Transportation-Related Air Quality and Economic Growth in American Cities, 1981 to 1991

WALTER E. MARTIN, DAVID T. HARTGEN, AND ANDREW J. RESER

Can urban area economic growth be maintained while reducing transportation-related air pollution? To answer this question trends in transportation-related air pollution, employment, traffic, and population were traced for 98 nonattainment U.S. cities over the period 1981 to 1991. Data on 18 measures of pollution (ozone and carbon monoxide), three measures of traffic (vehicle miles traveled and roadway miles), five measures of economic activity (employment), and five measures of climatological circumstances are analyzed. Cities were ranked in order of progress on reducing air pollution while holding down traffic growth and encouraging economic activity. Simple repeated-measures analysis of variance models were used to analyze the data. Results show that (a) spurred by federal emissions standards, U.S. transportation-related air pollution declined 85 percent for carbon monoxide (CO) and 35 percent for ozone from 1981 to 1991, whereas employment increased 25 percent and traffic increased 52 percent; (b) progress in CO reduction was unrelated to city size, employment growth, or traffic growth, being caused primarily by improvements in automotive technology; and (c) generally cities with the most rapid population, traffic, and employment growth showed the greatest reductions in ozone. It is suggested that economic growth is compatible with progress toward cleaner air.

The Clean Air Act Amendments of 1990 place considerable pressure on many U.S. cities to make concerted progress in reducing air pollution. Cities are classified into categories of nonattainment status for carbon monoxide (CO), ozone, and particulates. In the higher categories specific actions are required along with a time frame for making progress. The cities with moderate or worse ozone nonattainment status must reduce volatile organic compounds (VOCs) by 15 percent from 1990 to 1996 and these reductions must be over and above reductions that will be caused by continuing vehicle fleet turnover. If the present plans cannot be shown to produce the required reductions, they must be modified and expanded with transportation control measures (TCMs) (*1*). Given the rapidly approaching dates and delays in rule making, it is likely that many cities will not meet the substantive reductions called for (*2*).

Meanwhile motor vehicle emission standards continue to tighten. Table 1 shows historically mandated emissions standards for automobiles and light trucks as enacted in the Clean Air Act Amendments. Partially as a result, air quality in most metropolitan areas is projected to continue to improve, and (except in a few areas such as Southern California) it may not be necessary to implement very low (Tier II) new car emissions standards (*4*). But despite emission controls and fleet turnover, analysts note less-than-forecast reductions in emissions (*5*) per mile (1 mi = 1.6093 km). And for the future some forecast increasing emissions (*6*), as travel [vehicle miles of travel (VMT)] increases. Because VMT growth is also historically linked with economic activity, the implication is clear: tighter emissions requirements or TCMs that constrain VMT also have the potential to slow economic growth.

A particularly severe issue is ozone. A by-product of photochemical reactions, ozone has emerged as a threat to air quality for nearly 120 million Americans and much of the nation's crop and forest harvests. The concentration of surface ozone depends on several factors including emission levels of hydrocarbons (HCs), emission levels of nitrogen oxides (NO_x), as well as geographic factors such as terrain and meteorological factors. Because higher levels of ozone are associated with concentrated levels of anthropogenic (human-caused) emissions found in and downwind from larger cities, economic growth and population growth are often assumed to be positively associated with higher levels of photochemical oxidants such as ozone. But trends in ozone pollution have also been obscured by short-term changes in weather, long-term changes in levels of fossil fuel combustion and evaporative emissions, and longer-term changes in the effective level of emission control. Thus the link between traffic, economic activity, and ozone pollution has been difficult to resolve.

Can economic growth be maintained while making significant reductions in transportation-related air pollution? This is perhaps the central issue in the air quality era. The nature of trade-offs among jobs, economic growth, and environmental quality is examined by Hahn (*7*), who discusses Wisconsin's attempt to balance economic and environmental objectives. This study shows that there is a tendency for the political process to ignore market mechanisms for rationing scarce environmental resources. Rapid economic growth can harm the environment, and if mismanaged the environment can severely limit economic growth. From a global perspective development can support many environmental benefits, first through improvements in technology that prevent environmental damage and second through higher income levels that are correlated with greater environmental concern and a willingness to value environmental protection (*8,9*). Additional questions concerning the seemingly different goals of improved transportation and improved air quality should be raised.

This paper focuses on several critical questions underlying the air quality-transportation debate.

1. Are U.S. cities getting cleaner? How much, for what pollutants, and where?
2. What is the relationship between air quality, city size, economic activity, and VMT?

Center for Interdisciplinary Transportation Studies, University of North Carolina at Charlotte, Charlotte, N.C. 28223.

TABLE 1 U.S. Light-Duty Vehicle Emission Standards, 1967–1994 (*3*) (40 CFR 86)

	Autos				Light Duty Trucks[a]			
Model Year	HC	CO	NOx	Particulates	HC	CO	NOx	Particulates[b]
1967*	8.7	87.0	3.6	—[c]	6.5	75.0	3.6	—
1970	2.1	22.0	3.6	—	2.2	22.0	3.6	—
1976	1.5	15.0	3.1	—	2.0	20.0	3.1	—
1979	1.5	15.0	3.1	—	1.7	18.0	2.3	—
1980	0.41	7.0	2.0	—	1.7	18.0	2.3	—
1981	0.41	3.4	1.0	—	1.7	18.0	2.3	—
1982	0.41	3.4	1.0	0.6	1.7	18.0	2.3	0.60
1984	0.41	3.4	1.0	0.6	0.8	10.0	2.3	0.60
1987	0.41	3.4	1.0	0.2	0.8	10.0	2.3	0.26
1988	0.41	3.4	1.0	0.2	0.8	10.0	1.2[d]	0.26
Tier I 1994	0.25	3.4	0.4	0.08	0.25	3.4[a]	1.2[d]	0.26
Tier I 1995	0.25	3.4	0.4	0.08	0.25d	3.4[d]	0.4[d]	0.08
Tier II 2003	0.125	1.7	0.4	0.08	0.25	3.4	0.4	0.08

Notes: a: trucks <6000 GVW to 1978, 8500 GVW 1979+
b: diesel engines only
c: no standard
d: trucks <2750 LVW
*: pre controls

3. What has been the role of technology in transportation-related air quality change?
4. What will happen in the future?
5. Are the TCMs in the 1990 Clean Air Act Amendments misplaced in their emphasis?

Fundamental to this debate are hard data. Although it is widely recognized that air pollution has generally improved even as cities have grown, as yet the link between urban growth and transportation-related air pollution has not been extensively investigated. Two competing hypotheses about this relationship were tested.

1. A direct-correlation model, hypothesizing that as cities grow they get dirtier and more congested, thus increasing air pollution. In this model air pollution is positively correlated with economic growth [Figure 1(*a*)].
2. A more complex model, hypothesizing that population growth and economic growth permit changes in technologies that reduce air pollution. In this model air pollution is negatively correlated with economic growth [Figure 1(*b*)].

Although temporal cross-sectional analyses emphasize the generally inverse association between city size and air quality, the long-term effects of cleaner technologies are ignored. Longitudinal studies by contrast might show the opposite effect: that implementation of technology-based emission control strategies during the 1980s achieved reductions in air pollution while cities also experienced population growth. The nature of these relationships and the direction and magnitude of change are examined in this paper.

Reduced atmospheric levels of particulates, lead, and CO during the past 15 years are results of effective emission control strategies. Ozone presents the greatest challenge to continued improvements in air quality and will receive the greatest attention.

OZONE'S HEALTH AND ECONOMIC IMPACTS

The health effects of photochemical oxidants are primarily respiratory. Acute, short-term, reversible effects include reductions in one-sec forced expiratory volume (FEV) and forced vital capacity. Reduced lung function at concentration of less than 300 parts per billion (ppb), unsubstantiated before 1980, have been confirmed at levels of between 120 and 240 ppb (*10–13*). Recent work by Folinsbee et al. (*14*) has found decreases in mean FEV of between 7 and 13 percent in subjects performing moderate exercise for more than 6 hr at ozone concentrations of between 80 and 120 ppb. The onset of symptoms, coughing and pain when breathing deeply, occurs in young healthy adults exercising heavily for 1 to 3 hr at ozone concentrations of as low as 120 ppb (*10–13,15*).

Long-term effects of ozone on human health remain difficult to determine. Suspected potential effects of low-level exposure, between 80 and 250 ppb, include permanent changes in lung function and structure (*16–19*), effects on growth or aging of the lung (*20*), and increased susceptibilities to bacterial and viral infections (*21,22*). Evidence that long-term low-level exposure is linked with disease does not exist; the long-term studies have not been done. Acute changes, especially among sensitive individuals, athletes, and outdoor workers, are well documented, and many researchers are concerned that permanent damage to the lung may result from exposure over many years (*23*). Although several studies suggest that levels of as high as 120 ppb are unhealthful and levels of between 80 and 120 ppb are potentially unhealthful, the issue of precisely where the health threshold for ozone may lie remains persistently unresolved (*23–25*).

Many effects of ozone and other oxidants on vegetation are well documented (*26–28*), and current research is now beginning to uncover the mechanisms by which crops and trees are damaged (*29,30*). Because prevailing levels of ozone during the growing season in most U.S. agricultural regions are double the biogenic background level (25 to 30 ppb), plants cannot repair cell damage

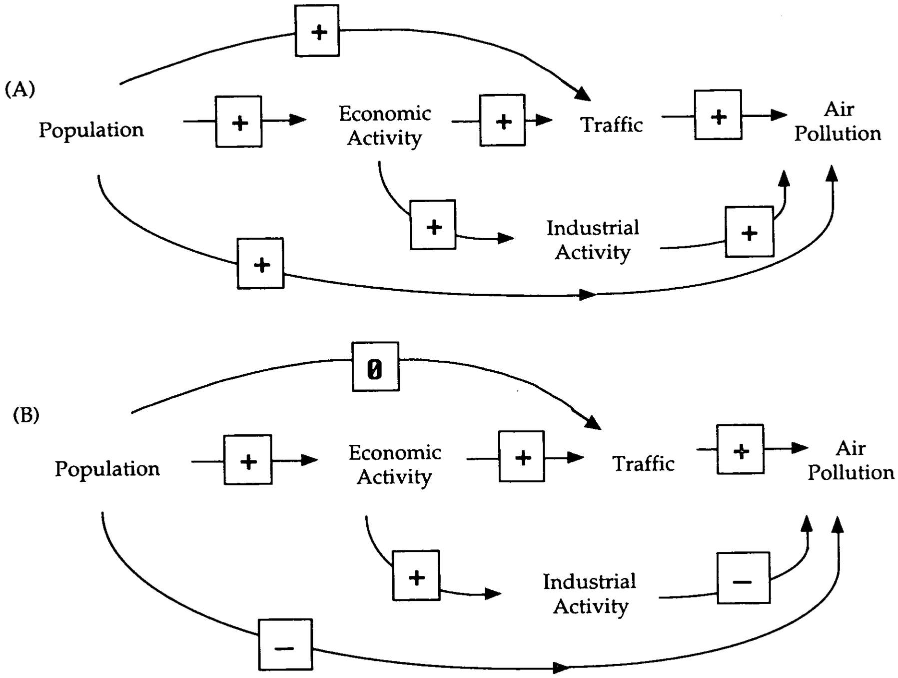

FIGURE 1 **Alternative models of air pollution and economic activity.**

quickly enough. Effects include yellowing, reduced growth, lower yields, and poor quality. Total ozone pollution is estimated to reduce crop yields by 5 to 10 percent, with high yield losses for soybeans, corn, wheat, and peanuts. U.S. agricultural losses from ozone pollution were estimated to be as much as $5 billion in 1987 (*31*). Heck (*32*) states that cutting ozone levels by 40 percent would increase yields for eight major crops by up to $3 billion annually. Although factors contributing to declines in forest productivity may include root fungi, bacteria, viruses, insect pests, and climatic stresses, the direct and chronic effects of oxidants such as ozone may also be a significant factor (*33*).

Theoretically ozone that forms and accumulates in the lower troposphere is derived from several sources, some natural and others anthropogenic. At least four categories of tropospheric ozone are recognized: natural or ''background'' ozone either from biogenic emissions or stratospheric origin, locally generated anthropogenic ozone, regional ozone from precursors accumulated in high pressure cells, and ozone formed in urban plumes downwind from cities (*34*).

These diverse origins for ozone suggest that (a) control of a single source (e.g., transportation emissions) cannot be completely effective and (b) if only one source is controlled, ozone reduction may not be dramatic. Compared with CO, which is largely transportation based, ozone is not so easily traceable or controllable (*4*). According to recent estimates transportation accounts for 69.92 percent of CO emissions, 38.7 percent of NO_x emissions, 30.1 percent of VOC emissions, and 21.2 percent of particulate emissions (*3*).

METHOD

In the study described here 98 nonattainment metropolitan statistical areas (MSAs) in the United States were examined to determine recent changes in four data components. These components were

1. Air quality,
2. Traffic and transportation,
3. Economic and population, and
4. Climatological indicators.

Air quality data were obtained from the Environmental Protection Agency's (EPA's) Aeromatic Information Retrieval System (*35*). The 1981 and 1991 Pollutant Standard Index (PSI) summaries were used. The PSI is a ratio (1.0 = 100) of local air pollution measurements (by hour) compared with the National Ambient Air Quality Standard (NAAQS) for that pollutant. Thus an ozone concentration of 150 ppb would be assigned a PSI of 125 (150/120). Since 1990 the transportation provisions of the Clean Air Act Amendments have emphasized ozone and CO reductions. Data for these two pollutants were used. Note that air quality data for some metropolitan areas may not be as complete or as accurate as desired owing to a limited number of sites, poorly located sites, and variations in the age and accuracy of monitoring equipment. Local and state commitments to clean air and budgetary support for air quality monitoring may vary. Information included in the data set include annual number of days good (0 to 50 PSI), moderate (51 to 100 PSI), unhealthful (101 to 200 PSI), very unhealthful (201 to 301 PSI), and hazardous (301 to 400 PSI) air quality.

Additional summary statistics used are (a) total number of days of unhealthful or worse (in each calendar year), (b) average PSI (year), (c) highest PSI (year), and (d) 75th percentile PSI (year). Although the NAAQS indicates unhealthful conditions (i.e., total days unhealthful or worse), the 75th percentile PSI may be a better indicator of air quality because it reduces the effect of rare or extreme events in the trend of high pollution episodes.

Transportation data included (a) total daily VMT (DVMT), (b) DVMT per capita, and (c) total roadway miles for 1980 and 1991. Wherever possible data were obtained at the MSA level; however, the transportation data prepared by the U.S. Department of Transportation are reported only for urbanized areas (*36*). Because of this the data for this component were analyzed only in a very general way to indicate basic traffic trends. As with air quality data VMT estimates are difficult to verify and may suffer for some spatial and temporal variations. Economic, population, and climatic profile data were retrieved from the American Chamber of Commerce Research Association (ACCRA) Community Profiles data base (*37*).

Employment and population data from the 1980 and 1990 censuses were used for the economic component, which included (a) nonfarm employment, (b) manufacturing employment, (c) retail employment, (d) service employment, and (e) population.

Climate data included (a) heating degree days, (b) cooling degree days, (c) maximum yearly temperature, (d) mixing potential and turbidity, and (e) forecast days of high air pollution per 5 years (*38*).

Data were analyzed in simple tables and charts. Analysis of variance (ANOVA) techniques were used to determine the strengths of the models.

FINDINGS: GENERAL

Figures 2 and 3 suggest that, using cross-sectional data (1981 and 1991), an apparent positive correlation between city size and air pollution exists for both years. This appears to confirm the model shown in Figure 1(*a*). However closer inspection of the data for individual cities over time reveals that most cities in the data base experienced a decline in average PSI (pollution) and an increase in population more similar to the model shown in Figure 1(*b*). Temporal change is masked by the use of simple cross-sectional data. Most cities saw increases in air quality and population in 1991 compared with the values in 1981.

Table 2 shows the aggregate U.S. trends that confirm this interpretation. Transportation-related air pollution (ozone and CO) both improved considerably during the 1980s, despite significant increases in economic activity and traffic. Reductions for CO were generally greater than those for ozone. Meanwhile economic activity, measured in jobs and population, grew 25.4 and 12.4 percent, respectively, and VMT increased 52.5 percent.

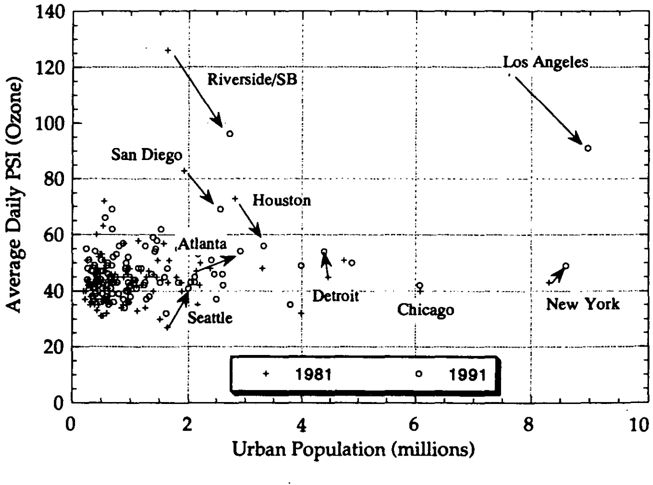

FIGURE 2 Changes in ozone concentration and population size.

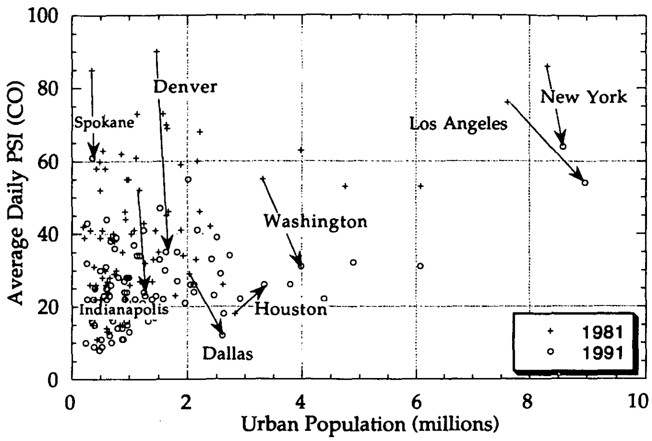

FIGURE 3 Changes in CO concentration and population size.

As an aggregate index of air quality the PSI remains a standard statistic; however, it is also necessary to examine measures of individual pollutants. Ozone and CO show trends similar to those for CO, but the changes are much less substantial for ozone. Indeed a few ozone parameters show increases in pollution (Table 2), whereas most show modest reductions. On the key statistics (CO and ozone days over NAAQS), average reductions were 85 and 35 percent, respectively.

Findings: Cities Making Most Progress

To better understand some of the trends across the country, a ranking scheme was created to compare MSAs according to air quality, economic growth, and traffic. The higher-ranking MSAs are the ones that improved air quality while also maintaining economic growth and keeping traffic growth modest. Ranks were computed for each of four measures, which included:

1. Number of unhealthy days (PSI 100) for ozone in 1991,
2. Number of unhealthy days for CO in 1991,
3. Percent change in nonfarm employment for 1980 to 1990, and
4. Percent change in DVMT (reversed) for 1980 to 1991 (traffic figures are for urbanized areas).

The four ranks were summed, with the lowest sum receiving the highest overall score. The best overall cities (the fewest days of unhealthy air, but with economic growth and traffic control) were

1. Tampa–St. Petersburg, Fla.;
2. Jacksonville, Fla.;
3. South Bend, Ind.;
4. Orlando, Fla.; and
5. Fort Lauderdale, Fla.; Fayetteville, N.C.; and Omaha, Nebr.

TABLE 2 Aggregate Trends in Air Pollution and Economic Growth

	Averages for 88 Non-Attainment U.S. Cities*		
Air Pollution	1981 Average	1991 Average	%Change
Carbon Monoxide			
# days unhealthful	12.49	1.95	-84
# days very unhealthful	1.35	0.06	-95
# days hazardous	0.02	0.00	-100
# days >100 PSI	13.86	2.01	-85
highest PSI	145.48	91.59	-37
75th percentile PSI	49.39	31.78	-36
Average PSI	40.15	26.27	-35
Ozone			
# days unhealthful	9.20	6.61	-28
# days very unhealthful	2.40	0.94	-61
# days >100 PSI	11.60	7.56	-35
highest PSI	141.4	123.08	-13
75th percentile PSI	57.80	58.78	+2
Average PSI	45.57	47.31	+4
Economic Activity	1980 Average	1990 Average	% Change
Nonfarm employment	709,584	889,615	+25.4
Manufacturing employment	126,204	115,702	-8.3
Retail employment	113,565	144,777	+27.5
Service employment	173,240	269,427	+55.5
Population (1981-1991)	1,379,759	1,550,423	+12.3
Traffic (urbanized area)	1980 Average	1991 Average	% Change
Daily VMT**	19,434,133.0	29,638,651.0	+52.5
DVMT/capita	15.5	20.9	+34.5
Roadway Miles	4,257.1	4,984.3	+17.1

* A number of (generally smaller) cities had missing data items and are not included.

** One mile equals 1.6093 kilometers.

Cities with the lowest index scores were

98. Los Angeles–Long Beach, Calif.;
97. Fresno, Calif.;
96. El Paso, Tex.;
95. New York, N.Y.; and
94. Worchester, Mass.

A similar ranking is achieved when 1991 VMT per capita is substituted for the change in VMT. Florida cities still held four of the top eight scores, while Philadelphia, Pennsylvania; Modesto, California; and the New York City area made some minor gains in rank. One potential contributing factor in the case of New York was the relatively high rate of job loss within the New York metropolitan area during the nationwide slowdown that began in 1990 and 1991. New York is also typical with regard to its relatively high rate of transit use and consequent low VMT per capita. Cities that dropped because of high VMT per capita were Atlanta, Georgia; Raleigh-Durham, North Carolina; and Nashville, Tennessee. Florida cities were the overall big winners because of rapid economic growth and climate conditions that were not conducive to air stagnation and the lack of ventilation that can elevate pollution levels. Generally the losers were California cities and established cities where decennial economic growth was slower.

Findings: Models of Economic Change and Air Quality

Repeated-measures ANOVA was used to discern changes in air quality with respect to selected measures of demographic, economic, and transportation change between 1981 and 1991. Repeated-measures ANOVA differs from a standard multivariate analysis in that temporal autocorrelation is controlled. Repeated measures is frequently used to investigate identical measurements of each sample member across two or more time steps. In the present case nominal categories such as population decline, moderate population growth, and rapid growth were associated with an interval variable, the annual number of unhealthy days from CO or ozone. So measured, air quality was entered as the dependent variable. The independent variables and their levels are given in Table 3. *P*-values at the 0.05 alpha level were considered significant. The model form is

$$\Delta Y = \mu + \partial T + \beta X + \Psi TX + e$$

where ΔY is change in pollution, μ is a grand mean, ∂ is the time (technology) effect, β is the effect of X, Ψ is the interaction between time and X, and e is the error term.

TABLE 3 Repeated-Measures ANOVA Models of Independent Variables

Variable	Level
Population Change (percent)	Rapid: >15 Moderate: 0–15 Loss: <0
Population Density/mi^2 (1990) (1 mi^2 = 2.59 km^2)	High: >13.658 Medium: 4,579–13,658 Low: <4,579
Nonfarm Employment (percent change)	Rapid: >40.04 Moderate: 13.5–40.04 Slow: <13.5
Manufacturing Employment (percent change)	Gain: >8.32 Stable: −9.11–+8.32 Loss: <−9.11
Value Added by Manufacturing ($/employee, 1987)	High: >$10,044 Moderate: $3,570–$10,044 Low: <$3,570
DVMT (percent change)	Extensive: >97.05 Moderate: 43.58–97.05 Nominal: <43.58
DVMT/capita (percent change)	High: >47.86 Moderate: 21.54–47.86 Low: <21.54
Pollution Potential (number of days)	High: >28 Moderate: 10–28 Low: <10

Population Change

Although cities with rapid growth exhibited the highest levels of CO and ozone, they also demonstrated dramatic rates of air quality improvement (Figure 4). All population change categories showed tremendous improvement in unhealthy CO days, but cities with moderate growth and population losses showed almost no improvement in the number of unhealthy ozone days. Both models (CO and ozone) were significant (Table 4). CO levels improved regardless of the population density. Those cities with the highest densities showed the greatest improvement (P = 0.0002). No significant relationship could be found between population and levels of ozone (Table 4).

Economic Indicators

Total employment within the metropolitan area was measured as nonfarm employment. Each city was assigned to a job growth category (moderate, slow, or rapid growth) on the basis of the percent change in employment between 1981 and 1991. The status of New York City in this classification is somewhat distorted owing to the disproportionate number of jobs lost during 1990 and 1991. Rapidly growing cities demonstrated the greatest improvement in air quality; this was followed by cities that grew moderately and slowly (Figure 5). Although the association with ozone days was not statistically significant, a similar pattern identified for CO days was significant.

Cities with large gains in manufacturing employment displayed slightly greater rates of improvement than those with stable or negative manufacturing job growth, even though the latter groups achieved slightly higher air quality in terms of CO. Reductions in the number of ozone days were not significant, although the general pattern of change resembles the graph of CO-manufacturing employment relationships.

The relationship between value added in manufacturing in 1987 (classified as low, moderate, or high) and air quality is significant for both CO days and ozone days. There appear to be only trivial differences in the rates of improvement between groups. All three trend lines decline in parallel, suggesting that both mobile and stationary source controls have been effective. Cities with relatively low value added in manufacturing appear to begin and end the 10-year period with the worst air quality in terms of both CO and ozone.

Pollution Potential

High air pollution potential advisories are issued periodically as a service to aid those who may need to avoid exposure to high

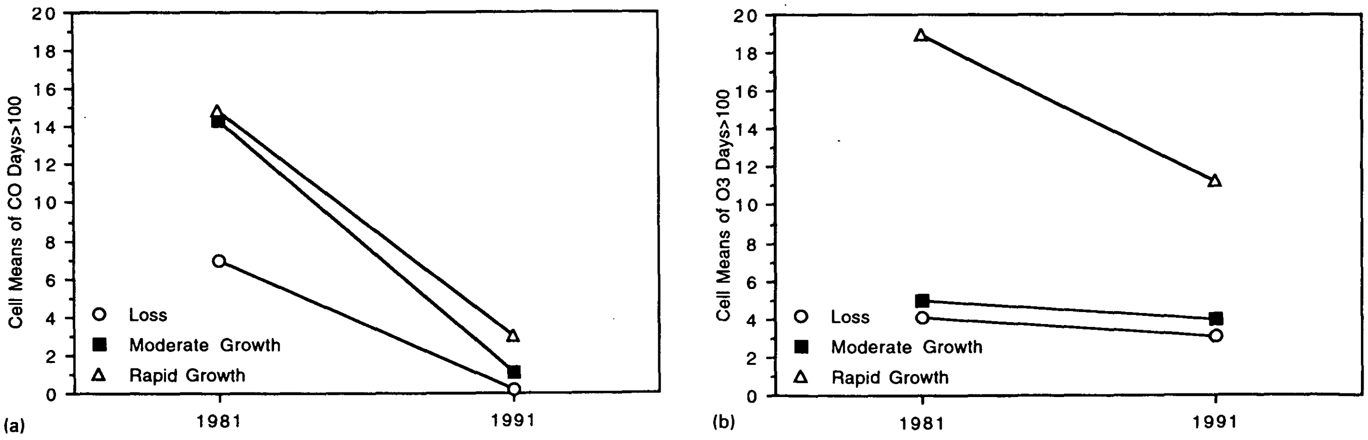

FIGURE 4 Change in air quality by percent change in population category: (*a*) dependent variable, CO days > PSI 100; (*b*) dependent variable, ozone days > PSI 100.

TABLE 4 Repeated-Measures ANOVA Models of Air Pollution, Time, and Economic Indicators

Carbon Monoxide and Growth	N	Model Sum of Squares	Error Sum of Squares	Total Sum of Squares	R Squared	Model F-Value	Model P-Value
Percent Change in Population	104	7461.99	48864.72	56326.72	0.13	5.77	**0.0001**
Population Density	104	6869.51	49457.21	56326.72	0.12	5.25	**0.0002**
Percent Change in Non Farm Employment	104	7141.27	49185.45	56326.72	0.13	5.49	**0.0001**
Percent Change in Manufacturing Employment	104	7881.39	48445.33	56326.72	0.14	6.15	**0.0001**
Value Added by Manufacturing (1987)	103	7075.35	49199.56	56274.91	0.13	5.41	**0.0001**
Percent Change in Daily Vehicle Miles Traveled	99	7208.27	48645.98	55854.25	0.13	5.31	**0.0001**
Percent Change in Daily VMT per Capita	101	6813.33	49300.67	56114.00	0.12	5.06	**0.0002**
Pollution Potential	104	7624.43	48702.29	56326.72	0.14	5.92	**0.0001**
Ozone and Growth							
Percent Change in Population	104	7296.34	97645.49	104941.83	0.07	3.02	**0.0119**
Population Density	104	917.76	104024.07	104941.83	0.01	0.36	0.8777
Percent Change in Non Farm Employment	104	3882.86	101059.02	104941.83	0.04	1.55	0.1753
Percent Change in Manufacturing Employment	104	2448.03	102493.80	104941.83	0.02	0.96	0.4404
Value Added by Manufacturing (1987)	103	5601.46	99186.74	104788.23	0.05	2.26	**0.0500**
Percent Change in Daily Vehicle Miles Traveled	99	1173.89	103306.81	104480.71	0.01	0.44	0.8228
Percent Change in Daily VMT per Capita	101	2371.61	102450.67	104822.28	0.02	0.91	0.4773
Pollution Potential	104	15882.19	89059.64	104941.83	0.15	7.21	**0.0001**

concentrations of certain air contaminants. The most important factor that contributes to the high air pollution forecast is limited atmospheric mixing. Many factors such as synoptic barometric patterns, land and sea effects, and terrain effects may conspire to reduce boundary layer ventilation and raise air pollution levels. The average annual number of forecast days of high air pollution potential was used to examine the relative improvements between locations with low, moderate, or high air pollution risk potentials. California and the Southeast have the greatest air pollution potential, whereas cities in the Great Plains, with higher average wind speeds and favorable ventilation, have the lowest air pollution potential.

Only minor differences can be discerned between group rates of CO improvement. Cities with high air pollution potential show the greatest rate of improvement in ozone days, whereas cities with moderate and low air pollution potentials demonstrate flat performance. Both models for CO and ozone are significant.

Traffic

Changes in the percent DVMT compared with changes in air quality suggest that those cities with the most extensive increases in DVMT between 1981 and 1991 did not sacrifice improvement in air quality. Starting with fewer CO events in 1981, cities with extensive increases in DVMT managed to maintain their lead. Unlike the CO model, changes in ozone versus DVMT were not significant (Table 4). Only small differences in improvement rates separate groups of cities on the basis of the percent change in DVMT per capita. Although not so for ozone, CO improvements are significant, suggesting that mobile source controls have generally been effective nationwide.

DISCUSSION OF RESULTS

The following were observed in the study described in this paper:

1. Transportation-related air pollution (CO and ozone) has improved significantly in recent years and shows promise of continued improvement. Generally CO has been improved much more than ozone.

2. Although the statistical relationships are quite weak, air pollution reductions have been greatest in those cities with the greatest pollution in 1981 and those cities with the most rapid population, economic, and traffic growth. Primarily because of a few high values, the range of the data is great. Consequently the best consolidated model (Table 5) explained only 19 percent of the variation in unhealthy ozone days.

3. Conversely air pollution reductions have been the lowest in those cities with lower pollution levels in 1981 and those cities with slower population, economic, and traffic growth.

4. As a result of these improvements transportation-related air pollution has not been hostile to growth, even in those areas with rapid growth.

Continued technological improvements to automobiles, which result in cleaner combustion and greater pollution control requirements for point-source emitters, have played the most significant role in improving air quality over the past 10 years. But in all likelihood cities may be facing diminished returns in air quality benefits from continued technological improvements. The 1990 Clean Air Act Amendments recognize this and require that metropolitan regions initiate programs to reduce VMT to such an extent that these reductions must outpace those from fleet turnover.

Because some of the most effective measures for reducing air pollution (such as vehicle exhaust regulations promulgated after 1990) cannot be counted toward the 15 percent reduction target, the emphasis of the present act is placed on TCMs. Despite the call to implement TCMs most states have not responded aggressively. As noted earlier all moderate nonattainment areas must show a 15 percent reduction in VOCs by 1996, and serious and worse areas must show a 3 percent a year reduction after 1996. TCMs are directed toward reducing emissions by improving traffic flow, reducing congestion, or reducing vehicle use. These TCMs must be part of a contingency plan, which will take effect if that state fails to meet the 15 percent emission reduction targets re-

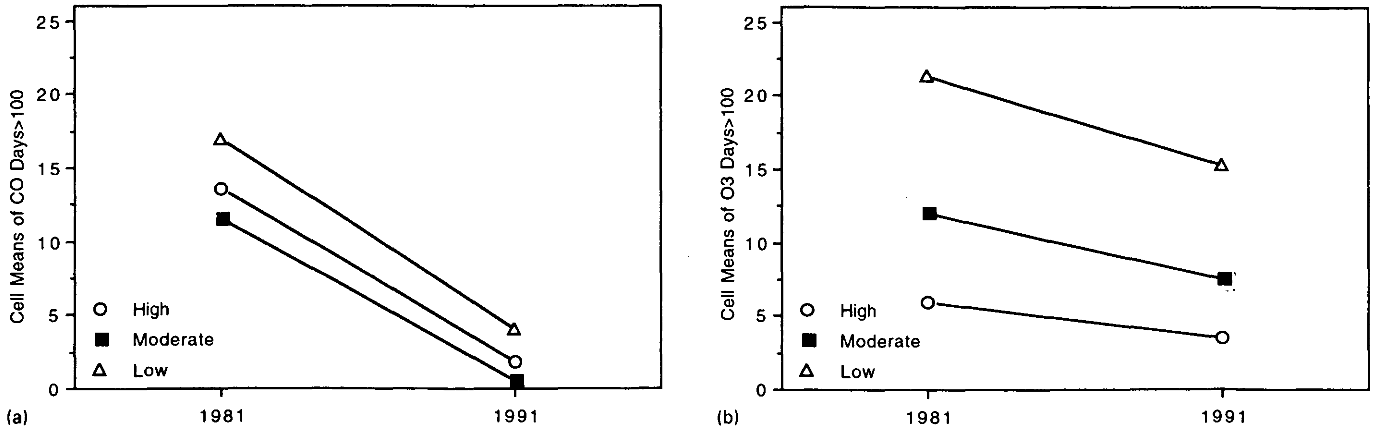

FIGURE 5 Change in air quality by manufacturing value added category: (*a*) dependent variable, CO days > PSI 100; (*b*) dependent variable, ozone days > PSI 100.

quired by 1996, fails to attain the NAAQS target date, or in the case of areas designated serious and above fails to meet the 3 percent annual emissions reductions required after 1996. Areas classified as serious or worse must submit a clean-fuel fleet program by May 15, 1994, in addition to carrying out the enhanced inspection and maintenance program. Severe and extreme areas must submit specific TCMs to reduce VMT or the numbers of trips, demonstrate compliance with employer trip reduction programs, and begin a reformulated gasoline program in 1995.

As can be shown from this paper, VMT increased at a rate of about 50 percent in the MSAs during the past 10 years. VMT per capita is also increasing. The rise in automobile traffic, driven by uncontrolled land development and very low cost automobile and truck use, is to many the very symbol of U.S. economic growth and vitality. The new challenge of these cities is to maintain economic prosperity while reducing air pollution and managing traffic growth. Fortunately progress in air pollution reduction and progress in economic growth (as defined by employment and population growth) during the 1980s were not incompatible.

The present analysis has highlighted the importance of technological change and its tie to economic performance in achieving clean air. What should now be the focus of air pollution reduction policy? Given that this progress occurred during a time of rapid traffic growth as well as major reductions in carpooling and transit use, these gains cannot be ascribed either to behavioral shifts (these were shifts in the opposite direction) or to urban densifi-

TABLE 5 Combined ANOVA Model of Ozone Pollution with Four Key Variables

Type III Sums of Squares
Dependent: Ozone Days >100

Source	df	Sum of Squares	Mean Square	F-Value	P-Value
Time	1	745.942	745.942	1.809	0.1802
Pollution Potential	2	10642.556	5321.278	12.905	0.0001
Value Added Mfg.	2	6698.778	3349.389	8.123	0.0004
%Population Change	2	2160.577	1080.289	2.620	0.0753
Residual	198	81646.215	412.355		

Model Summary
Dependent: Ozone Days > 100

Count	206
R	0.470
R-Squared	0.221
Adj. R-Squared	0.193
RMS Residual	20.301

	df	Sum of Squares	Mean Square	F-Value	P-Value
Model	7	23142.018	3306.003	8.017	0.0001
Error	198	81646.215	412.355		
Total	205	104788.233			

cation (cities spread out and became less dense during the 1980s). Therefore the authors make the following recommendations:

1. Substantive research should be undertaken to investigate the air quality-economic growth links uncovered here. Particularly fruitful would be research on
   - Climatological versus human factors in ozone pollution,
   - Fleet turnovers in individual cities and industrial modernization versus air pollution trends,
   - Effects of measurement site location on trends,
   - Data accuracy,
   - Changes in city "mix" of industrial-economic base versus pollutant sources over time, and
   - Impacts of transportation investments on air pollution trends.
2. The focus of future air pollution reduction strategies should be on
   - Stronger inspection and maintenance programs,
   - Encouraging the natural fleet turnover process to speed removal of high-polluting vehicles from the traffic stream,
   - Continued reductions in vehicle emissions (tailpipe), and
   - Fuel modifications.
3. Cities not in attainment with ozone standards should be permitted (first) to submit plans to improve inspection and maintenance programs and fuel modifications or remove high emitters. Behavioral (TCM) actions should be maintained in cities with no record of progress, but should be tied to programs that facilitate employment growth.
4. EPA should consider a change from sanctions intended to force compliance to active support for cities, particularly ways to encourage fleet turnover and economic growth.

The data examined here suggest that many cities are attaining the minimum standards for clean air and that most are showing improved air quality. The relationship between growth and improved air quality merits much greater attention. Innovative emission control strategies that pursue a win-win strategy for both economic growth and progress toward cleaner air are advocated.

REFERENCES

1. *Transportation Programs and Provisions of the Clean Air Amendments of 1990.* FHWA, U.S. Department of Transportation, Oct. 1992.
2. Hartgen, D. T., W. E. Martin, and A. J. Reser. *Non-Attainment Areas Speak: MPO Responses to the Clean Air Act of 1990: Report to the Federal Highway Administration.* FHWA, U.S. Department of Transportation, May 1993.
3. Davis, S. C., and S. G. Strang. *Transportation Energy Data Book,* Edition 13. ORNL-6743. U.S. Department of Energy, Office of Transportation Technologies, Oak Ridge National Laboratory, Oak Ridge, Tenn., March 1993.
4. Calvert, J. G., J. B. Heywood, R. F. Sawyer, and J. H. Seinfeld. Achieving Acceptable Air Quality: Some Reflections of Controlling Vehicles. *Science,* Vol. 261, July 2, 1993, pp. 37–45.
5. Howitt, A., and A. Alschurler. *The Challenges of Transportation and Clean Air Goals.* Kennedy School of Government, Harvard University, Cambridge, Mass., 1992.
6. Hawthorn, G. Transportation Provisions in the Clean Air Act Amendments of 1990. *ITE Journal,* 1991, pp. 17–24.
7. Hahn, R. W. Jobs and Environmental Quality: Some Implications for Instrumental Choice. *Journal of Policy Sciences,* Vol. 20, No. 4, 1987, pp. 289–306.
8. *World Development Report 1992: Development and the Environment.* World Bank, Oxford University Press, May 1992.
9. Cairncross, F. Costing the Earth: The Challenge for Governments. In *The Opportunities for Business.* Harvard Business School Press, 1992.
10. Avol, E. L., W. S. Linn, T. G. Venet, D. A. Shamoo, and J. D. Hackney. Comparative Respiratory Effects of Ozone and Ambient Oxidant Pollution Exposure During Heavy Exercise. *Journal of Air Pollution Control Association,* Vol. 34, 1984, pp. 804–809.
11. Folinsbee, L. J., J. F. Bedi, and S. M. Horvath. Pulmonary Function Changes After 1 h Continuous Heavy Exercise in 0.21 ppm Ozone. *Journal of Applied Physiology,* Vol. 57, 1984, pp. 984–988.
12. Gong, H., M. S. Bradley, D. P. Simmons, and D. P. Tashkin. Impaired Exercise Performance and Pulmonary Function in Elite Cyclists During Low-Level Ozone Exposure in a Hot Environment. *American Review of Respiratory Diseases,* Vol. 134, 1986, pp. 726–733.
13. McDonnell, W. F., D. H. Horstman, M. J. Hazucha, E. Seal, E. D. Haak, S. A. Sallam, and D. E. House. Pulmonary Effects of Ozone Exposure During Exercise: Dose Response Characteristics. *Journal of Applied Physiology,* Vol. 54, 1983, pp. 1345–1352.
14. Folinsbee, L. J., W. F. McDonnell, and D. H. Horstman. Pulmonary Function and Symptom Responses After 6.6 Hour Exposure to 0.12 ppm Ozone with Moderate Exercise. *Journal of Air Pollution Control Association,* Vol. 38, 1988, pp. 28–35.
15. Kulle, T. J., L. R. Sauder, J. R. Hebel, and M. D. Chatham. Ozone Response Relationship in Healthy Non-Smokers. *American Review of Respiratory Diseases,* Vol. 132, 1985, pp. 36–41.
16. Crapo, J. D., B. E. Barry, L.-Y. Chang, and R. R. Mercer. Alterations in Lung Structure Caused by Inhalation of Oxidants. *Journal of Toxicology and Environmental Health,* Vol. 13, 1984, pp. 301–321.
17. Detels, R., D. P. Tashkin, J. W. Sayre, S. N. Rokaw, A. H. Coulson, F. J. Massey, and D. H. Wegman. The UCLA Population Studies of Chronic Obstructive Respiratory Disease. *Chest,* Vol. 92, 1987, pp. 594–603.
18. Last, J. A., D. B. Greenberg, and W. L. Castleman. Ozone-Induced Alterations in Collagen Metabolism of Rat Lungs. *Toxicology and Applied Pharmacology,* Vol. 51, 1979, pp. 247–258.
19. Tyler, W. S., N. K. Tyler, J. A. Last, M. J. Gillespie, and T. J. Barstow. Comparison of Daily and Seasonal Exposures of Young Monkeys to Ozone. *Toxicology,* Vol. 50, 1988, pp. 131–144.
20. Bartlett, D. J., C. S. Faulkner, and K. Cook. Effect of Chronic Ozone Exposure on Lung Elasticity in Young Rats. *Journal of Applied Physiology,* Vol. 37, 1974, pp. 92–96.
21. Ehrlich, R., J. C. Findlay, J. D. Feners, and D. E. Gardner. Health Effects of Short-Term Inhalation of Nitrogen Dioxide and Ozone Mixtures. *Environmental Research,* Vol. 14, 1977, pp. 223–231.
22. Miller, F. J., J. W. Illing, and D. E. Gardner. Effect of Urban Ozone Levels on Laboratory-Induced Respiratory Infections. *Toxicology Letters,* Vol. 2, 1978, pp. 163–169.
23. Lippmann, M. Health Effects of Ozone: A Critical Review. *Journal of Air Pollution Control Association,* Vol. 39, 5, 1989, pp. 672–695.
24. U.S. Congress, Office of Technology Assessment. *Catching Our Breath: Next Steps for Reducing Urban Ozone.* Report OTA-O-412. U.S. Government Printing Office, Washington, D.C., July 1989.
25. Chestnut, L. G., and R. D. Rowe. Economic Measures of the Impacts of Air Pollution on Health and Visibility. *Air Pollution's Toll on Forests and Crops.* (J. J. MacKenzie and M. T. El-Ashry, eds.). Yale University Press, New Haven, Conn., 1989.
26. Lefohn, A. S. *Surface Level Ozone Exposures and Their Effects of Vegetation.* Lewis Publishers, Inc., Chelsea, Mich., 1992.
27. MacKenzie, J. J., and M. T. El-Ashry. Ill Winds: Air Pollution's Toll on Trees and Crops. *Technology Review,* Vol. 92, April, 1989, pp. 65–71.
28. Majumdar, S. K., E. W. Miller, and J. J. Cahir. *Air Pollution: Environmental Issues and Health Effects.* The Pennsylvania Academy of Sciences, Easton, 1991.
29. Runeckles, V. C., and B. I. Chevone. Surface Level Ozone Exposures and Their Effects on Vegetation. In *Crop Responses to Ozones* (A. S. Lefohn, ed.). Lewis Publishers, Chelsea, Mich., 1992.
30. Chappelka, A. H., and B. I. Chevone. Surface Level Ozone Exposures and Their Effects on Vegetation. In *Tree Responses to Ozone* (A. S. Lefohn, ed.). Lewis Publishers, Chelsea, Mich., 1992.
31. *Interim Assessment, the Cause and Effects of Acid Deposition:* Vol. 4, *Effects of Acid Deposition.* National Acid Precipitation Assessment Program. NAPAP IV. U.S. Government Printing Office, Washington, D.C., 1987.
32. Heck, W. W. Assessment of Crop Losses from Air Pollution in the United States. In *Air Pollution's Toll on Forests and Crops* (J. J.

MacKenzie and M. T. El-Ashry, eds.). Yale University Press, New Haven, Conn., 1989.

33. Bruck, R. I. Forest Decline Syndromes in the Southeastern United States. In *Air Pollution's Toll on Forests and Crops* (J. J. MacKenzie and M. T. El-Ashry, eds.). Yale University Press, New Haven, Conn., 1989.
34. Spicer, C. W., D. W. Joseph, P. R. Stickel, and G. F. Ward. Ozone Sources and Transport in the Northeastern United States. *Environmental Science and Technology*, Vol. 13, No. 8, 1979, pp. 975–985.
35. *Aerometric Information Retrieval System, AMP 410 Pollutant Standard Index Summary 1981, 1991*. Environmental Protection Agency, AIRS, Ann Arbor, Mich., May 1993.
36. *Highway Statistics 1991*. Report FHWA-PL-91-003. FHWA, U.S. Department of Transportation, Dec. 1992.
37. *ACCRA Community Profile*. Comparative Data for MSAs and Participating Counties. American Chamber of Commerce Research Association, Vol. 1, No. 1, 1:1:1993.
38. Eagleman, J. R. *Air Pollution Meteorology*. Trimedia Publishing Company, Lenexa, Kans., 1991.

Publication of this paper sponsored by Committee on Transportation and Air Quality.