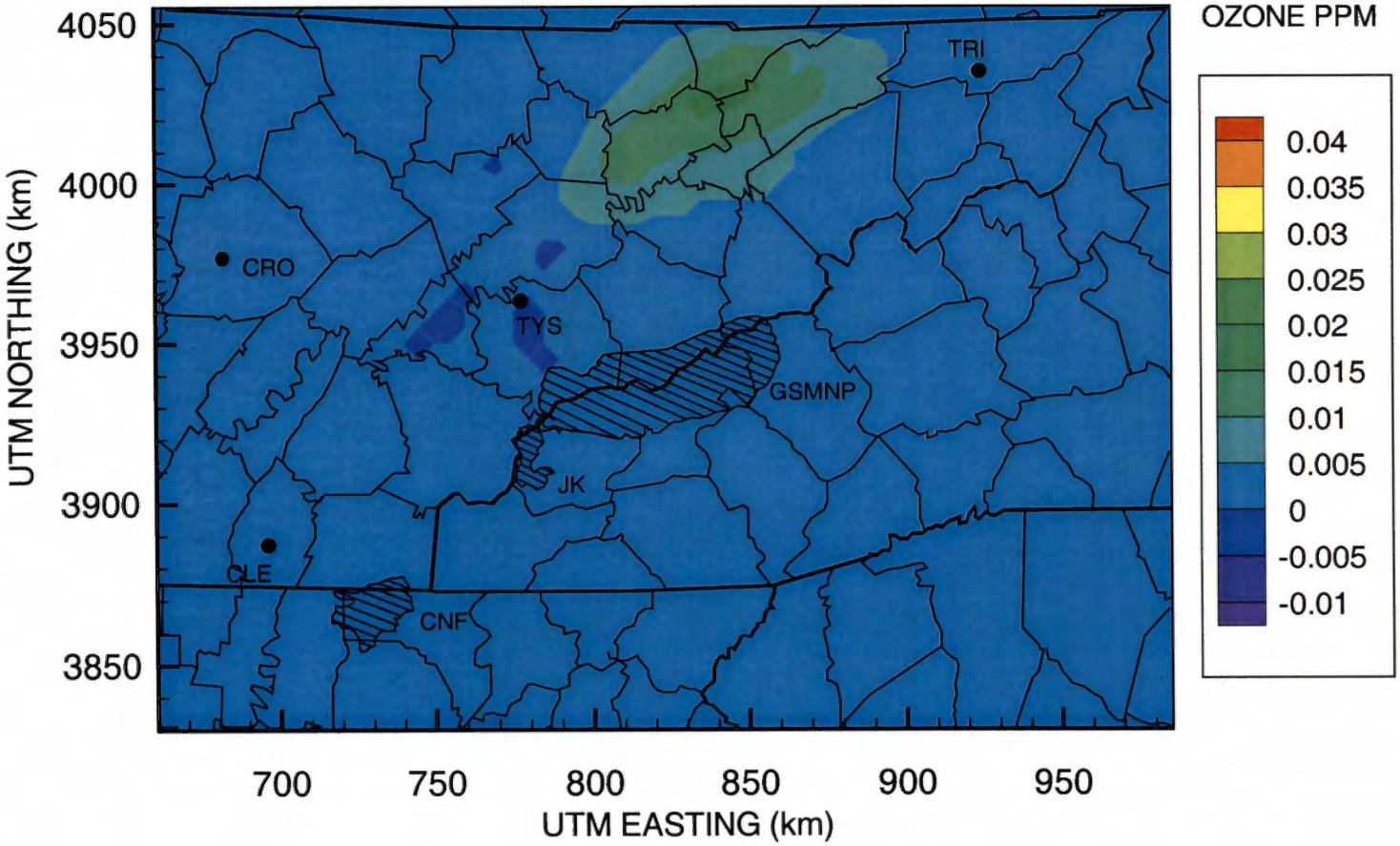


Figure 4-19. Difference Plot, July 20, 1995, 5 P.M., 8-Hour Average, Base Case Minus 50 Percent Area and Mobile Source NO_x Reduction.

DIFFERENCE PLOT, JULY 20, 1995, 5 P.M., 8-HOUR AVERAGE,
BASE CASE MINUS 50 PERCENT AREA & MOBILE SOURCE REDUCTION,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.016 PPM.

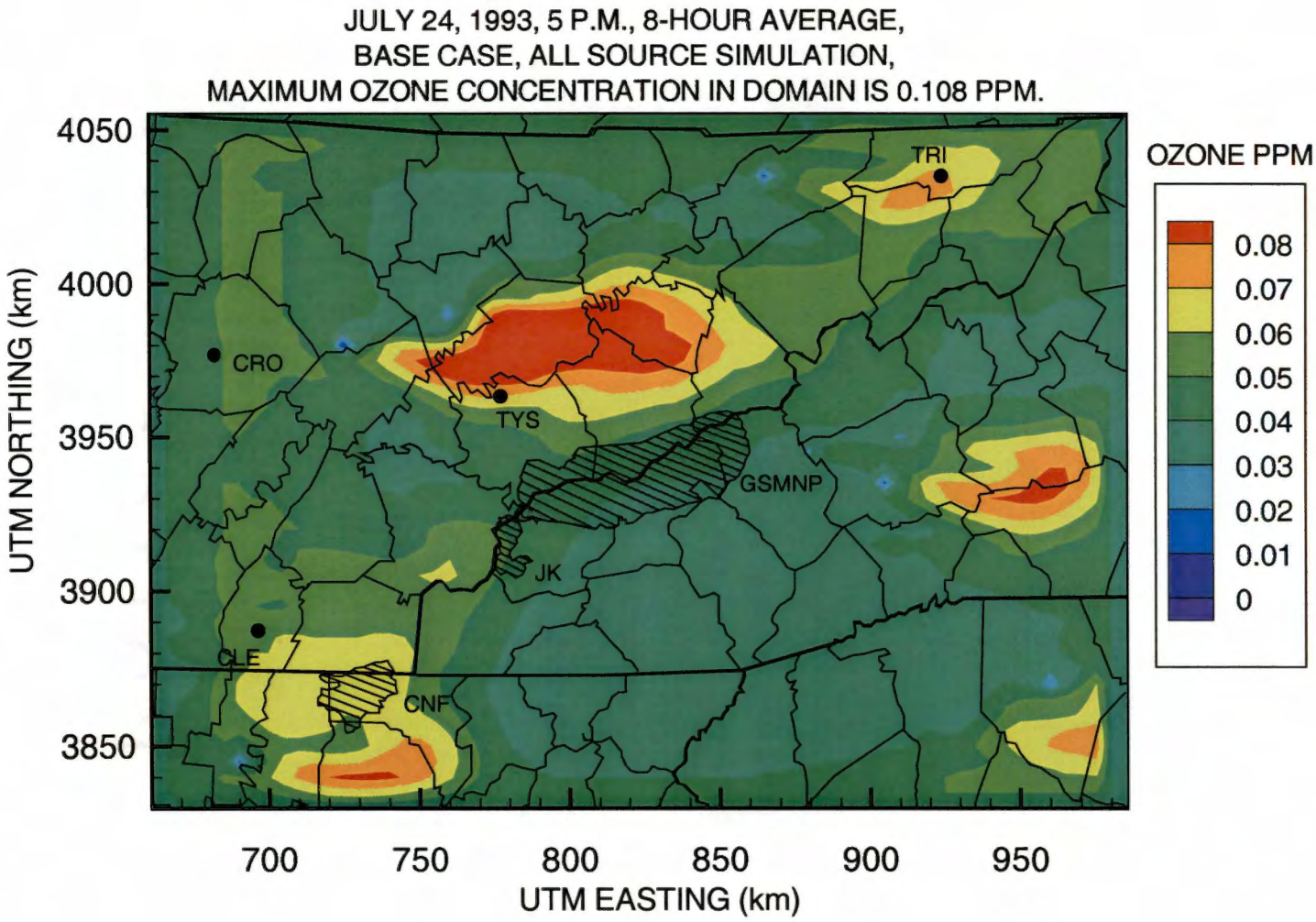


three TVA power plants or from NO_x reductions at all elevated point sources. The ozone decreases in Figure 4-19 are in a more easterly location than the decreases that resulted from NO_x reductions at Kingston or three TVA power plants or all elevated point sources. The decreases due to area and mobile source NO_x reductions originated at a different location - the Knoxville urban area. The decreases due to the other scenarios - Kingston, three TVA power plants, and all elevated point sources - appear to be dominated by NO_x emissions from Kingston and Bull Run Power Plants.

Showing much less effect were NO_x reductions of 10 and 30 percent from area and mobile sources. Maximum difference values from Table 4-2 show that 30 percent NO_x reductions produced half the ozone change that 50 percent NO_x reductions did or between 9 and 13 ppb. NO_x reductions of 10 percent from area and mobile sources altered ozone concentrations only 3 to 4 ppb, truly "shaving the peaks" on a high ozone day.

Another day, July 24, 1993, is shown graphically to illustrate the effect that meteorology has on model predictions. The peak 8-hour average ozone concentration is shown in Figure 4-20. The peak occurred at 5 P.M., the last 8-hour period of the day and was 108 ppb, well over the remanded NAAQS of 80 ppb. The portion of the plume with concentrations over the standard covered most of Knox County and large parts of Jefferson and Sevier Counties. Scavenging had begun by this time demonstrated by the blue dots at Kingston Power Plant, Bull Run Power Plant, John Sevier and other

Figure 4-20. July 24, 1993, 5 P.M., 8-Hour Average, Base Case, All Source Simulation.


JULY 24, 1993, 5 P.M., 8-HOUR AVERAGE,
BASE CASE, ALL SOURCE SIMULATION,
MAXIMUM OZONE CONCENTRATION IN DOMAIN IS 0.108 PPM.
UTM NORTHING (km)
4050
4000
3950
3900
3850
700
750
800
850
900
950
UTM EASTING (km)
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
OZONE PPM
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

locations. The large quantity of NO_x emissions from these point sources scavenged ozone and lowered local ozone concentrations.

A difference plot for July 24 is shown in Figure 4-21. The scenario is base case minus 70 percent NO_x reduction at three TVA power plants, and the maximum difference was 35 ppb at 5 P.M. The reduced ozone concentration occurred mainly in Knox County, and large portions of Jefferson and Sevier Counties experienced lesser ozone reductions in the 10 to 20 ppb range. An area in the northeast corner of the domain, near the Tri-Cities, had ozone reductions of 5 to 10 ppb due to NO_x reductions at John Sevier Power Plant. For this particular day, controlling NO_x emissions from Kingston and Bull Run Power Plants made a 35 ppb change in Knox County ozone levels. Again, the purple areas in a difference plot represent areas where scavenging occurred in the base case and where no scavenging occurred when NO_x emissions were reduced in the emission-altered scenario. The purple areas do not represent increased ozone levels.

The difference scenario of 50 percent area and mobile source NO_x reductions is presented in Figure 4-22. The maximum difference in ozone levels was 19 ppb for this scenario. The difference plume was centered further east in this scenario than it was in the previous scenario, shown in Figure 4-21, of 70 percent NO_x reduction at three TVA power plants. The reason is the NO_x reductions originated in an area located further east. Area and mobile source emission reductions, in Figure 4-22, originated in the highly populated

Figure 4-21. Difference Plot, July 24, 1993, 5 P.M., 8-Hour Average, Base Case Minus 70 Percent NO_x Reduction at 3 TVA Power Plants.

DIFFERENCE PLOT, JULY 24, 1993, 5 P.M., 8-HOUR AVERAGE,
BASE CASE MINUS 70 PERCENT NOx REDUCTION AT 3 TVA POWER PLANTS,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.035 PPM.

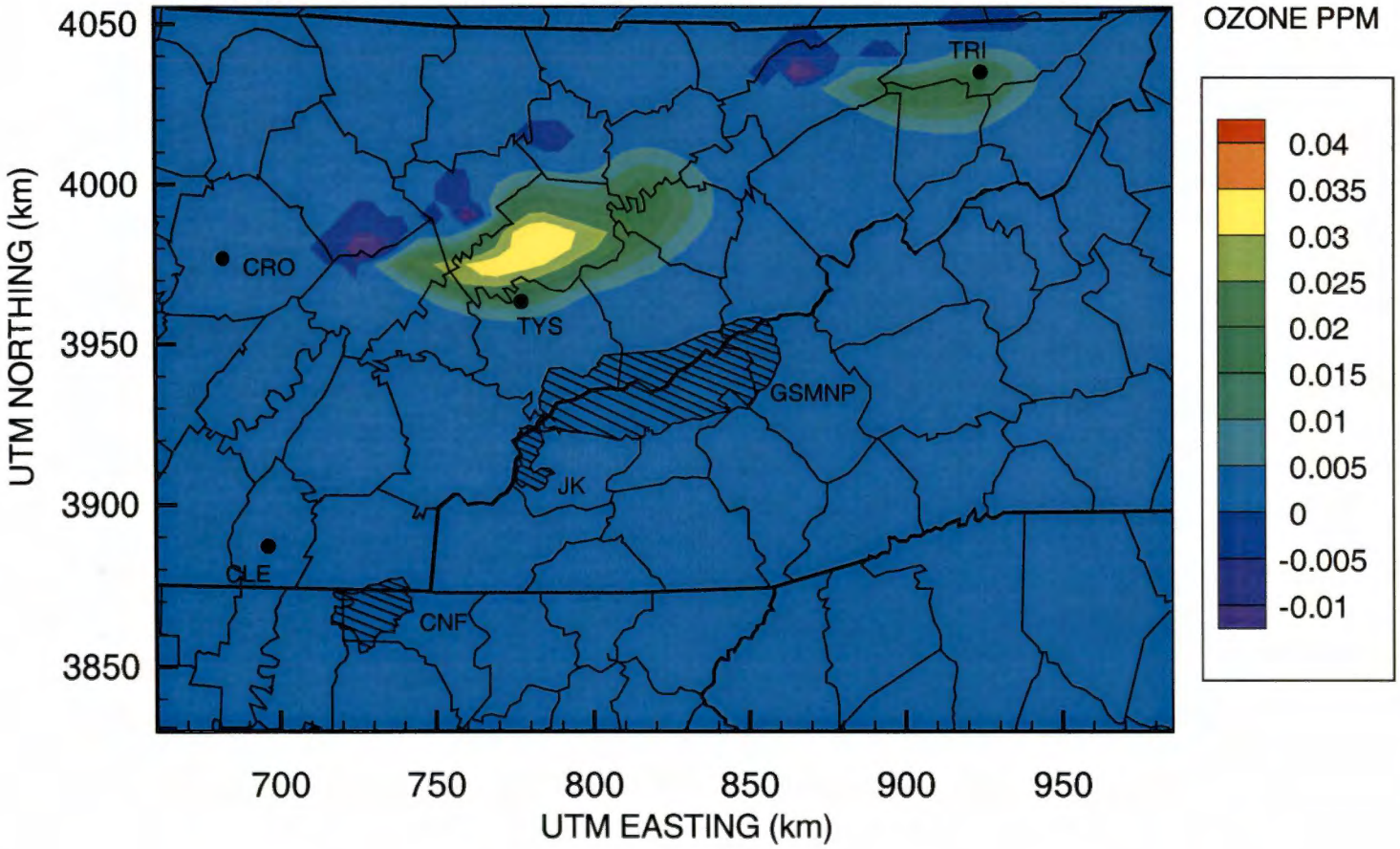
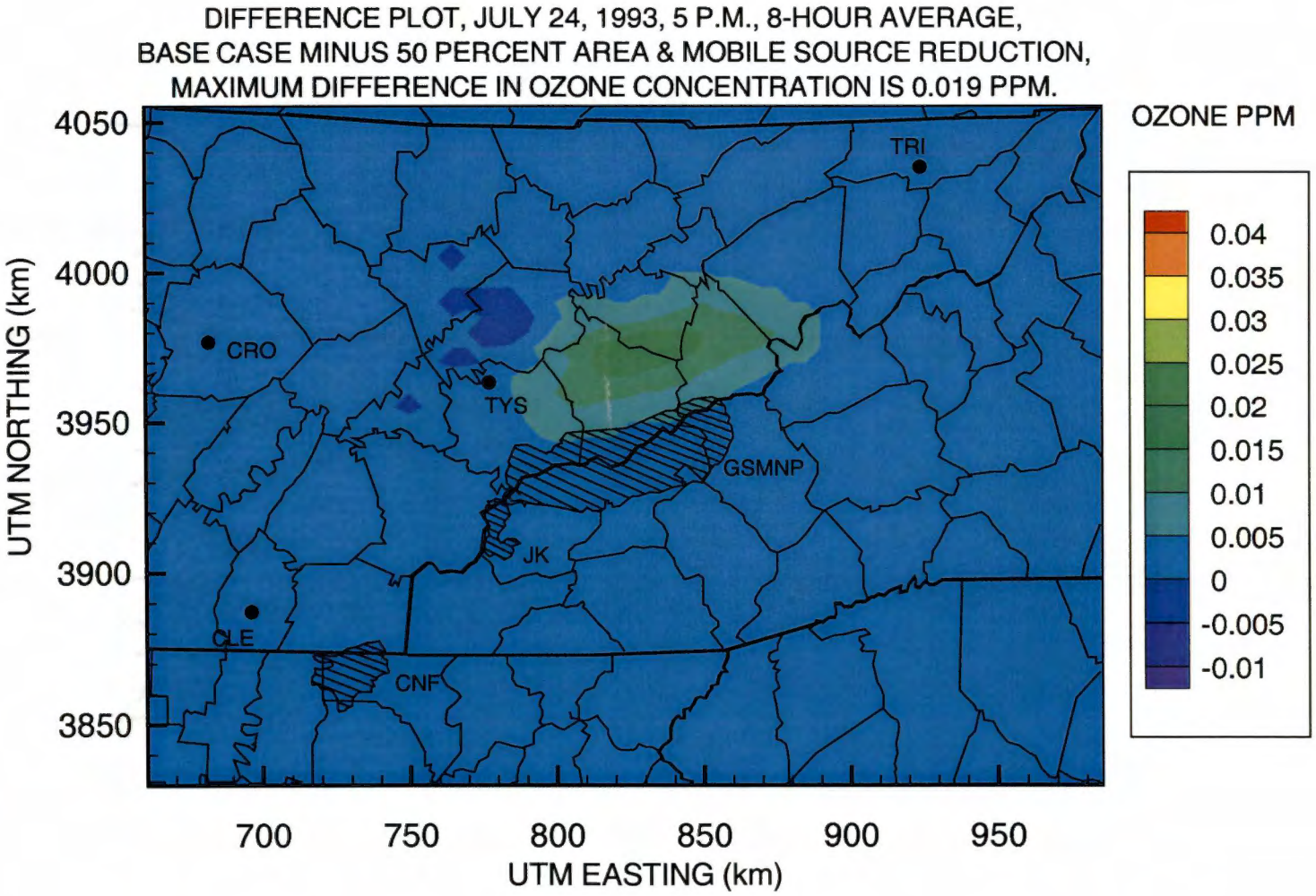


Figure 4-22. Difference Plot, July 24, 1993, 5 P.M., 8-Hour Average, Base Case Minus 50 Percent Area and Mobile Source NO_x Reduction.


DIFFERENCE PLOT, JULY 24, 1993, 5 P.M., 8-HOUR AVERAGE,
BASE CASE MINUS 50 PERCENT AREA & MOBILE SOURCE REDUCTION,
MAXIMUM DIFFERENCE IN OZONE CONCENTRATION IS 0.019 PPM.
OZONE PPM
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
-0.005
-0.01
TRI
CRO
TYS
GSMNP
JK
CLE
CNF
4050
4000
3950
3900
3850
UTM NORTHING (km)
700
750
800
850
900
950
UTM EASTING (km)

Knox County urban area, east of Kingston and Bull Run Power Plants that were the source of emission reductions in Figure 4-21.

Cost Analysis

A cost analysis of NO_x reductions was performed to determine the cost effectiveness of different NO_x reduction scenarios. The following sections present cost data for point source NO_x reductions and for area and mobile source reductions.

COST OF POINT SOURCE NO_X REDUCTIONS

Costs of point source NO_x reductions using SCR were estimated for four different emission scenarios:

70 percent NO_x reduction at Kingston Power Plant,
70 percent NO_x reduction at Bull Run Power Plant,
70 percent NO_x reduction at three TVA power plants, and
70 percent NO_x reduction at All Elevated Point Sources.

Table 4-3 lists the results of the point source cost analysis. Cost factors from Table 3-6 were used to calculate a range of costs for both annual and seasonal operation of a SCR system. NESCAUM/MARAMA was the only reference to provide seasonal cost factors. The other two references, OTAG and STAPPA/ALAPCO, provided annual cost factors which were used to calculate seasonal costs. NESCAUM/MARAMA cited 67 percent and 85 percent removal efficiencies with accompanying cost factors. The 67 percent efficiency was chosen for this analysis because it is easier to achieve, less expensive, and closest in comparison with the efficiencies cited in OTAG and STAPPA/ALAPCO.

Tons of NO_x removed were calculated from the base case emission rates using both 67 and 70 percent removal. Tons per ozone season were calculated from a daily emission rate and multiplied by 153 days per ozone season. The ozone season as used in this study is defined as 153 days long and encompasses May, June, July, August and September.

The size of each source is listed in megawatts (MW) except for All Elevated Point Sources. Not all of these sources generate electricity, some generate steam and are rated differently so a size in megawatts was not applicable. The three TVA power plants account for 58 percent of elevated point source NO_x emissions. Kingston and Bull Run Power Plants together account for 44 percent, almost half of all elevated point source emissions.

The range of costs was calculated in millions of 1998 dollars for seasonal controls and annual controls. For Bull Run Power Plant, SCR NO_x controls were assumed to be operated seasonally, 153 days per year, and ranged in cost from $4 million to $15 million. With annually operated controls, the cost would range from $9 million to $28 million. Kingston Power Plant has almost twice the megawatts of power and NO_x emissions that Bull Run does, and Kingston control costs are almost twice those of Bull Run. Seasonal control costs at Kingston are estimated to be between $7 and $28 million. Costs of

Table 4-3. Cost of Selective Catalytic Reduction for Elevated Point Sources.

Point Source (Size) Reference for Cost	NO_x Removal Efficiency (percent)	NO_x Removed (tons / ozone season)	NO_x Removed (tons / year)	Cost Range for NO_x Removal in Millions of 1998 Dollars[a] (dollars / ozone season)[b] low	(dollars / ozone season)[b] high	(dollars / year) low	(dollars / year) high
Bull Run (950 MW)							
OTAG[c]	70	4587	10,943	6	12	15	28
NESCAUM[d]	67	4390	10,473	8	15	9	16
STAPPA/ALAPCO[e]	70	4587	10943	4	6	10	13
Kingston (1723 MW)							
OTAG	70	8481	20,231	11	22	27	53
NESCAUM	67	8117	19,364	14	28	16	30
STAPPA/ALAPCO	70	8481	23,231	7	10	18	24
John Sevier (800 MW)							
OTAG	70	4391	10,476	6	11	14	27
NESCAUM	67	4204	10,030	7	14	8	15
STAPPA/ALAPCO	70	4391	10,476	4	5	9	13
All Three TVA Plants (3473 MW)							
OTAG	70	17,459	41,650	23	45	56	108
NESCAUM	67	16,711	39,867	29	57	33	61
STAPPA/ALAPCO	70	17,459	41,650	15	21	37	50
All Elevated Point Sources (N/A)							
OTAG	70	29,774	71,130	40	77	96	185
NESCAUM	67	28,539	68,083	78	134	56	104
STAPPA/ALAPCO	70	29,774	71,130	26	36	63	86

Table 4-3. Continued.

a. OTAG cost data were originally in 1996 dollars. STAPPA/ALAPCO cost data were in 1993 dollars. Using the Consumer Price Index (CPI), dollars were brought to a reference year of 1998 to make cost comparisons easy. The CPI for 1993 to 1998 was 1.1283, and for 1996 to 1998 it was 1.0393. <http://www.dismal.com/toolbox/cpi_index.stm>

b. NESCAUM/MARAMA is the only reference to provide costs data specifically for seasonal controls. Data for other seasonal costs (OTAG and STAPPA/ALAPCO) were calculated using annual cost factors and multiplying the tons of NO_x removed in 153 days or the ozone "season." The ozone season extends from May 1 through September 30 and is 153 days long.

c. OTAG - Ozone Transport Assessment Group (OTAG 1996). Costs are on a current dollar basis which accounts for inflation. OTAG cost values are for retrofitted, tangentially-fired, baseload duty utility boilers with 55 to 65 % capacity factors. The costs assume that Low NO_x Burners with Over-Fire Air are already installed. An annual Capital Recovery Factor (CRF) of 0.17 is used in a current dollar analysis. A 20 year recovery period is assumed with a discount rate of 9.2 %. The CRF in constant dollars would be 0.12 if following EPRI Technical Assessment Guide (TAG). Annual operating costs were levelized with a factor of 1.3 based on EPRI TAG, 9.2 % discount rate, 4.1 % inflation rate and zero real escalation rate. Catalyst replacement, on a 4 year cycle, is levelized with a factor of 1.24. Average catalyst life is assumed to be 4-6 years for a retrofit. Catalyst costs are $400 per cubic foot, coal is $1.50 per MBtu, and anhydrous ammonia is $250 per ton.

d. NESCAUM/MARAMA - Northeast States for Coordinated Air Use Management/Mid-Atlantic Regional Air Management Association (NESCAUM/MARAMA 1998). This is retrofit cost. Costs are on a constant dollar basis, disregarding inflation. A capacity factor of 65 % is assumed. Typical boiler size is 330 MW. The CRF is 0.1067 and based on a 15 year life. Nominal cost of money is 9.75 %, inflation is 3 % and real cost of money is 6.55 %. Effects of depreciation and debt service on corporate income tax is ignored. For seasonal controls, extended life is ignored for capital equipment. Catalyst volume is assumed as 300 cubic meters in two layers. Layers are replaced after 24,000 operating hours. Catalyst disposal costs, from German data, are $1200 per cubic meter. Fixed operating and maintenance costs are $100,000 per year.

e. STAPPA/ALAPCO - State and Territorial Air Pollution Program Administrators/Association of Local Air Pollution Control Officers (STAPPA/ALAPCO 1994). These costs assume a 500 MW utility boiler with a 65 % capacity factor. Catalyst life is 5 years at a cost of $400 per cubic foot, catalyst volume is defined by 4000 per hour space velocity. Annual costs of 5 % of total capital are assumed to pay for operation and maintenance, taxes, insurance and administration.

controls operated all year round are $16 to $53 million. All three TVA power plants together, with 3473 megawatts of power, would have seasonal NO_x reduction costs of $15 million to $57 million and annual costs of $33 million to $108 million. All Elevated Point Sources, when running SCR on a seasonal basis, would incur between $26 and $134 million. Annual SCR costs would range from $53 million to $185 million for All Elevated Point Sources in the modeling domain.

The cost factors used to calculate Table 4-3 costs were based on several assumptions, many of which vary from reference to reference. The assumptions are described in the notes to Table 4-3 and also in Table 3-6.

COST OF MOBILE SOURCE NO_x REDUCTIONS

Costs of mobile source emission reductions were estimated for three methods: using reformulated gasoline in the 8-county area, voluntarily reducing the number of trips made in the 8-county area, and reducing allowable vehicle speeds on interstate highways in the 8-county area. These methods are described in the next sections.

Voluntary Trip Avoidance

Emission reduction levels were 10, 30 and 50 percent of mobile source emissions in the 8-county area. Tons per day of NO_x reductions that were simulated in the modeling runs were obtained from MRGUAM.MSG files. Those files totaled up the speciated emissions hour by hour and for the entire day. The NO_x emission reductions were in moles of NO

and NO_2. A 10 percent NO_x reduction in mobile sources was 133,000 moles per day of NO_x, multiplied by 46 grams of NO_2 per mole of NO_2 and NO, equal to 6,118,000 grams of NO_x per day.

10% mobile source NO_x reduction:

(133,000 moles NO_x/day) x (46 grams NO_2/mole NO_2) = 6,118,000 grams NO_x /day.

30% mobile source NO_x reduction:

(444,000 moles NO_x/day) x (46 grams NO_2/mole NO_2) = 20,424,000 grams NO_x /day.

50% mobile source NO_x reduction:

(766,000 moles NO_x/day) x (46 grams NO_2/mole NO_2) = 35,236,000 grams NO_x /day.

After establishing the quantity of NO_x emission reductions for each scenario, the number of trips necessary to produce identical emissions was calculated. Assuming the average trip length was 9.1 miles (ORNL, 1999) and daily VMT in 1997 Knox County were 13,012,662, and daily NO_x emissions were 35,817 kilograms per day (Knoxville Urban Area Metropolitan Planning Organization, 1999), average NO_x emissions per mile were calculated as follows:

(35,817,000 g/day) / (113,012,662 VMT) = 2.752 grams of NO_x emissions per mile.

If one trip was 9.1 miles, the number of trips that had to be avoided was:

10% mobile source NO_x reduction:

(6,118,000 g NO_x) / [(9.1 miles/trip) (2.752 g NO_x/mile)] = 244,298 trips avoided.

30% mobile source NO_x reduction:

(20,424,000 g NO_x) / [(9.1 miles/trip) (2.752 g NO_x/mile)] = 815,551 trips avoided.

50% mobile source NO_x reduction:

(35,236,000 g NO_x) / [(9.1 miles/trip) (2.752 g NO_x/mile)] = 1,407,009 trips avoided.

The cost of a trip avoided was calculated using per capita money income for Tennessee which in 1989 was $12,555 per year (University of Tennessee, 1996/97). Using the Consumer Price Index (U.S. Bureau of Labor Statistics, 2000) of 1.3151 for changes in price from 1989 to 1998, per capita money income was $16,117 per year in 1998. If an individual worked 2000 hours in a year, the hourly value of a person's time, or the opportunity cost, was $8.06 an hour. Per capita money income may not be the correct gage of the opportunity cost of foregoing a trip as it may under- or over-estimate true costs. As an estimate, however, it is a realistic value and is used as the opportunity cost of time in this analysis. One half of an hour was used as the trip duration.

The national average vehicle occupancy rate in a car is 1.6 passengers (ORNL, 1999). Based on these assumptions, the total cost of the voluntarily avoided trips including all passengers was calculated:

10 percent NO_x reduction:

244,298 trips/day x 0.5 hour x 1.6 people/trip x $8.06/hour = $1,575,234/day.

30 percent NO_x reduction:

815,551 trips/day x 0.5 hour x 1.6 people/trip x $8.06/hour = $5,258,673/day.

50 percent NO_x reduction:

1,407,009 trips/day x 0.5 hour x 1.6 people/trip x $8.06/hour = $9,072,394/day.

Cost effectiveness was calculated in dollars per ton of NO_x removed. The cost of trips avoided to achieve a level of NO_x reduction was divided by the tons of NO_x reduced.

10 percent NO_x reduction:

($1,575,234/day) / (6.7 tons NO_x/day) = $235,110/ton of NO_x removed.

30 percent NO_x reduction:

($5,258,673/day) / (22.5 tons NO_x/day) = $233,719/ton of NO_x removed.

50 percent NO_x reduction:

($9,072,394/day) / (38.8 tons NO_x/day) = $233,825/ton of NO_x removed.

Cost and cost effectiveness of voluntary reductions are displayed in Table 4-4 along with NO_x reductions. To achieve a 10 percent reduction in NO_x emissions in the 8-county area, 244,298 trips would have been foregone at a cost of $1.6 million that day. A total of 6.7 tons of NO_x would have been reduced, and the cost effectiveness of the voluntary reductions was $235,000. Cost-effectiveness is about the same for whatever the number of trips foregone and total emissions reduced by this control method. However, total cost does go up with the number of trips foregone and amount of NO_x reduced. A 50 percent reduction in NO_x by voluntary trip reduction would cost $9.1 million per day but $234,000 per ton of NO_x reduced.

Lower Interstate Highway Speeds

Changes in NO_x emissions from lower allowable interstate speeds were estimated for the 8-county area. Table 4-5 shows the NO_x reductions, cost per day, cost per ozone season, and cost effectiveness due to lower allowable interstate highway speeds. By dropping the speed limit to 45 mph on rural and urban interstates in the 8-county area, 10.25 tons per day of NO_x was reduced. This is 15 percent of the 8-county area mobile source NO_x emissions and 2.6 percent of total mobile source emissions in the East Tennessee Modeling Domain. This control method does not correlate directly with a modeled scenario. It was calculated to show costs of an alternative NO_x control method.

Table 4-4. Cost of Trips Voluntarily Foregone for Mobile Source NO_x Reductions.

8-County Area NO_x Reduction (percent)	ETMD NO_x Reduction (percent)	NO_x Reduced (tpd)	Trips Foregone	Cost* (dollars/day)	Cost* Effectiveness of NO_x Removal (dollars/ton)
10	1.7	6.7	244,298	1,600,000	240,000
30	5.6	22.5	815,551	5,300,000	230,000
50	9.7	38.8	1,407,009	9,100,000	230,000

* Cost is in 1998 dollars.

Table 4-5. Cost of Lower Allowable Interstate Speeds to Reduce NO_x Emissions.

8-County Area NO_x Reduction (percent)	ETMD NO_x Reduction (percent)	NO_x Reduced (tons/day)	Cost* ($/day)	Cost* ($/season)	Cost* Effectiveness of NO_x Removal ($/ton)
15	2.6	10.25	463,000	71,000,000	45,000

* Cost is in 1998 dollars.

Dropping allowable interstate speeds cost $463,000 per day and had a cost effectiveness of $45,000 per ton of NO_x removed.

NO_x emission changes were calculated from VMT per day for urban and rural interstate highways in the 8-county area, composite NO_x emission factors for interstate highways, average trip length, average vehicle occupancy and per capita money income. The composite NO_x emission factors were obtained from Table 3-8, NO_x Emissions Predicted by MOBILE5b for Rural and Urban Mobile Sources. For a rural interstate, the 45 mph emission factor was 3.59 grams of NO_x per mile, and for urban interstates it was 2.97 grams of NO_x per mile. Factors for normal interstate speeds were 5.6 grams of NO_x per mile corresponding to 62.5 mph on a rural interstate and 3.45 grams of NO_x per mile for 52.5 mph on an urban interstate. Total rural interstate VMT per day were 3,623,294, and urban interstate VMT were 4,200,248 in 1998 (Davis, et. al., 1999).

Emission factors for normal speeds were multiplied by VMT for the appropriate road type and factors for lowered speeds were also multiplied by appropriate VMT. The difference between the two, normal minus lowered, equaled NO_x emissions avoided. For example:

Rural interstate with normal speed limit:

(3,623,294 VMT/day) x (5.6 grams NO_x /mile at 62.5 mph) = 20,290,446 grams NO_x.

Rural interstate with lowered speed limit:

(3,623,294 VMT/day) x (3.59 grams NO_x /mile at 45 mph) = 13,007,625 grams NO_x.

The difference between these two emission rates equaled 7,282,821 grams of NO_x per day or 8 tons per day, the emissions avoided on rural interstates by lowered speed limits. On urban interstates, emissions avoided were calculated as follows:

Urban interstate with normal speed limit:

4,200,248 VMT/day x 3.45 grams NO_x /mile at 52.5 mph = 14,490,856 grams NO_x.

Urban interstate with lowered speed limit:

4,200,248 VMT/day x 2.97 grams NO_x /mile at 45 mph = 12,474,737 grams NO_x.

Normal speed emissions minus lower speed emissions gave avoided urban interstate NO_x emissions equal to 2,016,119 grams or 2.2 tons. Total emissions avoided on urban and rural interstates combined were 9,298,940 grams or 10.2 tons per day.

Costs of lower interstate speeds were estimated in a manner similar to those of voluntary trip avoidance. The VMT per day was assumed to be made entirely by trips with 1.6 occupants per vehicle (ORNL, 1999). Additional time required for travel on interstate roads with lower speed limits was calculated by dividing by the travel speed for each of

the two different speed limits and taking the difference between them. A sample calculation follows.

Cost to rural users of lower interstate speed limit:

At 45 mph:

(3,623,294 miles/day) x (1.6 people/trip) x (1/45 mph) x ($8.06/hour) = $1,038,356/day.

At 62.5 mph:

(3,623,294 miles/day) x (1.6 people/trip) x (1/62.5 mph) x ($8.06/hour) = $747,616/day.

Calculating the cost difference between the two rural interstate speed limits:

($1,038,356/day at 45 mph) – ($747,616/day at 62.5 mph) = $290,740/day is the cost of a lower speed limit to users of rural interstates.

Cost to urban users of lower interstate speed limit:

At 45 mph:

(4,200,248 miles/day) x (1.6 people/trip) x (1/45 mph) x ($8.06/hour) = $1,203,698/day.

At 52.5 mph:

(4,200,248 miles/day) x (1.6 people/trip) x (1/52.5 mph) x ($8.06/hour) = $1,031,741/day.

Calculating the cost difference between the two urban interstate speed limits:

($1,203,698 at 45 mph) – ($1,031,741/day at 52.5 mph) = $171,957/day is the cost of a lower speed limit to users of urban interstates.

Total cost, for both rural and urban interstate speed changes, was $462,697 per day in 1998 dollars for lower interstate speeds of 45 mph in the 8-county area.

Cost effectiveness of lower interstate speeds was calculated by dividing cost by the tons of NO_x per day reduced.

($462,697/day) / (10.25 tons NO_x/day) = $45,141 per ton of NO_x reduced.

Reformulated Fuels

Reformulated fuel is another method of reducing NO_x emissions. A variety of reformulations have been created, and the percentage of NO_x emissions reduced depends on the particular fuel (Cummings, et. al., 1997). They are listed in Table 4-6.

NO_x reductions in tons per day were estimated from the gallons of gasoline sold in the 8-county area, daily NO_x emissions from mobile sources, and the percentage of emission reductions from burning that fuel. Mobile source NO_x emissions were 77.68 tons per day in the 8-county area, taken from the MRGUAM.MSG file of UAM. The ratio of NO_x generated by gasoline fuel versus diesel fuel was assumed to be the same as that of the

Table 4-6. Costs of On-Road Mobile Source NO_x Emission Reductions from Reformulated Fuels.

	NO_x Reductions[a] (percent)	(tons per day)	(tons per season)	Price Increase[a] (dollars per gallon)	Cost (dollars per day)	Cost (dollars per season)	Cost Effectiveness of NO_x Removal (dollars per ton)
CA Rfg[b]	14.40%	7.0	1071	0.2125	226,892	34,714,539	32,195
OTAG Rfg	12.00%	5.9	903	0.0855	91,291	13,967,497	15,545
EPA Phase I Gas	1.60%	0.8	122	0.0625	66,733	10,210,159	85,223
EPA Phase II Gas	6.80%	3.3	505	0.0965	103,036	15,764,485	30,961
Rfd Diesel	4.04%	1.2	184	N/A			5,870

Mobile Source NO_x Emissions in 8-County Area

	(tpd)
Gasoline	48.94[c]
Diesel	28.74[c]
Total	77.68

Fuel Sold in 8-County Area in 1996

	(gallons/year)	(gallons/day)	(gallons/season)
Gasoline	3.9E+08[d]	1,067,729	163,362,594
Diesel	1.06E+08[d]	289,582	44,306,067

a. Percent NO_x Reductions and Price Increase were taken from Cummings et. al., 1997.
b. Rfg – reformulated gasoline.
c. Fractions of total NO_x emissions were assumed based on Atlanta data (Cummings, et. al., 1997). Total mobile source NO_x emissions in the 8-county area were 77.68 tons per day.
d. Gallons of fuel sold in Tennessee were obtained from the Tennessee Statistical Abstract, 1996/97.

Atlanta 13-county nonattaiment area, 63 percent due to gasoline and 37 percent due to diesel fuel (Cummings, et. al., 1997). Mobile source emission rates in tons per day were multiplied by the percentage of emission reductions associated with burning that particular fuel to give NO_x reductions in tons per day. Similar calculations were made for seasonal emission rates.

Table 4-6 gives the price increase of the reformulated fuels in dollars per gallon of fuel. The gallons of gasoline sold in the 8-county area of the modeling domain were also needed to determine the cost of burning reformulated fuel. This was calculated by multiplying the volume of gasoline sold in the entire state of Tennessee by the ratio of VMT in the 8-county area to VMT in the entire state, so gasoline sales were ratioed by 14 percent to estimate sales in the 8-county area. Diesel fuel was calculated in the same manner.

2,783,723,000 gallons gas sold in Tennessee x 0.14 =

389,721,220 gallons gas sold in 8-county area.

754,982,000 gallons diesel sold in Tennessee x 0.14 =

105,697,480 gallons diesel sold in 8-county area.

Cost was calculated from gallons of fuel sold and price increase per gallon. Seasonal costs assumed a five month ozone season or 153 days. The most efficient fuel for NO_x

reductions was California reformulated gasoline. It reduced NO_x emissions 14.4 percent, or 7 tons per day in the 8-county area. The cost was $227,000 per day and the cost effectiveness was $32,195 per ton of NO_x removed. EPA Phase I gasoline would reduce NO_x emissions only 1.6 percent or 0.8 tons per day at a cost of $67,000 per day. Its cost effectiveness was the worst at $85,000 per ton of NO_x removed.

Of the mobile source emission reduction methods examined, the most cost effective was reformulated gasoline ranging from $6000 to about $32,000 and as high as $85,000 per ton of NO_x removed. The least cost effective method was voluntarily foregoing trips at $230,000 per ton of NO_x removed. In between was lower allowable interstate speed, and at $45,000 per ton of NO_x removed, it was more cost effective than EPA Phase I reformulated gasoline at $85,000.

COST OF AREA SOURCE NO_x REDUCTIONS

For the cost analysis, area source emission reductions were quantified for one method, foregone wages of landscapers and horticulturists. They were assumed to not work one day because of high ozone levels. Total foregone NO_x emissions were 2.4 tons per day for the 8-county area. The range of foregone income to the landscapers and horticulturists was $19,800 to $853,312 per day. The cost effectiveness was between $8,000 to $356,000 per ton of NO_x removed. Table 4-7 explains how NO_x emissions were estimated for the 8-county area. Table 4-8 displays costs and cost effectiveness, respectively, of the foregone wages and NO_x emission reduction method.

Table 4-7. NO_x Emissions from Lawn and Garden Equipment.

County	Number of Single and Double Family Homes[a]	NO_x Emissions from Lawn and Garden Equipment in 1996 (tons/year)	Ratio of NO_x Emissions to Single and Double Family Homes	Calculated NO_x Emissions by County (tons/year)	Calculated NO_x Emissions by County (tons/day)
Knox	143,052	199[b]	0.00139	199	1.3
Blount	36,892		0.00139	51	0.3
Loudon	13,275		0.00139	18	0.1
Anderson	29,045		0.00139	40	0.3
Union	5523		0.00139	8	0.05
Grainger	6814		0.00139	9	0.06
Jefferson	13,353		0.00139	19	0.1
Sevier	22,387		0.00139	31	0.2
Total	270,340			376	2.4

a. (USEPA, 2000a)
b. (Pechan, 1996)

Table 4-8. Foregone Wages from Landscapers and Horticulturists.

County	Employees in Landscape and Horticulture Services[a]	Foregone Income Based on Minimum Wage[b], Low ($ / day)	Foregone Income Based on Minimum Wage, High ($ / day)	Foregone Income Based on Per Capita Income[c], Low ($ / day)	Foregone Income Based on Per Capita Income, High ($ / day)
Knox	300 – 10,382	16,500	571,010	24,180	836,789
Loudon	30 – 100	1650	5500	2418	8060
Blount	30 – 100	1650	5500	2418	8060
Anderson	0 - 1	0	55	0	81
Union	0 - 1	0	55	0	81
Grainger	0 - 1	0	55	0	81
Jefferson	0 - 1	0	55	0	81
Sevier	0 - 1	0	55	0	81
Total		19,800	582,285	29,016	853,312
		Cost Effectiveness of NO_x Removal ($ / ton)			
		8,250	242,619	12,090	355,547

a. (USEPA, 2000b)
b. Minimum wage is $5.50 per hour; employees work 10 hours per day.
c. Per capita income is $8.06 per hour; employees work 10 hours per day.

Pechan (1996) estimated NO_x emissions for Knox County from lawn and garden equipment at 199 tons per year. EPA estimated the number of single and double family homes in Knox County (USEPA, 2000a), and the number of employees in landscape and horticulture services in the 8-county area (USEPA, 2000b). NO_x emissions from lawn and garden equipment were divided by the number of single and double family homes in Knox County to calculate the average NO_x emissions per home.

(199 tons NO_x from lawn and garden equipment) / (number of single and double family homes) = 0.00139 tons NO_x per home

This ratio was used to calculate NO_x emissions from the other seven counties.

(0.00139 tons NO_x per home) x (36,892 homes in Blount County)
= 51 tons NO_x emissions in Blount County per year.

NO_x emissions for the eight counties were totaled and equaled 376 tons per year or, assuming all of the lawn and garden emissions occur during the ozone season and spreading 376 tons over 153 days of the ozone season, 2.4 tons of NO_x per day during the ozone season.

Costs were estimated using EPA's range of the number of employees in each county and foregone income. These are shown in Table 4-8. Employees were assumed to work a 10

hour day for two different wages, $5.50 per hour, approximating the minimum wage, and $8.06 per hour, per capita income in Tennessee in 1998. In Knox County, between 300 and 10,382 employees were estimated to be in the landscape and horticulture business. At a wage rate of $5.50 per hour and working 10 hours per day, their total wages ranged from $16,500 to $571,010 per day. At the higher wage rate of $8.06 per hour, the range of wages for Knox County was $24,180 to $836,789 per day. Foregone wages for the seven other counties were computed in the same manner and are shown in Table 4-8.

To calculate cost effectiveness in dollars per ton, foregone income based on the lower wage and low end of the range of employees, $19,800 per day, from Table 4-8 was divided by 2.4 tons of NO_x per day from Table 4-7:

low wage and low end of number of employees range,

($19,800/day) / (2.4 tons NO_x/day) = $8,250 per ton of NO_x removed.

low wage and high end of number of employees range,

($582,285/day) / (2.4 tons NO_x/day) = $242,619 per ton of NO_x removed.

high wage and low end of number of employees range,

($29,016/day) / (2.4 tons NO_x/day) = $12,090 per ton of NO_x removed.

high wage and high end of number of employees range,

($853,312/day) / (2.4 tons NO_x/day) = $355,547 per ton of NO_x removed

The complete range of foregone income was $19,800 to $853,000 to landscapers and horticulturists for a day of not working. The cost effectiveness of this NO_x control measure, for 2.4 tons per day of NO_x reductions, ranged from $8,000 per ton to $356,000 per ton of NO_x removed.

5. DISCUSSION OF RESULTS

Ozone Concentrations

The most significant results of the effects of NO_x reductions are summarized in Table 5-1. NO_x emission reductions and corresponding ozone concentration reductions, for 1-hour and 8-hour averages, are shown for July 20, 1995. The peak ozone concentration reduced was the consequence of controlling NO_x emissions by the amount in the corresponding scenario. Maximum difference in ozone was the largest difference in ozone concentrations occurring anywhere in the domain, not necessarily at the point of peak concentration, that resulted from the corresponding reduction in NO_x emissions.

PEAK CONCENTRATIONS

Point source controls were the most effective control technique for lowering peak ozone concentrations in the East Tennessee Modeling Domain. UAM predicted that reducing 55.4 tons per day of NO_x emissions from Kingston Power Plant would lower the peak ozone concentration 18 ppb for the 1-hour average and 16 ppb for the 8-hour average. In the scenario of 70 percent reduction at all elevated point sources, NO_x emissions were reduced by 194.6 tons. The peak 1-hour ozone concentration was lowered 18 ppb, the same as for 55.4 tons of NO_x from Kingston, but the 8-hour peak average was lowered even more at 25 ppb. Almost as effective was the scenario of 70 percent NO_x reduction at 3 TVA power plants that lowered the 1-hour average by 18 ppb and the 8-hour average by 24 ppb. This scenario predicted the effects of NO_x reductions from Kingston and Bull Run Power Plants, in concert, and not effects from John Sevier Power Plant since its

Table 5-1. Reductions in NO_x Emissions and Ozone Concentrations, for July 20, 1995.

Modeling Scenario	NO_x Reduction (tons/day)	Amount Peak Ozone Concentration Reduced		Maximum Difference in Ozone Concentration	
		1-Hour (ppb)	8-Hour (ppb)	1-Hour (ppb)	8-Hour (ppb)
70 % NO_x Reduction at Kingston	55.4	18	16	35	28
70 % NO_x Reduction at All Elevated Point Sources	194.6	18	25	41	35
70 % NO_x Reduction at 3 TVA Power Plants	114.1	18	24	40	35
50 % NO_x Reduction from Area and Mobile Sources	38.8	1	2	18	16
10 % NO_x Reduction from Area and Mobile Sources	6.7	0	0	3	3

plume blew out of the modeling domain and did not impact the peak concentration or reduction in the peak concentration. In essence, reducing NO_x emissions from 2 TVA plants, Kingston and Bull Run and not John Sevier, would give almost the same reduction in peak ozone concentration in east Tennessee as controlling NO_x emissions from all elevated point sources under the conditions modeled.

Mobile and area source NO_x reductions had little effect on peak ozone concentrations. A 50 percent NO_x reduction from area and mobile sources, 38.8 tons per day less NO_x emissions, resulted in a 1 ppb lower peak ozone concentration for a 1-hour average and 2 ppb for an 8-hour average, a small reward for a large effort. The scenario with least impact on peak ozone concentrations was 10 percent NO_x reduction from area and mobile sources with a 6.7 ton reduction. It had no impact on peak ozone concentrations. Figure 3-1 shows the exact boundaries of the region of area and mobile source NO_x reductions; for the most part, the region encompassed the Knoxville metropolitan area. East Tennessee is largely rural with lesser population density than the Knoxville metropolitan area, and area and mobile source NO_x emissions from the rural portions of the modeling domain were low. As a result, NO_x reductions from those portions would have little effect on ozone concentrations if an episodic control program were implemented.

Figure 5-1 presents NO_x effects on the peak ozone concentration in graphical form. For the 8-hour average, ozone reductions due to NO_x effects begin to level off at about 120 tons of NO_x per day and 25 ppb of ozone. The curve for the 1-hour average is flat after

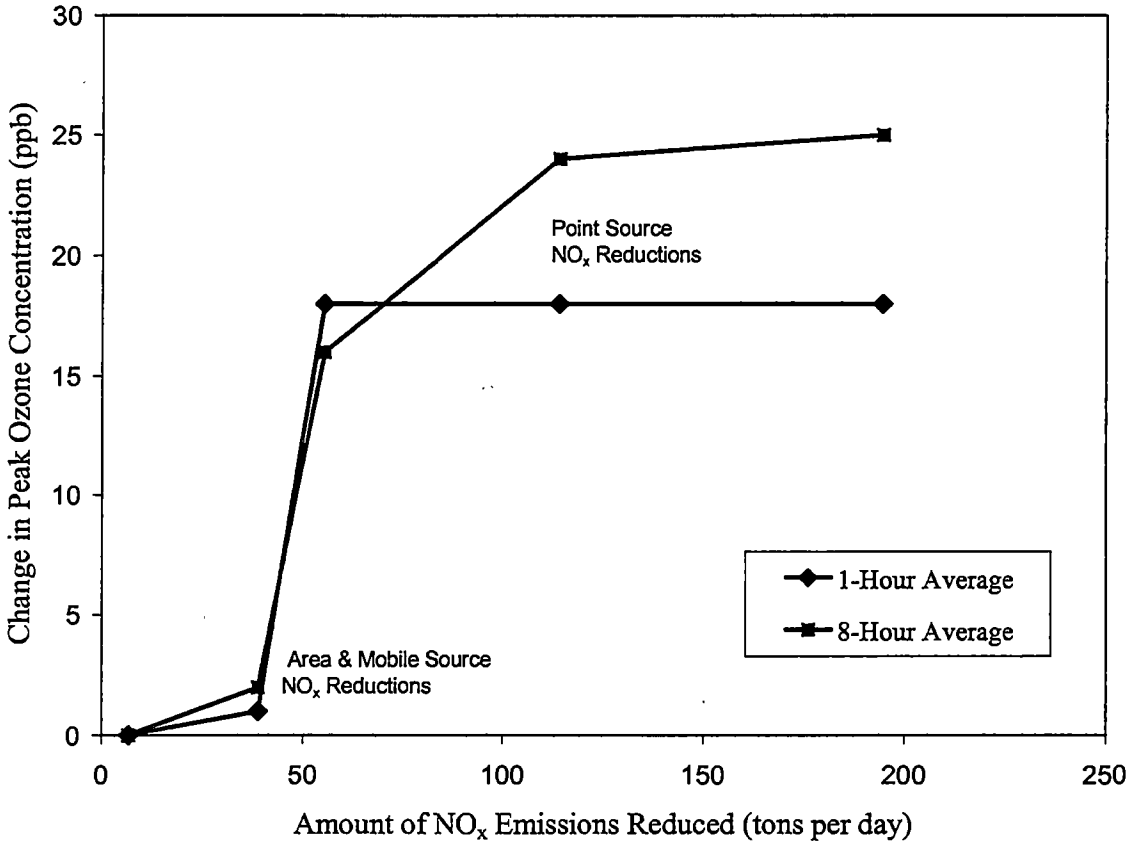


Figure 5-1. Effect of NO_x Emission Reductions on Peak Ozone Concentrations in the Domain, for July 20, 1995. (Includes both area/mobile and point source NO_x reduction scenarios.)

50 tons of NO_x reductions. More data would be necessary to fully describe the shapes of the curves.

MAXIMUM DIFFERENCES

An examination of maximum differences provides a more robust picture of the effects of reducing NO_x emissions than do peak concentrations alone. While mobile and area source NO_x reductions made very little impact on peak ozone concentrations, on maximum differences they made close to the same impact as did point source reductions. Maximum differences do not count when assessing concentrations for attainment demonstrations, but they do reveal information about exposure of the population to ozone concentrations that can be masked when solely studying peak concentrations.

In the two modeling scenarios, 70 percent NO_x reductions at three TVA power plants and 70 percent NO_x reductions at all elevated point sources, the size and location of the affected areas differed little, and consequently, exposure to ozone differed little for the people living in the affected area. Reductions at all elevated point sources made a 41 ppb difference in 1-hour ozone concentrations and reductions at 3 TVA power plants made a 40 ppb difference. For the 8-hour average, both scenarios made a 35 ppb difference in ozone concentrations. Controlling NO_x emissions from all elevated point sources creates little difference in ozone exposure when compared with controlling NO_x emissions from 3 TVA plants in east Tennessee. Figure 5-2 shows the maximum changes in ozone concentrations, occurring anywhere in the modeling domain, due to reductions in NO_x

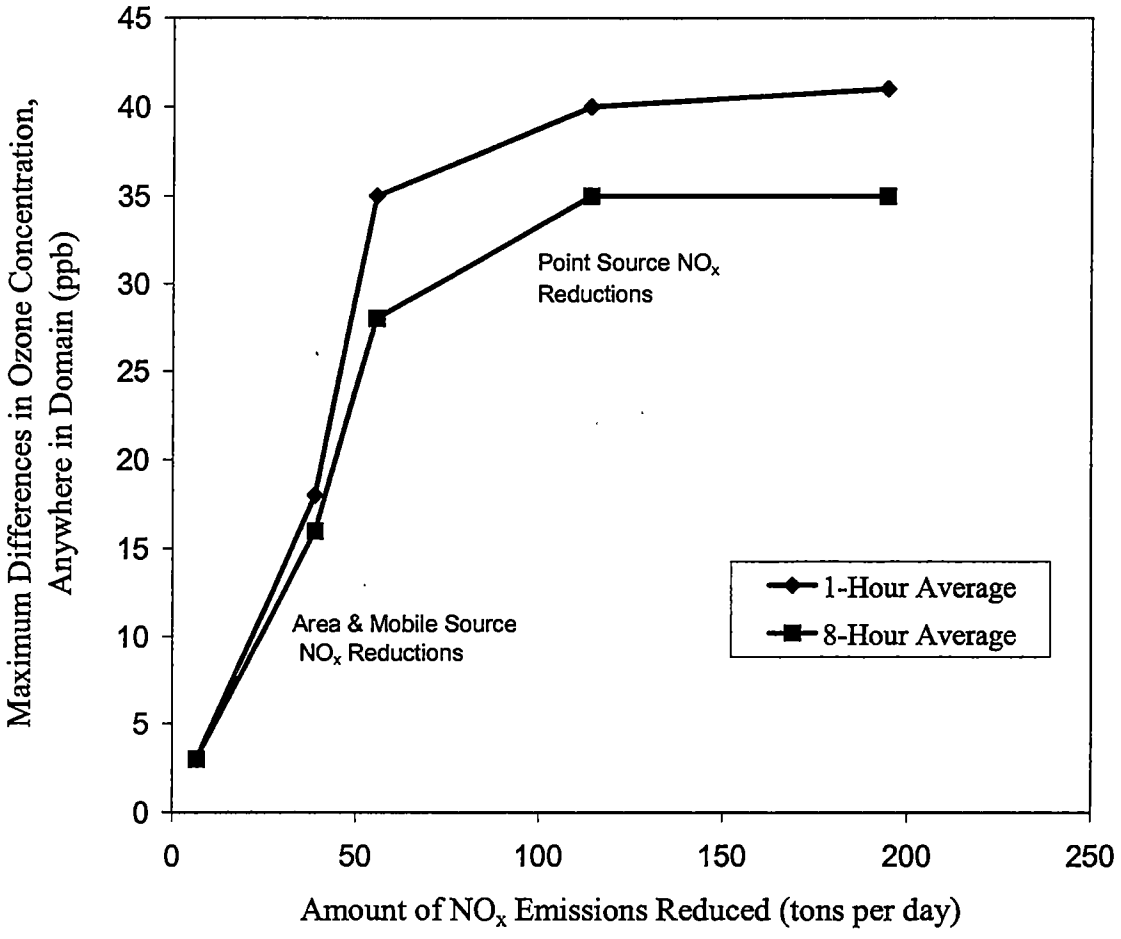


Figure 5-2. Effect of NO_x Emission Changes on Maximum Differences in Ozone Concentrations Occurring Anywhere in Modeling Domain, for July 20, 1995. (Includes both area/mobile and point source NO_x reduction scenarios.)

emissions. The curve shape is initially steeper than in Figure 5-1, and ozone concentration reductions begin to level off at about 120 tons per day of NO_x reductions for both 1-hour and 8-hour averages.

The 50 percent area and mobile source NO_x reduction scenario resulted in changes to ozone concentrations of about half the magnitude that point source reductions caused. In the multi-county region affected by the area and mobile source reductions, the 1-hour ozone concentration was lowered 18 ppb and the 8-hour was lowered 16 ppb. The site and magnitude of the peak concentration in the modeling domain were not affected by mobile and area source emissions, because the peak was due mainly to the large point sources. In a modeling domain where a few point sources did not dominate the peak concentration the way that Kingston and Bull Run Power Plants did, area and mobile source reductions in an episodic control program could govern the peak concentration. In such a region, area and mobile source reductions, on a large enough scale, could reduce ozone concentrations for attainment purposes and reduce exposure to high ozone concentrations in densely populated regions.

Maximum differences of 8-hour averages were close in magnitude to those of 1-hour averages. This means the 1-hour average differences were sustained for several hours at the same location in order to generate 8-hour concentrations of nearly the same magnitude. With calm winds, the ozone plume moved but a few miles, and the people who participated in reducing area and mobile source NO_x emissions were largely the same people who experienced the healthful benefits of reduced ozone concentrations.

Cost Effectiveness

COST EFFECTIVENESS OF REDUCING NO_x EMISSIONS

Point source controls were the most cost effective means of reducing NO_x emissions and peak ozone concentrations. Costs of point source controls with SCR ranged from $1750 to $3430 per ton of NO_x removed on a seasonal basis as seen in Table 3-7. On an annual basis, costs ranged from $825 to $2598 per ton of NO_x removed. The next lowest cost was for mobile source NO_x controls and was $6000 per ton of NO_x removed by using reformulated diesel fuel as stated in Table 4-6, but the impact on NO_x emissions was very small at 1.2 tons per day or 184 tons of NO_x reduced per ozone season. OTAG reformulated gasoline was the third most cost effective method for NO_x control with a cost of $16,000 per ton and would reduce NO_x emissions 5.9 tons per day or 900 tons per season.

Gasoline reformulations for mobile source NO_x emission reductions varied in cost effectiveness from $6000 to $85,000 per ton; even the cheapest reformulated gas was almost twice the cost of point source controls. In addition, the point source controls made a much larger impact on NO_x emissions and peak ozone concentrations.

Cost effectiveness for reductions of NO_x from area sources, shown in Table 4-8, was based on a single cost analysis and ranged from $19,800 to $850,000 per ton of NO_x reduced. This emission reduction was achieved by foregone work from landscapers and horticulturists for one day. Seasonal values of foregone wages could theoretically be

calculated, but it was considered unrealistic to expect landscapers and horticulturists to forego wages for five months, and their busiest time of year. The impact on NO_x reductions was 2.4 tons per day, less than the amount called for by 10 percent area source reductions (4 tons), 30 percent reductions (11 tons) and 50 percent reductions (17 tons).

Lower allowable interstate speeds, at $45,000 per ton of NO_x removed, was in the middle as a cost effective method for controlling NO_x. Least cost effective controls for NO_x emission reductions were trips voluntarily foregone at $230,000 per ton of NO_x removed, listed in Table 4-4. With 9.7 tons per day of NO_x reductions, the foregone trips would have had a small impact on ozone concentrations, somewhere between that of 10 and 30 percent NO_x reduction for mobile and area sources. Episodic control programs typically advocate this type of emission reduction. program. For some individuals, the value of an opportunity to practice environmental stewardship would offset the cost of foregoing a trip, and therefore, costs of the NO_x control method would be less than those calculated. On the other hand, the value of a trip taken must be greater than its cost or it would not be taken. In such a case, costs are underestimated. Even if the cost effectiveness of voluntarily foregoing a trip were half its calculated value, it would still be $115,000 per ton and 30 times more costly than the point source NO_x reduction cost effectiveness.

COST EFFECTIVENESS OF LOWERING OZONE CONCENTRATIONS

Another way to analyze ozone concentrations and costs is in cost effectiveness as dollars per ppb of ozone reduced. Table 5-2 lists peak ozone concentration reductions, cost and

Table 5-2. Costs and Peak Ozone Concentrations for July 20, 1995.

Modeling Scenario	Reduction in Peak Ozone Concentration		Cost	Cost Effectiveness	
	1-Hour (ppb)	8-Hour (ppb)	($ million, 1998)	1-Hour ($ million per ppb)	8-Hour ($ million per ppb)
70 % NO_x Reduction at Kingston	18	16	17[a]	0.97	1.1
70 % NO_x Reduction at All Elevated Point Sources	18	25	80[a]	4.4	3.2
70 % NO_x Reduction at 3 TVA Power Plants	18	24	36[a]	2	1.5
50 % NO_x Reduction from Area and Mobile Sources	1	2	9.5[b]	9.5	4.8
10 % NO_x Reduction from Area and Mobile Sources	0	0	0.66[c]	X	X

a. Costs are for installation of Selective Catalytic Reduction for NO_x control and were taken from Table 4-3. Seasonal operation was assumed.

b. Mobile source costs are for trips voluntarily foregone and were taken from Table 4-4. Area source costs were taken from Table 4-8 and are the average of lowest and highest foregone income. Area source NO_x emission reductions from landscapers and horticulturists foregoing work were 2.4 tons per day, less than the emission reductions that were modeled. Costs would be greater if full area source NO_x emission reductions were included. Mobile and area source costs are per day.

c. Mobile source costs are for California Reformulated Gasoline and were taken from Table 4-6. Area source costs were taken from Table 4-8 and are the average of lowest and highest foregone income. Area source NO_x emission reductions from landscapers and horticulturists foregoing work were 2.4 tons per day, less than the emission reductions that were modeled. Costs would be greater if full area source NO_x emission reductions were included. Mobile and area source costs are per day.

cost effectiveness for the same modeling scenarios as in the previous table. If considering cost effectiveness in terms of dollars per ppb of ozone, the scenario of 70 percent NO_x reduction at Kingston, with SCR installed as the NO_x control device, was most cost effective with costs approximating $970,000 per ppb of ozone reduced for both 1-hour and 8-hour averaging times. Close behind in second place was the scenario of 70 percent NO_x reduction at 3 TVA power plants with costs of about $2,000,000 per ppb. If NO_x controls were installed on only two of the three power plants, on Kingston and Bull Run, the cost effectiveness values would be lower yet. The scenario of 10 percent NO_x reductions in area and mobile sources made no difference in peak ozone concentrations, and its cost effectiveness is listed as X. Least cost effective was 50 percent reduction in NO_x emissions from area and mobile sources at $9,500,000 per ppb for a 1-hour average and $4,800,000 per ppb for an 8-hour average. Of the $9,500,000 cost, $400,000 was for area source NO_x reduction costs calculated from foregone income from landscapers and horticulturists and using the average of lowest and highest values of foregone income listed in Table 4-8. The remaining $9,100,000 was for voluntary NO_x emission reductions from mobile sources shown in Table 4-4. This was the only emission reduction technique for mobile sources that could achieve the 50 percent NO_x reduction. The area source example, landscapers and horticulturists foregoing a day of work and wages, had 2.4 tons of NO_x reduced per day, not enough to achieve the emission reductions that were modeled and not enough to influence ozone concentrations. Mobile source cost effectiveness by itself is already two times higher than the least cost effective point source reductions, and if costs for full area source NO_x emission reductions were included, the cost effectiveness values would be even larger.

Figure 5-3 shows the data of Table 5-2 graphically as the marginal cost of reducing ozone concentrations. Marginal cost is the cost of the next unit, in this case, the cost of the next pbb of ozone. Marginal costs are fairly flat until the level of 15 to 20 ppb is reached, and then rise exponentially. Including area source costs of full NO_x emission reductions in the scenario 50 percent NO_x reduction from area and mobile sources would increase the starting cost effectiveness shown in Figure 5-3 to a value greater than $9,500,000 for a 1-hour average or $4,800,000 for an 8-hour average. More data of additional modeling scenarios of NO_x control levels and methods would allow a fuller graphical description of the curve.

Maximum differences in ozone concentrations, occurring anywhere in the modeling domain, are displayed in Table 5-3 with cost and cost effectiveness data. The most cost effective scenario, in millions of dollars per ppb of ozone reduced, was 10 percent NO_x reduction from area and mobile sources. The impact on ozone concentration of this scenario was minimal. Costs of area source reductions were for 2.4 tons of NO_x reduced, about half the emission reductions that were modeled. The next two most cost effective scenarios were very similar in cost though their impact on ozone concentration varied by factors of two. The scenario of 50 percent NO_x reduction from area and mobile sources made 18 ppb difference in the 1-hour ozone concentration, 16 ppb difference in the 8-hour concentration. Its cost effectiveness was $530,000 and $590,000 per ppb of ozone for the 1-hour and 8-hour averaging times, respectively. If full costs for area source NO_x reductions were included, cost effectiveness values would be larger for the scenarios of NO_x reductions from area and mobile sources. The scenario similar in cost effectiveness

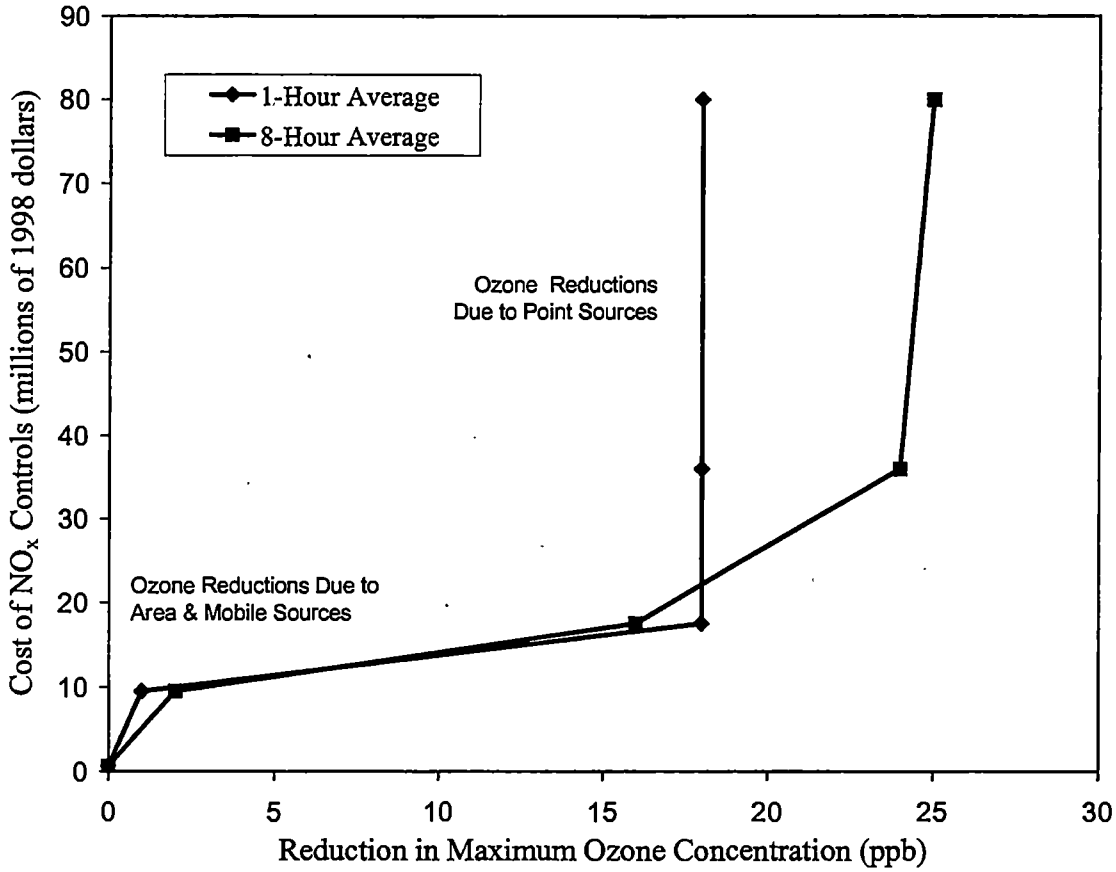


Figure 5-3. Cost of Reducing Ozone Concentrations, for July 20, 1995. (Includes both area/mobile and point source NO_x reduction scenarios.)

Table 5-3. Cost and Maximum Differences in Ozone Concentration for July 20, 1995.

Modeling Scenario	Maximum Difference in Ozone Concentrations 1-Hour (ppb)	8-Hour (ppb)	Cost ($ million, 1998)	Cost Effectiveness 1-Hour ($ million per ppb)	8-Hour ($ million per ppb)
70 % NO_x Reduction at Kingston	35	28	18[a]	0.51	0.62
70 % NO_x Reduction at All Elevated Point Sources	41	35	80_a	2.0	2.3
70 % NO_x Reduction at 3 TVA Power Plants	40	35	36[a]	0.90	1.0
50 % NO_x Reduction from Area and Mobile Sources	18	16	9.5[b]	0.53[b]	0.59[b]
10 % NO_x Reduction from Area and Mobile Sources	3	3	0.66[c]	0.22[c]	0.22[c]

a. Costs are the average of lowest and highest values for installation of Selective Catalytic Reduction and were taken from Table 4-3. Seasonal operation was assumed.

b. Mobile source costs are for trips voluntarily foregone and were taken from Table 4-4. Area source costs were taken from Table 4-8 and are the average of lowest and highest foregone income. Area source NO_x emission reductions from landscapers and horticulturists foregoing work were 2.4 tons per day, less than the emission reductions that were modeled. Costs would be greater if full area source NO_x emission reductions were included. Mobile and area source costs are per day.

c. Mobile source costs are for California Reformulated Gasoline and were taken from Table 4-6. Area source costs were taken from Table 4-8 and are the average of lowest and highest foregone income. Area source NO_x emission reductions from landscapers and horticulturists foregoing work were 2.4 tons per day, less than the emission reductions that were modeled. Costs would be greater if full area source NO_x emission reductions were included. Mobile and area source costs are per day.

was 70 percent NO_x reduction at Kingston Power Plant with $510,000 per ppb of ozone lowered for a 1-hour average and $620,000 per ppb for an 8-hour average. About twice as expensive was the scenario of 70 percent NO_x reduction at 3 TVA power Plants with cost effectiveness of $900,000 per ppb of ozone reduced for a 1-hour average and $1,000,000 per ppb for an 8-hour average. The impact on ozone concentration of this scenario was more than twice that of 50 percent NO_x reduction from area and mobile sources and was 40 ppb for a 1-hour average and 35 ppb difference the 8-hour average.

These data are shown in a graph of cost data and maximum ozone differences in Figure 5-4. The cost effectiveness for all five scenarios varies little, but costs and the impact on ozone concentrations vary substantially. If full area source costs were included with mobile sources, the initial portion of the curve would be somewhat higher than is shown. The curve rises sharply for the last two points, indicating that large improvements in ozone concentrations require large investments of money.

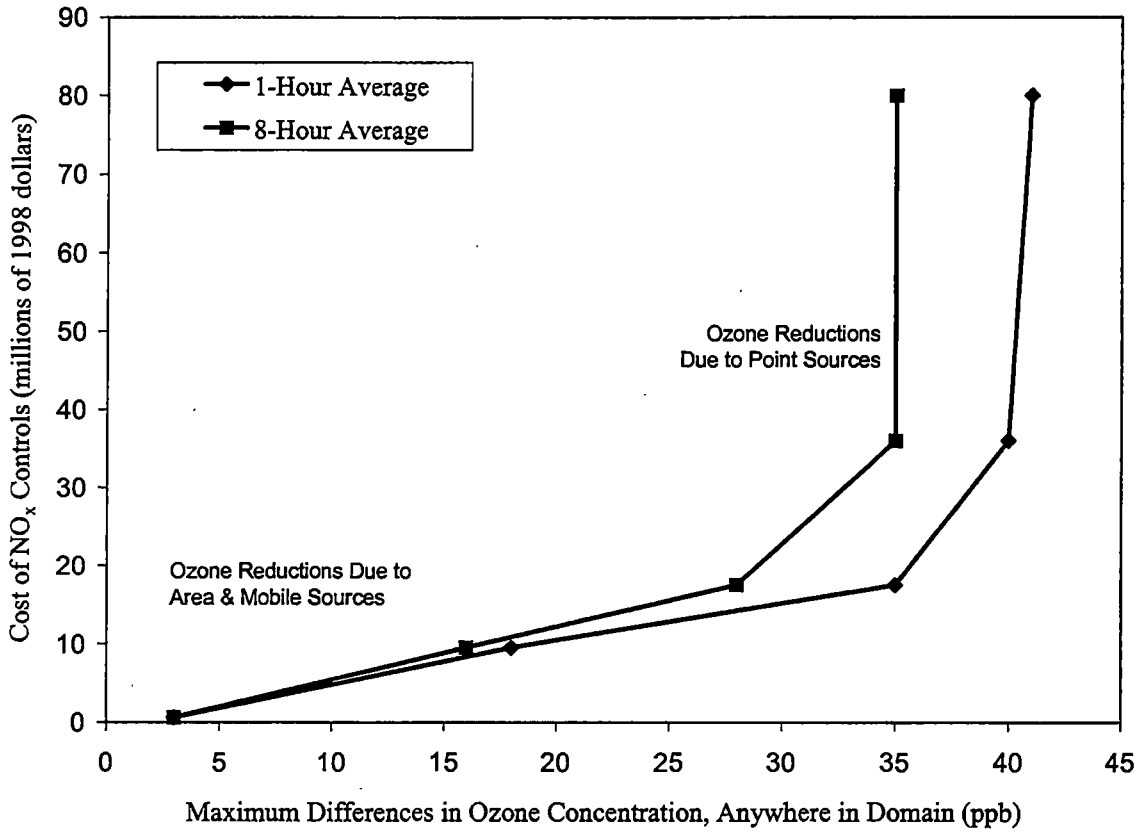


Figure 5-4. Marginal Cost of Differences in Ozone Concentrations, for July 20, 1995. (Includes both area/mobile and point source NO_x reduction scenarios.)

6. CONCLUSIONS

Episodic controls of NO_x emissions can reduce peak ozone concentrations and can lower ozone concentrations in densely populated areas. The policy decision concerning what type of emission controls to implement first (for point sources, area sources or mobile sources) depends on the goals of the episodic control program, and it is not obvious which type of control will have the most impact on a particular goal. A modeling analysis similar to the one performed in this study should be completed by an agency before implementing an episodic control program in order to determine which controls are most effective in achieving their goals under the controlling conditions in their region.

Point source NO_x emissions dominate peak ozone concentrations in the East Tennessee Modeling Domain. An episodic control program directed toward large point sources would have the largest impact on peak concentrations in the East Tennessee Modeling Domain, reducing peak concentrations for 1-hour and 8-hour averages and helping to attain or maintain the NAAQSs for ozone. If Kingston and Bull Run Power Plants were to substantially reduce their NO_x emissions by installing SCR, then it is possible that area and mobile source emissions would dominate the peak ozone concentration in future control analyses.

Maximum differences were most influenced by point source controls. The most cost effective scenario was for area and mobile sources with 10 percent NO_x reduction, but its small impact on ozone concentration diminishes its value as an ozone management tool.

The influence of mobile and area source NO_x reductions was seen not so much at the location of the peak concentration but at other locations near urban areas. This is an important contribution toward reducing the local populations' exposure to high ozone concentrations. The lowered ozone concentrations from mobile and area source NO_x reductions were located close to urban centers of high population. This phenomenon is to be expected because population centers generate more area and mobile source NO_x emissions, and episodic control programs focus their efforts on urban areas. In contrast, a point source can be located anywhere and in many instances is intentionally located in a distant rural area. For area and mobile source emissions, dependent on population, the scenarios of NO_x reductions have a more localized, albeit smaller, impact on peak ozone concentration.

Cost effectiveness estimates of reducing NO_x emissions show that point source controls cost less than area source and mobile source NO_x controls. The purpose of an episodic control program is to lower ozone concentrations, though; NO_x reduction is only an intermediate step. On the basis of dollars per ppb of peak ozone concentration lowered, cost effectiveness values are two to ten times lower for point sources than for area and mobile sources in the East Tennessee Modeling Domain. Of the point source scenarios, 70 percent NO_x reduction at Kingston Power Plant is the most cost effective, it has a large impact on ozone concentration and the fewest impediments to reducing NO_x emissions. For reducing those ozone concentrations to which the largest population is exposed, area

and mobile sources may be more cost effective. An exposure analysis would be necessary to ascertain that result and would be a logical next step in continuing this study.

A voluntary episodic control program directed at area and mobile source NO_x emission reductions is unlikely to see an impact on ozone concentrations until more than 10 percent emission reductions are made. A 50 percent reduction in area and mobile source NO_x emissions in the East Tennessee Modeling Domain will merely "shave the peaks" from an ozone concentration. The magnitude of area and mobile source emissions reductions necessary to impact ozone concentrations is higher than any program of voluntary episodic controls is reporting. For an episodic control program to be chosen for implementation, the program should be able to demonstrate with modeling that its emission reductions will create at least a 5 ppb reduction in ozone concentration. This level of significance is consistent with the lowest quantity of ozone that is accurately measurable using state of the art measurement techniques.

Public response to voluntary controls is not sufficient at this time to reduce peak ozone concentrations. Mandatory controls are necessary in order for area and mobile sources to create emission reductions large enough that will influence ozone concentrations.

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APPENDICES

APPENDIX A

Plate 1. Example Files for the Urban Airshed Model
See CD Rom in pocket.

APPENDIX B

Table B-1. Max and Max Difference Ozone Concentration, Hour and Cell of Occurence.

05/15/2000

	MAX CONC 1-HR AVG (ppb)	HOUR	MAX CONC 8-HR AVG (ppb)	HOUR	MAX DIFF 1-HR AVG (ppb)	HOUR	MAX DIFF 8-HR DIFF (ppb)	HOUR
20J95								
BASE	117		104					
	cell 2599	1900	cell 2601	1700				
70KING	99		88		35		28	
	cell 988	1900	cell 2674	1700	cell 2264	1600	cell 2599	1700
70BULLRUN	113		96		23		17	
	cell 2599	1900	cell 2601	1700	cell 2669	1800	cell 2738	1700
70TVA3	99		80		40		35	
	cell 988	1800	cell 2475	1600	cell 2599	1900	cell 2601	1700
70ALLELEV	99		79		41		35	
	cell 988	1800	cell 2475	1700	cell 2599	1900	cell 2601	1700
AM50PCT	116		102		18		16	
	cell 2599	1900	cell 2601	1700	cell 2678	1900	cell 2611	1700
AM30PCT	117		103		10		9	
	cell 2599	1900	cell 2601	1700	cell 2678	1900	cell 2611	1700
AM10PCT	117		104		3		3	
	cell 2599	1900	cell 2601	1700	cell 2678	1900	cell 2611	1700
24J93								
BASE	121		108					
	cell 2071	1800	cell 2008	1700				
70KING	103		96		36		33	
	cell 2009	1900	cell 2010	1600	cell 1937	1800	cell 1937	1700
70BULLRUN	115		98		22		18	
	cell 2134	1600	cell 2007	1700	cell 2209	1800	cell 2211	1700
70TVA3	98		83		40		35	
	cell 591	1500	cell 2011	1500	cell 2005	1800	cell 2072	1700
70ALLELEV	98		83		40		35	
	cell 591	1500	cell 2009	1400	cell 2005	1800	cell 2072	1700
AM50PCT	120		106		20		19	
	cell 2071	1800	cell 2007	1700	cell 1882	2000	cell 1949	1700
AM30PCT	120		106		11		10	
	cell 2071	1800	cell 2008	1700	cell 1882	2000	cell 1949	1700
AM10PCT	121		107		3		3	
	cell 2071	1800	cell 2008	1700	cell 1881	1900	cell 1949	1700

Table B-1. Continued.

	MAX CONC 1-HR AVG (ppb)	HOUR	MAX CONC 8-HR AVG (ppb)	HOUR	MAX DIFF 1-HR AVG (ppb)	HOUR	MAX DIFF 8-HR DIFF (ppb)	HOUR
25J93								
BASE	146		125					
	cell 1874	1700	cell 1872	1400				
70KING	129		115		50		41	
	cell 2014	1700	cell 2012	1400	cell 1806	1500	cell 1872	1400
70BULLRUN	146		125		32		25	
	cell 1874	1700	cell 1872	1400	cell 2070	1300	cell 2010	1400
70TVA3	118		96		49		41	
	cell 1376	1300	cell1314	1400	cell 1805	1500	cell 1872	1400
70ALLELEV	118		96		49		41	
	cell 1376	1300	cell 1314	1400	cell 1806	1500	cell 1873	1400
AM50PCT	141		120		19		15	
	cell 1874	1700	cell 1872	1400	cell 1819	1100	cell 1950	1400
AM30PCT	143		122		11		9	
	cell 1874	1700	cell 1872	1400	cell 1819	1100	cell 1950	1400
AM10PCT	145		124		3		3	
	cell 1874	1700	cell 1872	1400	cell 1819	1100	cell 1950	1400
26J93								
BASE	161		139					
	cell 2272	1200	cell 2338	1100				
70KING	148		127		52		38	
	cell 2398	1300	cell 2337	1100	cell 2326	1400	cell 2196	1100
70BULLRUN	161		138		39		24	
	cell 2272	1200	cell 2206	1000	2464	1300	cell 2400	1000
70TVA3	142		120		52		39	
	cell 2272	1200	cell 2206	1000	cell 2326	1500	cell 2400	1300
70ALLELEV	140		119		52		40	
	cell 789	1200	cell 2206	1000	cell 2326	1400	cell 2400	1300
AM50PCT	154		129		31		22	
	cell 2195	1500	cell 2334	1200	cell 2210	1900	cell 2148	1700
AM30PCT	154		132		18		13	
	cell 2195	1500	cell 2338	1100	cell 2210	1900	cell 2148	1700
AM10PCT	158		136		6		4	
	cell 2272	1200	cell 2338	1100	cell 2210	1900	cell 2148	1700

Table B-2. Mixing Height Data

20-Jul-95			24-Jul-93		
Julian Day	Hour	Mixing Height (m)	Julian Day	Hour	Mixing Height (m)
95201	0	230	93205	0	280
95201	1	230	93205	1	280
95201	2	230	93205	2	280
95201	3	230	93205	3	280
95201	4	230	93205	4	280
95201	5	230	93205	5	280
95201	6	391.1	93205	6	280
95201	7	552.2	93205	7	476
95201	8	713.3	93205	8	673
95201	9	874.4	93205	9	869
95201	10	1035.6	93205	10	1065
95201	11	1196.7	93205	11	1261
95201	12	1357.8	93205	12	1458
95201	13	1518.9	93205	13	1654
95201	14	1680	93205	14	1850
95201	15	1680	93205	15	1850
95201	16	1680	93205	16	1850
95201	17	1680	93205	17	1850
95201	18	1680	93205	18	1850
95201	19	1680	93205	19	1850
95201	20	1680	93205	20	1850
95201	21	1405	93205	21	1850
95201	22	1130	93205	22	1317
95201	23	850	93205	23	783
95202	0	580	93206	0	250
95202	1	580	93206	1	250

Table B-2. Continued.

25-Jul-93			26-Jul-93		
Julian Day	Hour	Mixing Height (m)	Julian Day	Hour	Mixing Height (m)
93206	0	250	93207	0	200
93206	1	250	93207	1	200
93206	2	250	93207	2	200
93206	3	250	93207	3	200
93206	4	250	93207	4	200
93206	5	250	93207	5	200
93206	6	250	93207	6	200
93206	7	419	93207	7	394
93206	8	588	93207	8	588
93206	9	756	93207	9	781
93206	10	925	93207	10	975
93206	11	1094	93207	11	1169
93206	12	1262	93207	12	1363
93206	13	1431	93207	13	1556
93206	14	1600	93207	14	1750
93206	15	1600	93207	15	1750
93206	16	1600	93207	16	1750
93206	17	1600	93207	17	1750
93206	18	1600	93207	18	1750
93206	19	1600	93207	19	1750
93206	20	1600	93207	20	1750
93206	21	1600	93207	21	1750
93206	22	1133	93207	22	1260
93206	23	667	93207	23	770
93207	0	200	93208	0	280
93207	1	200	93208	1	280

Table B-3. Wind Input File For July 20, 1995.

```
95201
10.0
0          0.1000000000D+02     0.1000000000D+02
1          0.0000000000D+00     -0.556100000D+04
2          0.3574000000D+04     -0.426000000D+04
3          0.1000000000D+02     0.1000000000D+02
4          -0.190200000D+04     -0.522600000D+04
5          0.3574000000D+04     -0.426000000D+04
6          -0.966000000D+03     -0.547600000D+04
7          -0.481600000D+04     -0.278000000D+04
8          -0.370800000D+04     -0.642200000D+04
9          -0.802700000D+04     -0.463400000D+04
10         0.7302000000D+04     -0.128800000D+04
11         0.8027000000D+04     0.4634000000D+04
12         0.9269000000D+04     0.0000000000D+00
13         0.9940000000D+04     0.8341000000D+04
14         0.1072400000D+05     0.1278100000D+05
15         0.8521000000D+04     0.7150000000D+04
16         0.0000000000D+00     0.1483000000D+05
17         0.1284300000D+05     0.7415000000D+04
18         0.8521000000D+04     0.7150000000D+04
19         0.5680000000D+04     -0.476600000D+04
20         0.1000000000D+02     0.1000000000D+02
21         0.1000000000D+02     0.1000000000D+02
22         0.1000000000D+02     0.1000000000D+02
23         0.2536000000D+04     0.6968000000D+04
```

Table B-4. Wind Input File For July 24, 1993.

```
93205
10.0
0           0.1000000000D+02     -.7415000000D+04
1           0.1000000000D+02     0.1000000000D+02
2           -0.253600000D+04     -0.696800000D+04
3           0.1000000000D+02     0.1000000000D+02
4           0.1000000000D+02     0.1000000000D+02
5           0.1000000000D+02     0.1000000000D+02
6           0.1000000000D+02     0.1000000000D+02
7           -0.522600000D+04     -0.190200000D+04
8           -0.476600000D+04     0.5680000000D+04
9           0.5561000000D+04     0.9632000000D+04
10          0.9632000000D+04     0.5561000000D+04
11          0.5958000000D+04     -0.710000000D+04
12          0.8520000000D+04     0.7149000000D+04
13          0.4766000000D+04     -0.568000000D+04
14          0.7415000000D+04     0.1000000000D+02
15          0.8027000000D+04     -0.463400000D+04
16          0.8710000000D+04     -0.317000000D+04
17          0.5561000000D+04     0.1000000000D+02
18          0.5226000000D+04     -0.190200000D+04
19          0.1000000000D+02     0.1000000000D+02
20          0.6968000000D+04     0.2536000000D+04
21          0.1000000000D+02     0.1000000000D+02
22          -0.522600000D+04     0.1902000000D+04
23          0.1000000000D+02     0.1000000000D+02
```

Table B-5. Wind Input File For July 25, 1993.

93206		
10.0		
0	-0.104520000D+05	-0.380400000D+04
1	0.1000000000D+02	0.1000000000D+02
2	0.1000000000D+02	-0.556100000D+04
3	0.1000000000D+02	0.1000000000D+02
4	0.1000000000D+02	0.1000000000D+02
5	0.1000000000D+02	0.1000000000D+02
6	0.1000000000D+02	0.1000000000D+02
7	0.4816000000D+04	-0.278100000D+04
8	0.5680000000D+04	0.4766000000D+04
9	0.3708000000D+04	-0.642200000D+04
10	0.9632000000D+04	0.5561000000D+04
11	0.4766000000D+04	-0.568000000D+04
12	0.1112300000D+05	0.1000000000D+02
13	0.9940000000D+04	-0.834100000D+04
14	0.6968000000D+04	0.2536000000D+04
15	0.1045200000D+05	0.3804000000D+04
16	0.6968000000D+04	-0.253600000D+04
17	-0.463400000D+04	-0.802700000D+04
18	-0.129760000D+05	0.1000000000D+02
19	0.1000000000D+02	0.9269000000D+04
20	-0.802700000D+04	0.4634000000D+04
21	0.8520000000D+04	0.7149000000D+04
22	0.6968000000D+04	0.2536000000D+04
23	0.5680000000D+04	-0.476600000D+04

Table B-6. Wind Input File For July 26, 1993.

```
93207
10.0
0          0.1000000000D+02     0.1000000000D+02
1          0.1000000000D+02     0.1000000000D+02
2          0.1000000000D+02     0.1000000000D+02
3          0.1000000000D+02     0.1000000000D+02
4          0.1000000000D+02     0.1000000000D+02
5          0.1000000000D+02     0.1000000000D+02
6          0.1000000000D+02     0.1000000000D+02
7          0.1000000000D+02     0.1000000000D+02
8          0.1000000000D+02     0.1000000000D+02
9          0.7100000000D+04     0.5958000000D+04
10         0.5680000000D+04     0.4766000000D+04
11         -0.317000000D+04     0.8710000000D+04
12         -0.568000000D+04     0.4766000000D+04
13         0.8027000000D+04     -0.463400000D+04
14         0.4766000000D+04     -0.568000000D+04
15         0.9632000000D+04     0.5561000000D+04
16         0.8027000000D+04     0.4634000000D+04
17         0.8027000000D+04     0.4634000000D+04
18         0.8710000000D+04     0.3170000000D+04
19         0.8027000000D+04     -0.463400000D+04
20         0.9269000000D+04     0.1000000000D+02
21         0.4260000000D+04     -0.357500000D+04
22         0.1000000000D+02     0.1000000000D+02
23         -0.317000000D+04     -0.871000000D+04
```

VITA

Carol Norman grew up in the small town of Manchester, Tennessee. In 1979 she went to Knoxville to attend the University of Tennessee where she earned a Bachelor of Science in Civil Engineering in 1983 and a Master of Science in Environmental Engineering in 1986. After graduating, she moved to Charleston, South Carolina and worked for a year as an engineer with the South Carolina Coastal Council. She decided she wanted to gain a wider range of technical experience and took a job as a consulting engineer with IT Corporation in Knoxville, Tennessee where she worked for seven years on projects concerning air quality. In 1995, at the suggestion of a friend, she enrolled in the civil engineering doctoral program at the University of Tennessee and concentrated her studies in policy decisions affecting air quality. During her student years, she attended short courses on environmental conflict negotiation and mediation in The Hague, The Netherlands and in Boston. She traveled to Santiago, Chile and Manaus, Brazil, visiting with environmental professionals and learning about the challenges of their environments. She continues her interest in air quality issues and hopes to work on both technical and policy-oriented research.