Air Pollution and Urban Form: Evidence from Satellite Data

JULIAN D. MARSHALL[1], HEATHER SANDER[2], STEVEN M. MANSON[3]
[1]Department of Civil Engineering, [2]Department of Conservation Biology, [3]Department of Geography
University of Minnesota
Minneapolis, MN 55455
USA
Website: http://www.ce.umn.edu/people/faculty/marshall/

Abstract: - We consider here the extent to which urban form (the physical layout of a city, e.g., sprawl versus density) can impact urban air pollution. Using available satellite-based measurements for 89 urban areas throughout the globe, we compare air pollution (nitrogen dioxide) and spatial patterns of built-up areas (urban contiguity and compactness). Linear regression modeling reveals that, as expected, air pollution is proportional to city size (urban population and land area), with larger cities having worse pollution. Consistent with Environmental Kuznets Curve (EKC) theory, the relationship between air pollution and per capita GDP is an inverse "U" shape. Rising income increases pollution levels for per capita GDP less than US$23,000 but decreases pollution for per capita GDP greater than US$23,000. Urban form – specifically, a combined measure of urban contiguity and compactness – has a modest but statistically significant impact on air pollution levels: at mean values for independent variables, 1-standard-deviation increase in contiguity/compactness yields a 14% reduction in air pollution concentrations. This finding indicates that striving to increase the contiguity/compactness of a city may reduce air pollution, an encouraging result. Additional work is necessary to confirm these initial findings.

Key-Words: urban air pollution; urban development; satellite data; Kuznets; smart growth

1 Introduction

Air pollution is a problem facing cities throughout the world. The World Health Organization's Global Burden of Disease project estimated that urban air pollution causes 800,000 deaths annually, making it one of the top 15 causes of death, and a major contributor to environmental health impacts [1]. A challenge in many cities, especially in developing countries, is how to accommodate growth in population, vehicle emissions, and land area, while reducing air pollution.

Motor vehicles are an important and growing contributor to air pollution in many cities. Three general approaches for reducing transportation emissions are (1) changes to vehicles (e.g., reducing emission per mile), (2) changes to fuels (e.g., reducing emissions per gallon), and (3) shifts in people's use of the transportation system (e.g., reducing vehicle-miles or fuel-gallons). Examples of the third approach include increased substitution of mass-transit for private vehicle use; "smart growth" approaches that reduce transportation demand; and, various economic policies (e.g., incorporating externalities into prices).

From an engineering perspective, changes in technologies (vehicles, fuels) are often considered to be more a robust approach than aiming to change people's actions. For example, reliably quantifying emission impacts is often easier for a technology such as a catalytic converter than for policies to reduce urban sprawl. However, improving air quality might be cheaper and easier using the latter type of approaches than using technology mandates.

The aim of this study is to explore whether and how urban form impacts air pollution concentrations. We employ satellite data and other empirical evidence to understand whether modifications in urban form yield air-pollution benefits.

2 Problem Formulation

Our research considers the following questions: (1) How much do air pollution concentrations vary among urban areas; (2) how much of this variability is explained by attributes such as city size and average income, versus attributes of urban form; and (3) what are the policy implications of these results.

We employ a top-down approach, comparing trends among urban areas (as opposed to a bottom-up approach, evaluating behavior by individuals or in specific neighborhoods). An important feature of this type of analysis is that data and methods are consistent among the cities we compare. If the dataset included values for which definitions varied among cities, then it would be unclear whether data variability were attributable to true differences among cities, versus differences in definitions only. Satellite and other remote sensing data offer a unique approach that can be applied consistently to dozens of urban areas.

As described next, the three main inputs to our analysis are air pollution concentrations; per capita income; and, city attributes such as population, area, and urban contiguity/compactness. Step-wise linear regression modeling (SAS v9.1, PROC REG), using air pollution as the independent variable and other attributes of each city (income, population, etc.) as independent variables, was employed to determine whether urban form is a statistically significant causal variable for air pollution.

2.1 Input data

Air pollution concentrations are obtained from global daily satellite measurement. The Ozone Monitoring Instrument (OMI), on the Earth Observing System Aura satellite (EOS-Aura) continuously records nitrogen dioxide (NO_2) troposphere column density [2]. Data are available on a 0.25 degree latitude x 0.25 degree longitude grid, with NO_2 column-density values in units of molecules per cm^2 (typical urban value: 5×10^{15} molecules per cm^2, roughly equivalent to a troposphere-average dilution volume of 0.2 ppb).

The following data were obtained from a World Bank database of 89 cities globally [3]: population, land area, per capita gross domestic product, contiguity index, and compactness index (one value per city). We used the latitude/longitude location for each urban area, as given in the World Bank database, to look-up OMI-NO_2 pollution levels. The compactness/contiguity values, which are provided in the World Bank report, were derived from *Landsat* satellite imagery of built-up areas in each city.

3 Problem Solution

Air pollution measurements (units: 10^{15} molecules per cm^2) are log-normally distributed, with mean = 5.6, geometric mean = 3.8, and geometric standard deviation (unitless) = 2.5. The correlations of air pollution with compactness and with contiguity is -0.14 and -0.03, respectively. Thus, air pollution levels are cleaner in more compact and contiguous cities, but the correlation is modest.

The linear regression model employs as the independent variable the base-10 logarithm of air pollution. Model results are presented in Table 1. Model adjusted-R^2 is 0.56.

TABLE 1: Linear Regression Model Results

Variable	Coefficient	Std. error	|P| > t
Income (US$)	4.8e-5	1.2e-5	<0.001
Population	3.3e-8	9.2e-9	0.001
$(\text{Income})^2$	-1.1e-9	3.7e-10	0.005
Urban form	-0.55	0.24	0.024
Area (km^2)	1.9e-4	8.9e-5	0.039
constant	0.22	0.088	0.012

Given the small number of variables in the model, and the significant variability in air pollution levels, we feel the model to offer a useful description of underlying trends in the data. A discussion of the regression model is presented next.

As expected, large urban areas experience worse air pollution. Based on coefficients above, at mean values for independent variables, a 1-standard deviation increase in population or in land area would yield a 21% or a 33% increase in air pollution concentrations, respectively. Environmental Kuznets Curve (EKC) theory suggests that the relationship between air pollution and per capita GDP would be an inverse “U” shape, with rising income first increasing pollution levels for low per capita GDP, then decreasing pollution for higher per capita GDP. Our results are consistent with this expectation, with an approximate peak in the curve around US$23,000 per capita GDP. Starting at this peak (US$23,000) and again employing mean values for independent variables, a 1-standard-deviation increase/decrease in per capita GDP yields an 11% reduction in air pollution levels.

The variable “urban form” in the regression model is the estimate of compactness/contiguity. Specifically, the World Bank report offers one compactness measure and one contiguity measure per city. We hypothesized that both attributes would be important for smart growth, and that having one attribute without the other would not necessarily offer air pollution benefits. The results support that hypothesis: when considering the two attributes separately in a linear regression, neither was statistically significant. However, a combined variable ([compactness]x[contiguity]), as employed in Table 1, is statistically significant. At mean values for independent variables, a 1-standard-deviation increase in compactness/contiguity yields a 14% reduction in air pollution. Including compactness/contiguity as an independent variable in the regression model yields only a minor increase (from 0.54 to 0.56) in the model’s adjusted-R^2 value: Urban form does impact air pollution, but it is not sufficiently important as to be a major factor statistically for predicting air pollution levels.

The compactness/contiguity coefficient in the linear regression is negative (i.e., increasing compactness/contiguity reduces air pollution levels) and statistically significant. The magnitude of the regression coefficient suggests that the impact of urban form is of magnitude 14%, which is in the same range as other factors known to be important (income, population, land area; impact: 11% – 33%). Thus, our empirical analysis suggests that shifts in urban form, especially "smart growth" approaches that improve both compactness and contiguity, can potentially benefit urban air pollution. This finding is important both for urban sustainability theory and for urban planners striving to improve air pollution in their cities.

To our knowledge, ours is the first study to employ cross-sectional satellite data to empirically test impacts of urban form on air pollution. We expect it would be difficult to conduct this type of analysis – using a database of dozens of urban areas, with data definitions consistent among cities – using other types of approaches.

4 Conclusion

We compared existing satellite-based estimates of air pollution levels (nitrogen dioxide) and of urban form (compactness/contiguity). Linear regression modeling suggests that, after accounting for income, population, and land area (see Table 1), urban form has a modest but statistically significant impact on air pollution. The empirical evidence we have considered suggests that improving contiguity and compactness of an urban area can improve air pollution. Analyses presented here are relative simple; the findings suggest that further and more robust investigation is warranted.

References:

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