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Urban sprawl and air quality in large US cities

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Abstract

This study presents the results of a paper of urban spatial structure and exceedances of the 8-h national ambient air quality standard for ozone in 45 large US metropolitan regions. Through the integration of a published index of sprawl with metropolitan level data on annual ozone exceedances, precursor emissions, and regional climate over a 13-year period, the association between the extent of urban decentralization and the average number of ozone exceedances per year, while controlling for precursor emissions and temperature, is measured. The results of this analysis support the hypothesis that large metropolitan regions ranking highly on a quantitative index of sprawl experience a greater number of ozone exceedances than more spatially compact metropolitan regions. Importantly, this relationship was found to hold when controlling for population size, average ozone season temperatures, and regional emissions of nitrogen oxides and volatile organic compounds, suggesting that urban spatial structure may have effects on ozone formation that are independent of its effects on precursor emissions from transportation, industry, and power generation facilities.

Keywords: Urban form; Ozone formation; Urban planning; Land use; Air quality; Urban sprawl

1. Introduction

Identified in the popular media as the source of numerous social, environmental, and economic ills, the phenomenon of urban sprawl is increasingly the subject of more rigorous inquiry in the peer-reviewed literatures on economics, urban planning, and public health. Generally defined as decentralized land use patterns characterized by low population densities and auto-oriented design schemes, urban sprawl has been demonstrated to greatly elevate the cost of urban services by increasing the distance between new development and the established infrastructure of roads, sewer lines, and transit systems (Burchell et al., 2002; Real Estate Research Corporation, 1974). Additional work has associated sprawling urban development patterns with increased vehicle travel and congestion (Ewing et al., 2003; Downs, 1992), increased volumes of stormwater runoff (Stone and Bullen, 2006), loss of prime agricultural lands (Heimlich and Anderson, 2001), and, perhaps most provocatively, increased rates of obesity in children and adult populations (Frumkin et al., 2004).

In this study, I explore the implications of urban form for air quality within the largest metropolitan regions of the United States. Through the integration of data on land use attributes and air quality trends recorded in 45 of the 50 largest US metropolitan regions, a quantitative index of urban sprawl is associated with the emissions of ozone precursors and the annual number of high ozone days in each region between 1990 and 2002. While a handful of studies has demonstrated an association between various attributes of urban development and vehicle emissions in individual cities (Frank et al., 2000; Johnston et al., 2000), this work is the first to assess the implications of sprawl for an ambient measure of regional air quality in multiple cities while controlling for population, precursor emissions, and meteorological attributes significant to ozone formation.

Specifically, this study addresses two principal research questions. First, are metropolitan regions characterized by high levels of sprawl associated with a greater quantity of ozone precursor emissions from vehicles and industry than more compact regions? And, second, do metropolitan regions characterized by high levels of sprawl experience a

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greater number of annual ozone exceedances than more compact regions? The significance of these questions lies in their potential to inform land-use strategies to combat air pollution in large cities.

The results of this study indicate that for the 45 US metropolitan regions surveyed urban form is significantly associated with both ozone precursor emissions and ozone exceedances during a 13-year study period. Significantly, a positive association between sprawl and ozone exceedances was found to hold true when controlling for average ozone season (May through September) temperatures and annual emissions of chemical precursors to ozone formation, suggesting that the well-established linkage between decentralized development patterns and auto use may be only one of multiple mechanisms through which sprawl influences air quality. Overall, the most sprawling cities were found to experience over 60% more high ozone days than the most compact cities.

2. Background

The literature on land use and air quality has explored two principal mechanisms through which the physical dimensions of urban form can influence regional air quality. The first and most widely investigated set of interactions concerns the linkages between land use, vehicle travel, and vehicle tailpipe emissions. The second set of interactions, posited in a small but growing number of studies, concerns the linkages between land use, local meteorology, and regional air quality. A brief overview of these two areas of research is provided in the following paragraphs to establish a basis for understanding the potential significance of urban sprawl to ozone formation.

2.1. Urban form, vehicle travel, and emissions

A significant relationship between land use and vehicle travel has been widely documented (Transportation Research Board, 1995; Apogee, 1998). Perhaps the most compelling evidence of this relationship is provided by the handful of studies that has examined readily available measures of land use and travel within a large number of cities. In one of the most widely cited of these studies, Newman and Kenworthy (1989) documented a strong and significant negative relationship between population density and per capita fuel usage within 63 large metropolitan regions around the world ($R^2 = 0.86$).[1] Similar significant relationships have been found to exist between population density and vehicle ownership, vehicle trip generation, and vehicle miles traveled (VMT) in American cities and abroad (Pucher and Lefevre, 1996).

In addition to these widely cited multi-city studies, projects employing travel simulation models or travel survey data from a single metropolitan region have also tended to illustrate a weak to moderate but statistically significant relationship between urban form and travel behavior. Of 18 studies of this nature reviewed by the author, 15 documented a statistically significant relationship between the density of development, land use mix, and/or the configuration of the street network (i.e., street connectivity) and some measures of vehicle travel (e.g., Frank and Pivo, 1994; Cervero and Gorham, 1995). For example, in a study of land use and vehicle travel in Sacramento, California, Johnston et al. (2000) found the combined impacts of transit improvements and land use strategies to reduce VMT between 4% and 7% over 20 years. In one of the most widely cited studies of this nature, the Land Use, Transportation, and Air Quality (LUTRAQ) analysis conducted in Portland, Oregon, a compact development scenario emphasizing transit-oriented development, pedestrian infrastructure improvements, and transportation demand management policies was found to reduce daily VMT by 8% relative to the business as usual scenario of highway expansion (Cambridge Systematics, Inc. and Parsons Brinkerhoff Quade and Douglas, Inc., 1992).

While the relationship between land use and vehicle travel generally has been assumed to hold implications for tailpipe emissions and air quality, only a handful of studies has sought to statistically link urban form to vehicle emissions directly. In addition to establishing an association between transit-oriented development and daily VMT, the LUTRAQ study cited above also found the emissions of nitrogen oxides (NO_x) and carbon monoxide (CO) to be reduced by 6% and 3%, respectively, in response to various urban development scenarios (Cambridge Systematics, Inc. and Parsons Brinkerhoff Quade and Douglas, Inc., 1992). Through the integration of household travel survey data obtained in Seattle, Washington with a mobile source emissions model, Frank et al. (2000) found statistically significant relationships between household density, employment density, street connectivity, and tailpipe emissions. Specifically, vehicle emissions of CO, NO_x, and volatile organic compounds (VOC) were found to exhibit a significant negative relationship with household and employment density when controlling for household size, income, and vehicle ownership. While limited in number, these studies provide support for the hypothesis that lower density patterns of development are associated with a greater magnitude of vehicle emissions, with potential implications for regional air quality.

2.2. Urban form and regional climate

In addition to vehicle travel and emissions, the spatial structure of metropolitan regions has been associated with meteorological phenomena that are important to regional air quality. The most widely recognized meteorological

[1] It should be noted that the Newman and Kenworthy study has been challenged on methodological grounds pertaining to the authors' failure to control for demographic influences and the use of inherently related compound variables. For a more thorough discussion of these issues, see Brindle (1994) and Gordon and Richardson (1989).

effects of urbanization result from the urban ''heat island effect'' (Oke, 1987). Defined as a differential in the air temperatures of urban centers relative to adjacent rural areas, the urban heat island effect is driven by the displacement of natural vegetation by the impervious surfaces of roads and buildings, as well as by the emission of vast quantities of waste heat from buildings, industry, and automobiles. In combination, these properties of urbanization can serve to raise by several degrees the average air temperature of large cities. Because regionalized air pollutants such as ozone and fine particulate matter are sensitive to temperature, the resulting urban heat island holds important implications for both climate and air quality.

Numerous authors have illustrated a relationship between the intensity of urban heat islands and weather events downwind of large cities. Diem and Mote (2005) found heavy rainfall events to increase by more than 40% in one location in suburban Atlanta over a 50-year period and associated this phenomenon with the region's rapid pace of development and growing heat island. Likewise, Shepherd et al. (2002) found an approximate 20% increase in rainfall events downwind of the metropolitan Atlanta region relative to an upwind control region during the period of 1998–2000. Other studies have shown similar urban rainfall anomalies in New York, New York (Bornstein and LeRoy, 1990) and St. Louis, Missouri (Rozoff et al., 2003).

Of perhaps greater significance to public health in cities is the potential influence of the urban heat island effect on ground-level ozone formation. Ozone is a colorless gas that is formed in the presence of sunlight through the chemical interaction of NO_x and VOC, two classes of pollutants produced from the combustion of fossil fuels. Ambient heat influences ground-level ozone formation through its effects on the rate of emission of ozone precursors from both human and natural sources. Urban heat islands can intensify ozone formation through at least two mechanisms. First, enhanced temperatures during the warm season elevate the need for air conditioning, increasing the emission of ozone precursors from regional power plants (Rosenfeld et al., 1998). Second, the rate of evaporative VOC emissions from vehicle engines, as well as natural forms of VOCs emitted by some species of trees, increase in response to rising ambient temperatures (Cardelino and Chameides, 1990). Thus, heat island formation can exacerbate regional air quality problems by increasing the rate at which ozone precursors are emitted from both human and natural sources.

The influence of urban temperatures on regional ozone formation is well documented (Rao et al., 1995, 1992; Kelly et al., 1986). In a study of temperature trends and ozone formation in large US cities, Stone (2005) found a strong positive correlation beween mean temperature and the average number of high ozone days per year ($r = 0.86$; $p < 0.000$). More directly focused on the role of land use in ozone formation, Rosenfeld et al. (1998) developed a model to assess the impact of various heat island management strategies on ozone formation in the Los Angeles, California metropolitan region. The cooling benefits of a region-wide program designed to increase the surface reflectivity of development and the extent of tree canopy cover were found to reduce the number of annual ozone exceedances by about 12% (Rosenfeld et al., 1998).

In light of the established potential for urban spatial structure to influence ozone formation through two distinct mechanisms—the quantity of precursor emissions from vehicle travel and the meteorological effects of urban heat island formation—land use planning strategies designed to reduce vehicle travel and mitigate heat island formation may prove successful in improving air quality. Little work, however, has sought to establish a relationship between urban form and air quality measured at the metropolitan scale, and land use is only rarely employed as a control measure in state air quality plans. To assess the potential significance of land use to metropolitan air quality, this paper presents a methodology to measure the influence of urban form on annual ozone exceedances, reports the results of my analysis, and concludes with a discussion of the elements of urban form found to be most closely associated with air quality.

3. Measuring urban sprawl

While sprawling, decentralized land use patterns have long been associated with a number of social and environmental problems, it is only in recent years that researchers have attempted to quantify sprawl in a meaningful way. Most of these efforts have focused only on gross measures of population density or the proportion of the urban population living a minimum radius from the central business district. For example, in seeking to gauge the influence of sprawl on affordable housing and the distribution of urban population by race, Kahn (2001) quantified sprawl through measuring the proportion of employment situated more than 10 miles from the downtown district of large US cities. In a study of sprawl, land use values, and metropolitan governance, Pendall (1999) operationalized sprawl as the change in a city's population density over time. As argued by Ewing et al. (2003), however, sprawl is a complex phenomenon that can only be effectively measured through quantifying several dimensions of urban form. In light of this observation, Ewing et al. developed a composite index of sprawl based on four measures of urban form: centeredness, connectivity, density, and land use mix. As this index has been found to be a useful metric for measuring sprawl and a strong predictor of travel behavior, this present study employs the Ewing et al. data for 45 major US cities to assess the influence of sprawl on annual ozone exceedances.

The literature on sprawl has identified numerous spatial symptoms of the phenomenon. Four spatial dimensions commonly associated with sprawl include low density development, segregation of distinct land use types, growth in the absence of definable centers, and a lack of physical connectivity between new areas of growth (Burchell et al., 2005). Unable to capture each of these spatial dimensions within a single indicator of urban form, Ewing et al. (2003) employed data from the US Census Bureau, the American Housing Survey, and US Department of Agriculture, among other sources, to develop an integrated measure of urban sprawl through principal components analysis. Each of the four dimensions measured and the methods employed to do so are briefly outlined in Table 1.

Through the methods outlined in Table 1, a composite sprawl score was derived by Ewing et al. (2003) for 83 major US metropolitan regions and was found to exhibit statistically significant relationship with four measures of vehicle travel behavior. These measures included person hours of travel, person miles of travel, hours of delay, and number of annual vehicle fatalities. In addition, it should be noted that the sprawl index was also found to exhibit a significant positive relationship with a measure of metropolitan air quality, the fourth highest maximum 8-h ozone level measured in 2000. While supportive of the hypothesis explored herein—that decentralized development is conducive to ozone formation—the Ewing et al. analysis of urban form and air quality is deficient on a number of grounds. A brief discussion of these limitations follows to clearly differentiate this present study from previous work.

As discussed above, due to the fact that ozone formation is highly sensitive to meteorological variables, there is a critical need to control for regional climate when comparing ozone levels recorded in different regions of the country. Because a disproportionate number of cities ranking highly in terms of the Ewing et al. (2003) index are situated in southern latitudes of the country, the association found between the sprawl rankings and ozone levels may be a product of local meteorology, which was not incorporated into the analysis. On a similar note, the sensitivity of ozone to annual fluctuations in meteorology requires that any analysis of air quality trends focus on more than a single year of observations to avoid analysis of an anomalous year in the meteorological record. That is, ozone must be measured as a trend rather than as an occurrence. And, finally, the fourth highest 8-h ozone level does not capture the frequency of high ozone days during the course of a year, which is of more relevance to overall air quality than the magnitude of a single event.

In light of these observations, there remains a need to investigate further the relationship between urban land use patterns and regional air quality in large US cities. To do so, this study integrates data on annual ozone exceedances, precursor emissions, regional climate, and regional population size with the urban form measures developed by Ewing et al. (2003) for 45 of the 50 most populous metropolitan regions in the US. What follows is a discussion of a methodology to isolate the influence of urban sprawl on ozone formation while controlling for theoretically important meteorological and population factors and the presentation of study results and conclusions.

4. Research approach

To investigate the hypothesized influence of regional development patterns on annual ozone formation, data were obtained from several sources. The sprawl index and constituent land use data published by Ewing et al. (2002,

Table 1
Development of a sprawl index (Ewing et al., 2003)

Variable[a]	Derivation
Centeredness	The centeredness variable is a measure of the degree of mono or polycentrism within a metropolitan region and is based on three indicators: a density gradient, the percentage of the metropolitan population within a fixed radius of the central business district, and the number of population centers as defined by proximity of census tracts to regional density maxima. The composite measure is derived through principal components analysis with data obtained from the 2000 Census and the Claritas Corporation
Connectivity	The connectivity variable is a measure of the density of the street network and was based on the average block size and the percentage of blocks less than approximately 500 ft on a side (consistent with the dimension of a traditional urban block). As block size increases, the number of street intersections per unit of area decreases, which serves as an indicator of street network density. This measure was computed through principal components analysis with data obtained from US Census TIGER files
Density	A composite measure of population density was computed from four data sources, including the 2000 Census, the USDA Natural Resource Inventory, the American Housing Survey, and the Claritas Corporation. A single density factor was derived through principal components analysis incorporating measures of gross population density, the proportion of metropolitan populations living at very low or very high densities, and the proximity of census tracts to urban centers
Land use mix	Three elements of land use mix were integrated into a single, composite measure through principal components analysis. These elements include the ratio of jobs to population, the diversity of land uses, and the accessibility of residential uses to non-residential uses at the level of the transportation analysis zone and within a one mile radius. The data used to develop the mix factor were obtained from the American Household Survey and the Census Transportation Planning Package
Sprawl index	A composite measure of urban compactness or sprawl was developed through an integration of these four urban form factors through principal components analysis

[a]Each urban form attribute is reported on a scale with a mean value of 100 and a standard deviation of 25 (across the 83 regions included in the Ewing et al. study (2003)). Higher values of the scores for centeredness, connectivity, density, and land use mix reflect higher intensities of these attributes. Note that the Ewing et al. sprawl index scales in a negative direction (i.e., higher scores denote lower levels of sprawl) and has been modified in this study to scale in a positive direction (i.e., higher scores denote higher levels of sprawl) for ease of interpretation.

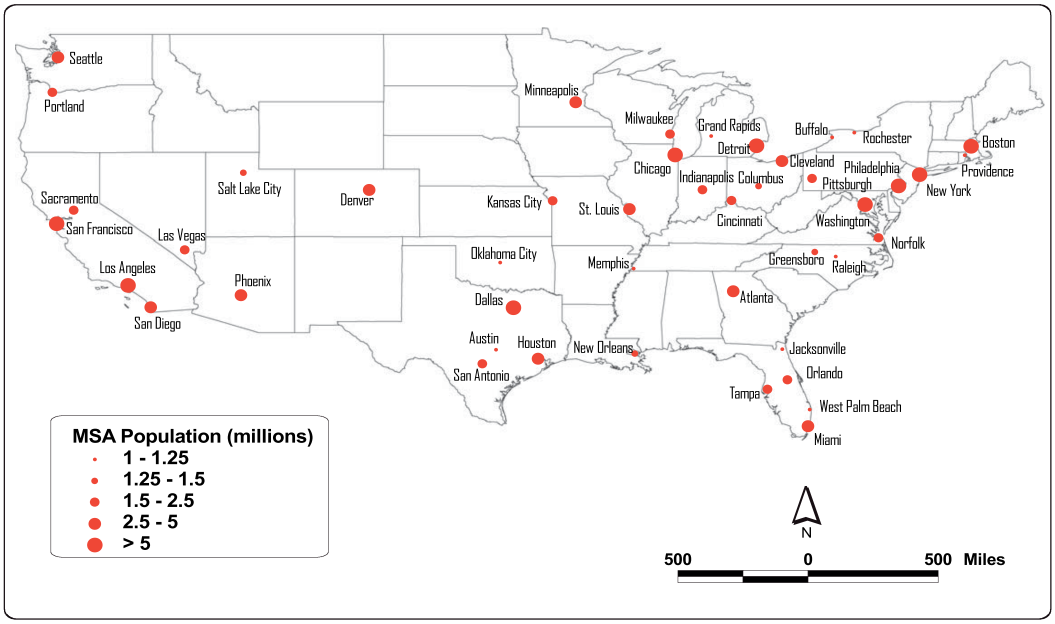

Fig. 1. Metropolitan statistical areas (only primary cities are listed).

2003) were used as the basis for quantifying urban spatial structure within major US metropolitan areas. As the published data includes statistics for 45 of the largest 50 metropolitan statistical areas (MSAs) by population, these regions, presented in Fig. 1, serve as the study areas for this analysis.

In addition to measures of urban spatial structure, data are needed on regional ozone precursor emissions and meteorological conditions for each year of the study. Through the National Emissions Inventory (NEI), the US Environmental Protection Agency (EPA) compiles data on aggregate annual emissions of all nationally regulated air pollutants at the county level. For this study, data on annual emissions of NO_x and VOC were obtained for all counties comprising each of the 45 MSAs included in the study and averaged between 1990 and 2002, which is the most recent year for which complete emissions data were available from the NEI.[2] The total average annual tonnage of NO_x and VOC emissions at the MSA level were summed to create a single measure of regional ozone precursor emissions.

As noted above, of most relevance to urban public health is the number of exceedances of the national standard for ozone rather than the maximum ambient concentration experienced during the course of a year. In its annual *Air Trends* report on national air quality, the EPA reports the number of days per year for which the national ambient air quality standard (NAAQS) for ozone was exceeded (referred to as an ozone ''exceedance'') for the 100 largest metropolitan regions in the country.[3] For this study, the number of annual ozone exceedances per region was compiled and averaged over the 13-year period between 1990 and 2002.

Because ozone formation is highly sensitive to regional meteorology, metropolitan data on annual temperature trends was obtained from the National Oceanic and Aeronautical Administration's National Climatic Data Center for each year of the study.[4] Used as a control variable, the average ozone season temperature for each city between 1990 and 2002 was included in the analysis to account for the effects of temperature on ozone formation rates in different climatic regions of the country. For the purposes of this analysis, the ozone season was defined as the months of May through September.

In addition to climatic variations, differences in population size among the sampled regions can be expected to influence ozone formation through its effects on precursor emissions. Naturally, as the number of vehicles and housing units increases, emissions of ozone precursors from tailpipes and regional powerplants are also expected to increase, potentially enhancing ozone formation. As a result, population size must be controlled in the analysis to effectively isolate the influence of urban form on air quality, independent of population. To account for differences in urban populations, data on MSA populations was obtained

[2] 1990 was selected as the initial year in this study due to its concurrence with passage of the most recent amendments to the Clean Air Act.

[3] This study makes use of the most commonly cited standard for ozone, the 8-h NAAQS.

[4] Mean temperature data for the months of May through September were obtained from airport weather stations in each of the 45 MSAs and averaged over the period of 1990–2002.

Table 2
Descriptive statistics

Variable	Minimum	Maximum	Mean	Standard deviation
Centeredness	52	145	98.0	21.1
Connectivity	37	155	102.8	25.2
Density	74	243	103.7	27.4
Land use mix	40	141	96.9	22.2
Sprawl index	22	153	98.2	24.7
MSA population in 2000 (millions)	1.0	21.2	3.3	3.8
Mean ozone season temperature (°C)	16.6	32	22.6	3.7
Mean annual emissions of NO_x and VOC (tons)	110,662	1,733,117	392,823	331,971
Mean annual ozone exceedances (days per year)	0.5	67.1	15.1	15.6

from the 2000 US Census and incorporated into the analysis as a control variable.

Table 2 presents descriptive statistics on each of the variables incorporated into the analysis.[5]

Once constructed, the resulting database was analyzed to test the following hypotheses:

(1) Urbanized regions characterized by high levels of sprawl are associated with a greater quantity of annual ozone precursor emissions than urbanized regions characterized by low levels of sprawl when controlling for average ozone season temperature and population size.
(2) Urbanized regions characterized by high levels of sprawl are associated with a higher number of average annual ozone exceedances than urbanized regions characterized by low levels of sprawl when controlling for average ozone season temperature and population size.
(3) Urbanized regions characterized by high levels of sprawl are associated with a higher number of average annual ozone exceedances than urbanized regions characterized by low levels of sprawl when controlling for average ozone season temperature and average annual emissions of NO_x and VOC.

In testing the first hypothesis, my goal is to confirm the existence of a statistical association between urban form and ozone precursor emissions. While a handful of studies has documented an association between land use and precursor emissions within individual cities, this analysis is the first to consider a link between land use and ozone precursor emissions across multiple MSAs and over a multiyear period. Because the emission of these pollutants is expected by vary by the size and climate of metropolitan regions—variables that are assumed to be unrelated to urban form—population size and average annual temperatures will be included in each model as control variables. Separate models testing the influence of the sprawl index and each of the four constituent urban form measures—centeredness, connectivity, density, and land use mix—on emissions are specified to test the combined and independent effects of specific urban form attributes on regional air quality.

The second hypothesis addresses the direct association between urban form and ozone exceedances. Because ozone formation is sensitive to both precursor emissions and regional meteorology, a finding of a significant association between urban form and precursor emissions is not sufficient to conclude that land use has a significant influence on ozone exceedances. Population size and mean temperatures are controlled in these models to account for regional variations in travel and energy demand and in climate. In the interest of testing the hypothesis that urban form influences ozone exceedances through both emissions and non-emissions-related phenomena, mean annual emissions of NO_x and VOC are not controlled in this set of models.

A final set of models is specified to test the hypothesis that urban form influences ozone exceedances through a mechanism that is independent of its effects on ozone precursor emissions.

To do so, mean annual precursor emissions will be incorporated into these models, along with mean ozone season temperature, as a control variable.[6] When controlling for precursor emissions, the finding of a significant coefficient on one or more of the urban form attributes will support the hypothesis that the spatial structure of cities influences ozone exceedances through a non-emissions-related mechanism, such as urban heat island formation.

5. Results

To investigate the hypothesized relationship between urban form and ozone precursor emissions, ordinary least squares was employed to derive model coefficients and measures of goodness of fit. In each of five models, a

[5]Statistics are reported for all regions included in Fig. 1, with the exception of San Antonio, Texas, which was found to be an influential outlier with respect to the number of annual ozone exceedances during the study period, and thus was not included in the analysis.

[6]Because population size and ozone precursor emissions are highly correlated at the MSA level, population will not be included in these models to avoid multicollinearity.

composite (sprawl index) or individual measure of urban form is combined with population size and mean temperatures and regressed against average regional precursor emissions. The results of this modeling process are presented in Table 3.

The model results show only one of the five urban form measures to be significantly related to regional emissions of NO_x and VOC. As indicated by the standardized coefficient on the density variable, for every one standard deviation increase in density, the mean annual tonnage of ozone precursors is reduced by approximately 74,700 tons, or by about 19% of the mean level of emissions. Overall, each of the models exhibited a high level of predictive power, with R^2 values exceeding 0.90. However, much of the predictive power is a product of the population size variable, which was found to have a standardized regression coefficient five times larger than that for the density measure. The composite sprawl index was not found to have a significant association with metropolitan precursor emissions over the 13-year study period.

In sum, these findings suggest a significant and moderately strong association between one urban form attribute—population density—and ozone precursor emissions in large US metros, providing support for the study's first hypothesis. However, due to the fact that ozone is sensitive to both precursor emissions and regional meteorology, any association found between urban form and emissions may not be found to exist between urban form and ozone exceedances. As a result, a second set of models was specified to assess the relationship between the spatial structure of large metros and ozone exceedances directly. The results of this modeling process are reported in Table 4.

As indicated by the model results, several attributes of urban form, including the composite sprawl index, were found to have a statistically significant association with mean annual ozone exceedances when controlling for MSA population size and mean ozone season temperature. With a standardized regression coefficient of −1.04, density was again found to be the most powerful urban form predictor, indicating that each standard deviation increase in density is associated with a reduction of approximately 16 high ozone days per year, on average, in large US metros. Also found to be a significant and strong predictor of ozone exceedances was the connectivity measure. With a standardized regression coefficient of −0.35, each standard deviation increase in connectivity is associated with a reduction of approximately 5.5 high ozone days per year.

In combination, the four urban form attributes were found to influence ozone exceedances in the form of the composite sprawl index. With a significant standardized coefficient of 0.42, each standard deviation increase in the sprawl index is associated with an increase of approximately 6.6 high ozone days in large US metros. Overall, the predictive power of the models for density, connectivity, and the sprawl index were found to be moderate to strong, with adjusted R^2 ranging from 0.47 to 0.63.

These results suggest that the spatial structure of large US metros has a strong association with the average number of annual ozone exceedances, one that appears to

Table 3
Regression results for urban form and mean annual emissions of NO_x and VOC (tons)[a]

Variable	*B*-coefficient	Standardized coefficient	Significance	Model adj. R^2
Centeredness	−708.0	−0.045	0.370	0.91
Connectivity	−463.1	−0.035	0.508	0.91
Density	−2,732.3	−0.225	0.020**	0.92
Land use mix	222.4	0.015	0.778	0.91
Sprawl index	735.1	0.055	0.300	0.91

[a]MSA population size and mean ozone season temperatures are incorporated into each model as control variables. Mean annual precursor emissions are computed by summing the average emissions of NO_x and VOC at the MSA level between 1990 and 2002.
**Significant at the $p<0.05$ level.

Table 4
Regression results for urban form and mean annual ozone exceedances[a]

Variable	*B*-coefficient	Standardized coefficient	Significance	Model adj. R^2
Centeredness	−0.166	−0.225	0.080*	0.41
Connectivity	−0.216	−0.350	0.008**	0.47
Density	−0.592	−1.04	0.000**	0.63
Land use mix	−0.109	−0.156	0.249	0.39
Sprawl index	0.266	0.422	0.001**	0.52

[a]MSA population size and mean ozone season temperature are incorporated into each model as control variables.
*Significant at the $p<0.10$ level.
**Significant at the $p<0.05$ level.

Table 5
Regression results for urban form and mean annual ozone exceedances (emissions controlled)[a]

Variable	*B*-coefficient	Standardized coefficient	Significance	Model adj. R^2
Centeredness	−0.144	−0.195	0.123	0.42
Connectivity	−0.187	−0.302	0.017**	0.47
Density	−0.286	−0.504	0.007**	0.49
Land use mix	−0.112	−0.160	0.227	0.41
Sprawl index	0.226	0.359	0.004**	0.50

[a]Mean annual emissions of NO_x and VOC and mean ozone season temperatures are included in each model as control variables.
**Significant at the $p<0.05$ level.

be stronger than the association between urban form and precursor emissions. Taken together, these first two sets of models support the hypothesis that urban form drives ozone formation through both an ''emissions-based'' and a ''non-emissions-based'' mechanism, and further raises the possibility that the non-emissions-based mechanism or set of mechanisms is the more powerful influence on ozone formation. To confirm the existence of a non-emissions-based effect of urban form on ozone formation, a final set of models was specified to regress the urban form attributes against mean annual ozone exceedances while controlling for mean regional temperature and precursor emissions. The results of these models are presented in Table 5.

The significant model coefficients reported in Table 5 for several of the urban form attributes confirms the existence of an association between land use and regional air quality that is independent of the influence of land use on precursor emissions. Having controlled for mean annual emissions of NO_x and VOC and mean ozone season temperatures, the density, connectivity, and sprawl index measures were each found to be statistically significant at the $p<0.05$ level, supporting the hypothesis of a non-emissions-based effect of urban form on ozone formation. As indicated by the standardized coefficient of 0.36, each standard deviation increase in the sprawl index is associated with an average increase of 5.6 high ozone days per year. A one standard deviation increase in density is associated with a reduction of about 8 high ozone days, and a one standard deviation increase in connectivity is associated with a reduction of 4.7 high ozone days per year. While the density measure was found to have the greatest magnitude of effect on ozone exceedances, the sprawl index model exhibited the most predictive power, with an adjusted R^2 of 0.50.

6. Discussion and conclusions

The results of this analysis demonstrate a significant association between regional land use patterns and air quality in the country's largest metropolitan areas. While urban form was found to have only moderate effects on precursor emissions measured at the MSA level, the spatial attributes of density and connectivity were found to have a statistically significant ($p<0.05$) and reasonably strong association with ozone exceedances when controlling for mean ozone season temperature, population size, and precursor emissions. The composite measure of sprawl also was found to have a significant and strong association with mean annual ozone exceedances when controlling for mean ozone season temperature, population size, and precursor emissions.

The potential for land use strategies to reduce ozone exceedances is most clearly illustrated through a comparison of the most sprawling and most compact cities included in the study. Fig. 2 presents the average urban form attributes and expected mean ozone exceedances between 1990 and 2002 for the metropolitan regions ranking in the 75th percentile and greater (sprawling) of the sprawl index to those ranking in the 25th percentile and lower (compact). The expected ozone exceedances are reflective of the modeled number of annual exceedances for each set of regions, controlling for population size and average ozone season temperature. For sprawling cities, levels of centeredness, connectivity, density, and land use mix are, on average, about one-third lower than in compact cities, and the average number of high ozone days per year is about 62% higher.

The results of this study support the hypothesis that urban form influences regional ozone formation through both an emissions-based and non-emissions-based mechanism. The finding of a significant association between population density and emissions of NO_x and VOC suggests that urban spatial structure plays a role in ozone formation through its effects on ozone precursor emissions. However, the influence of urban form on precursor emissions may account for only one of several mechanisms through which land use impacts regional air quality. While insufficient data are available through this study to identify the precise non-emissions-related mechanisms through which urban form influences ozone formation, at least two additional phenomena could explain the results presented herein. These include enhancement of the urban heat island effect and the geographic distribution of ozone monitors in highly decentralized cities.

As discussed in the preceding review of the literature on urban form and regional climate, urban heat island formation can significantly elevate surface and air

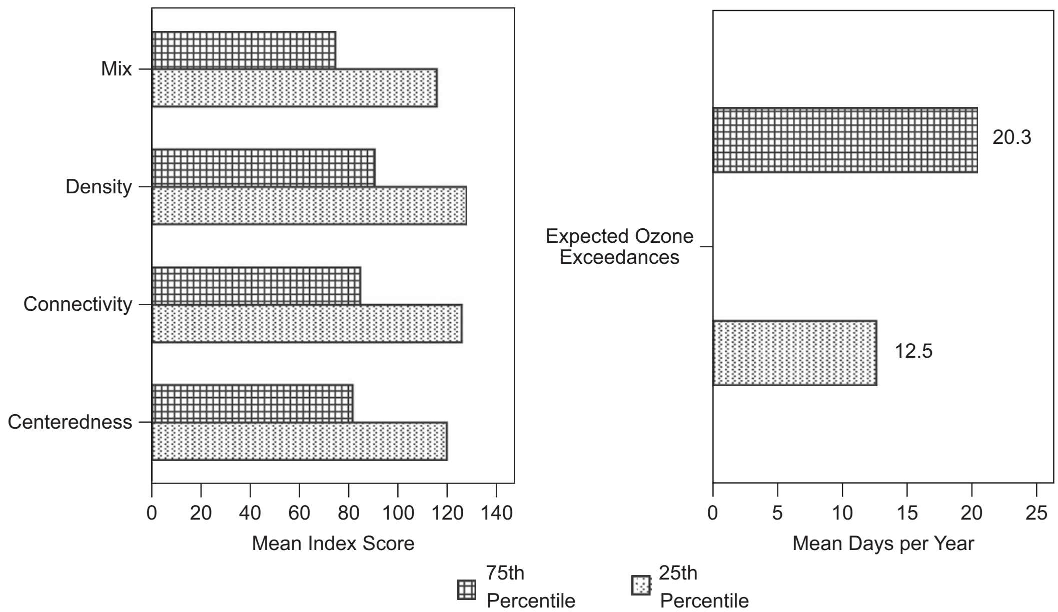

Fig. 2. Expected ozone exceedances for metropolitan regions ranking in the highest and lowest quartiles of sprawl index. *Note*: Expected ozone exceedances are based on model results reported in Table 4.

temperatures in large cities, with direct implications for air quality. Previous work on ozone formation in large US cities has found mean regional temperatures to exhibit a stronger association with ozone exceedances than the emission of ozone precursors (Stone, 2005). In addition, analyses of the effects of city size and neighborhood scale design on heat island formation have supported the hypothesis that lower density, decentralized patterns of urbanization generate more surface heat than higher density forms (Stone and Rodgers, 2001; Price, 1979). If true within the regions included in this analysis, cities characterized by a high degree of sprawl may experience a greater number of ozone exceedances than more compact cities due to enhanced heat island formation. Future work will investigate this hypothesis further through the measurement of heat island formation within the metropolitan regions included in this study.

The finding of a positive association between sprawl and ozone exceedances may also be an artifact of the geographic distribution of air quality monitors in large, decentralized cities. For cities characterized by a large geographic extent, the average distance between an ozone monitor and the region's central business district may be greater than that within the most compact cities. If true, advecting plumes of ozone precursor emissions may travel farther before reaching the most remote regional air quality monitors, potentially enabling higher ozone concentrations to form and be detected than within more spatially compact monitoring networks. While a potential artifact of the monitoring network, such a phenomenon would also be reflective of the fact that a greater proportion of the metro population in decentralized regions lives in these downwind locales and is thus subject to higher ozone exposures.

While the precise linkages between urban form and enhanced ozone formation will require further study, the finding of a strong association between the spatial structure of cities and regional air quality raises the question of whether environmental managers should give more serious consideration to land use strategies in developing air quality control plans. Two elements of urban form in particular—the density and connectivity of development—were found to be significantly related to precursor emissions and ozone formation and are directly responsive to land development policies instituted at the local or regional levels of government. In particular, "urban growth boundaries" and "form-based codes" are two planning strategies increasingly adopted in US cities that are worthy of consideration as long-term, regional scale approaches to reducing total emissions and ozone formation through urban form.

While long used outside of the United States as a means of protecting natural areas and limiting the peripheral spread of urban zones, urban growth boundaries have only in recent decades been instituted by a handful of state and municipal governments as a means to control growth. Growth boundaries establish circumferential zones beyond which urban population and employment densities are not permitted. Two sets of planning policies are typically employed to establish such zones. First, large minimum lot sizes (e.g., 40 acres) and use restrictions are established through zoning ordinances beyond the zone in which urban development densities are to be allowed. Second, limitations on the extension of public infrastructure and services, such as sewer lines and fire protection, are often coterminous with urban growth boundaries, serving to further discourage urban development beyond the designated zone. Today, Oregon, Washington, and Tennessee require cities to establish growth boundaries, and much of the limited evidence available suggests that such boundaries are effective in limiting peripheral growth and promoting density (Song and Knaap, 2004; Nelson, 1994), with potential benefits for reduced vehicle travel, greenspace preservation, and air quality.

A second land use planning strategy that may prove effective over the long term in improving air quality is the replacement of traditional zoning ordinances with ''form-based'' codes. Form-based codes are designed to place an emphasis on the physical dimensions of development, such as the size, placement, and integration of buildings and streets, rather than on the specific uses and densities permitted in a particular zone. The rationale for form-based codes is rooted in the observation that, while the use of buildings and parcels tends to change over time, the form of the built environment changes only very slowly, and it is the physical form of development that is of most significance to community interests, including environmental quality. One advantage of form-based codes related to this present analysis is the ability for municipalities to improve vehicle and pedestrian connectivity within and between development zones. While traditional zoning often permits developers to design and organize streets within defined block sizes, form-based codes more strictly control street, sidewalk, and pedestrian network designs, while permitting builders more flexibility in the uses and densities of the buildings that are constructed within the network. As higher levels of street connectivity have been associated with lower levels of vehicle travel and emissions, form-based codes designed to emphasize network connectivity could yield benefits to regional air quality.

In closing, it is important to note that more compact development patterns alone will not be sufficient to fully address our urban air quality problems. Technological advances in emissions controls have proven highly effective in reducing tailpipe emissions over the last several decades, and emerging technologies, such as hybrid vehicles and alternative fuels, are expected to continue these reductions. The significance of land use-oriented approaches to air quality management lies in the potential for these strategies to limit the dramatic annual growth in national vehicle miles of travel, which has greatly undermined the benefits of per mile tailpipe reductions since the 1960s, as well as in addressing the local-scale meteorological drivers of air pollution. Undoubtedly, the most effective approach to air quality management would seek to achieve a balance between stack and tailpipe emissions reductions with reductions in emissions-producing activities. To this end, land use strategies designed to promote more compact urban forms are needed to complement technological emissions controls as a means of addressing the root bases of urban air quality problems.

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