Is Compact Growth Good for Air Quality?

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Problem: Explicitly prohibited from regulating the land use planning activities of municipal and county governments by the Clean Air Act (42 U.S.C. 131), the U.S. Environmental Protection Agency (EPA) has been forced to pursue an end-of-the-pipe approach to air quality management that has not proved successful in fully reducing ozone and fine particulate matter below health-based standards in many large U.S. cities. The persistence of these pollutants, in combination with a rapid rise in vehicle travel in recent decades, has raised concerns within the planning and public health communities about the long-term success of an air quality management program that is effectively divorced from the land use planning process.

Purpose: This work, which is part of an EPA-sponsored study titled *Projecting the Impact of Land Use and Transportation on Future Air Quality* (PLUTO), was intended to assess the effectiveness of compact growth in improving air quality at a geographic scale compatible with secondary pollution formation and transport and over a planning horizon sufficient to capture the longer-term benefits of regional land use change.

Methods: Future air quality is associated with alternative land development scenarios in this study through the integration of three separate and previously unrelated modeling components. These components consist of a set of standard population projection techniques, a household vehicle travel activity framework, and a mobile source emissions model (MOBILE 6) developed by the EPA.

Results and conclusions: The results of our analysis find the median elasticity of vehicle travel with respect to density change over time to be –0.35, suggesting metropolitan areas can expect a 10% increase in population density to be associated with a 3.5% reduction in household vehicle travel and emissions. In addition, vehicle elasticities derived for urban and suburban census tracts across the 11 metro regions suggest density increments within urban zones (–0.43) to be more than twice as effective in reducing vehicle travel and emissions as density increments within suburban zones (–0.19).

Takeaway for practice: We found compactness to be associated with greater reductions in vehicle travel than in previous studies, which suggests land use change can play a measurable role in improving regional air quality over time. Importantly, we found where compact growth occurs to be critically important to determining the extent to which higher density development reduces vehicle travel and emissions. We found the densification of urban zones to be more than twice as effective in reducing vehicle miles of travel and emissions as the densification of suburban zones, suggesting compact growth to be better for air quality than historical patterns of growth when densifying urban zones is given priority over non-urban zones.

Keywords: air pollution, climate change, compact growth, smart growth, growth management, travel behavior

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Land use planning has never played a significant role in the U.S. government's approach to air quality management. A longstanding policy of addressing air pollution through technological means at the point of production, as opposed to strategies oriented toward emissions-producing activities, is the legacy of a historical tension between the trans-boundary nature of air pollution, which requires regional coordination, and the limited jurisdiction of the federal government over land use. Explicitly prohibited from regulating the land use planning activities of municipal and county governments by the Clean Air Act (42 U.S.C. 131), the U.S. Environmental Protection Agency (EPA) has been forced to pursue an end-of-the-pipe approach to air quality management that has been unsuccessful at reducing ozone and fine particulate matter below thresholds designed to protect health in many large U.S. cities. The persistence of these pollutants and the rapid rise in vehicle travel in recent decades have raised concerns within the planning

and public health communities about the long-term success of an air quality management program that is effectively divorced from the land use planning process.

In response to this concern, the EPA has initiated a set of programs to promote aspects of smart growth planning based on the premise that policies designed to increase the density, mix, and pedestrian and transit orientation of urban development may yield, over the medium- to long-term, measurable benefits for regional air quality. To date, however, few studies have sought to assess what air quality benefits might be achievable through managing land use (e.g., 1000 Friends of Oregon, 1996; Frank, Stone, & Bachman, 2000), and no study has focused on the long-term environmental benefits of compact growth across a multi-state region.

This article presents the results of a study of alternative development futures and their effects on vehicle travel and pollutant emissions across 11 major metropolitan areas of the Midwestern United States over a 50-year planning horizon. A component of an EPA-sponsored study titled *Projecting the Impact of Land Use and Transportation on Future Air Quality* (PLUTO), this study assesses the effectiveness of compact growth in improving air quality at a geographic scale compatible with secondary pollution formation and transport, and over a planning horizon sufficient to capture the long-term benefits of regional land use change. Specifically, we integrate population and vehicle activity forecasting techniques with a mobile source emissions model to estimate the 2050 pollutant emissions associated with "business as usual" and "compact growth" development scenarios modeled for the upper Midwestern United States.

Land Use, Travel Behavior, and Vehicle Emissions

Many empirical studies have addressed the relationship between land use and travel behavior (for extensive reviews, see Crane, 2000; Ewing & Cervero, 2001; and Handy, 2005). The majority of these studies has focused on the relationship between local or neighborhood-scale urban form and individual or household behavior, including mode choice, trips, trip length, and total travel (e.g., Friedman, Gordon, & Peers, 1994; Handy, Cao, & Mokhtarian, 2005; Kitamura, Mokhtarian, & Laidet, 1997; Kockelman, 1997; Krizek, 2003), as well as vehicle ownership and type (Cao, Mokhtarian, & Handy, 2006; Hess & Ong, 2002; Holzclaw, Clear, Dittmar, Goldstein, & Haas, 2002). Fewer studies have looked at the effects of large-scale land use patterns on travel behavior (Bento, Cropper, Mobarak, &

Vinha, 2005; Geurs & van Wee, 2006), and fewer still have focused on the linkages between land use and vehicle emissions (Frank et al., 2000; Johnston & Ceerla, 1995).

Five dimensions of land use and urban form are widely believed to influence travel behavior and, by extension, vehicle emissions: density, land use mix, street-network design (Cervero & Kockelman, 1997), regional accessibility (Handy, 1993), and proximity to transit (Cervero & Gorham, 1995). The negative association between urban density and vehicle travel is well established (e.g., Newman & Kenworthy, 1989; Schimek, 1996). Analyzing a number of recent empirical studies, Ewing and Cervero (2001) reported "typical" elasticities of vehicle miles of travel (VMT) with respect to local density, land use mix, and street design, of −0.05, −0.05, and −0.03, respectively, and typical elasticities with respect to regional accessibility of −0.20.[1]

The influence of these variables on vehicle emissions has been addressed by a handful of empirical studies conducted at the metropolitan level. Frank, Stone, and Bachman (2000) used household travel survey data from the Puget Sound Region of Washington state, together with tract-level data on urban form and EPA's MOBILE5 model, to evaluate the relationship between urban form, household vehicle use, and emissions. They found a significant inverse relationship between vehicle emissions and household and employment densities, and between vehicle-emitted nitrogen oxides (NOx) and street connectivity.

Growing numbers of long-term simulation studies have used variants of the traditional four-stage travel demand forecasting model, coupled with mobile emissions models, to predict the emissions impacts of alternative land use scenarios for individual metropolitan areas (e.g., 1000 Friends of Oregon, 1996; Johnston & Ceerla, 1995; Liu, 2003). In a recent review of a number of such modeling studies, Bartholomew (2007) found a median reduction of 2.3% in VMT and 2.1% in emissions of NOx from the implementation of alternative planning strategies over a 20-year planning horizon. Our own work builds on these studies by expanding the geographic and temporal scales of analysis to better account for long-term land use change, and by using an empirical land use and vehicle travel forecasting framework.

Research Approach

We associate future air quality with alternative land development scenarios by integrating three distinct and previously unrelated modeling components: a set of standard population projection techniques, a household-vehicle-

trip framework, and a mobile source emissions model developed by the EPA. We describe the purpose and design of the study's principal modeling components in the following sections. Our purpose in modeling land development over time is not to accurately forecast future land use conditions in the upper Midwest, but rather to assess the sensitivity of air quality to two very different development scenarios, which may or may not come to pass. While we do not believe it is feasible to predict land use conditions 50 years into the future with any degree of confidence, we do believe it is possible to gauge the effects of alternative development futures on regional air quality in response to a specified set of modeling assumptions. A description of our two future development scenarios and the assumptions that govern our modeling framework follows.

Population and Land Use Change Modeling

We model population and land use change in response to future levels of six demographic variables over a 50-year planning horizon. We then use these census-tract-level variables, including population, population density, number of households, median household income, mean vehicles per household, and employment rate (ratio of employed residents over the age of 15 to total residents) as inputs to a vehicle travel activity modeling framework described in the next section of the article. In this section, we describe the projection of these variables to future years under business-as-usual and compact-growth development scenarios.

Business-as-Usual Scenario (BAU). The BAU scenario assumes that demographic trends throughout the upper Midwest study region will be consistent with historical rates of change. We extrapolated county populations to 2050 using a combination of decennial census counts and intercensal estimates for the years 1970 through 2000 (U.S. Census Bureau, 1982, 1992, 2002), postcensal estimates for the years 2001 through 2004 (U.S. Census Bureau, 2005), and cohort-component projections for the years 2005 through 2030 (Woods & Poole Economics, 2005). We first specified nine different time-series regression models (linear and nonlinear) for each county in the study region based on the historical data points alone, and then in each case selected from these the one which had the lowest mean absolute percent deviation (MAPD) from the combined historical and projected trend (1970 to 2030). We used this extrapolated trend from 2001 to 2050. We then allocated these extrapolated future county populations to tracts by assuming each tract retained throughout the modeling period the same share of county population it had in Census 2000. We used the same or similar approaches to project number of households, median income, and

employment rate. For median income, we used the same extrapolation techniques to project county-level mean income and then projected tract-level median income according to the ratio between the two statistics in the year 2000. For employment, we projected civilian employment and total population over the age of 15 separately, and then calculated the rate. We assumed that change in mean household vehicle ownership at the county level would continue at the annualized rate of change between 1990 and 2000 for the entire forecast period, since previous censuses used different measurement scales and we had no outside, county-level forecasts of this variable.

Compact-Growth Scenario (CG). We assume that the population for a metropolitan statistical area (MSA) is the same in any future year for both CG and BAU scenarios, but we shift population between urban, suburban, and rural census tract classifications (referred to here as "community types"[2]) over time to model how population growth would respond to widespread adoption of growth management policies like urban growth and service boundaries, policies promoting transit-oriented development, and an array of pedestrian-scale streetscape design regulations, among others.

Given that change in the share of new residents captured by urban census tracts was negative for most MSAs in the Midwest during the 1980s and 1990s, we decided to obtain the CG scenario by adjusting the proportion of expected BAU population growth in each community type based on historical development trends in Portland, Oregon, a region with a widely recognized growth management program. Portland is one of the only major metropolitan areas in the United States to have implemented all of the policies mentioned above. Between the 1980 and 2000 Censuses the proportion of the Portland metropolitan region's population residing in urban and suburban census tracts increased at a significantly higher rate, while the proportion of the population residing in rural census tracts increased by a significantly lower rate, than was the case in Midwestern cities, on average. In this study we assume that this was primarily attributable to Portland's land development and transportation management policies, such as the urban growth boundary it put in place shortly before the 1980 Census.

It is important to note, of course, that growth management policies may have been only one of several forces driving Portland's increasing urbanization during this period. Regional differences in consumer preferences for housing, a healthy downtown business community, and the concentration of public amenities within Portland's higher density zones, were among other factors likely to have played a role in the growth of urban census tracts.

While the relative contribution of growth management policies and other regional characteristics to increased urbanization in Portland is difficult to discern, the region nonetheless provides an important example of what can be achieved over time when conditions are conducive to compact growth. To this end, Portland provides an empirical basis for modeling the effects of compact growth on air quality under what may be, at least in a U.S. context, the most ideal of conditions. Thus, we forecast future compact growth scenarios for our Midwestern study region based on the shares of regional population growth captured by urban, suburban, and rural census tracts in the Portland MSA between 1980 and 2000. Our approach consists of three basic steps:

1. Calculate the shares of population growth received by urban, suburban, and rural census tracts in the Portland MSA during the periods 1980–1990 and 1990–2000. A share is calculated as the ratio of the increase in population experienced in one community type to the increase in population in the MSA as a whole. The first and second pie charts in Figure 1 present these growth trends.

2. For each Midwestern MSA, allocate the projected 2000–2010 BAU metropolitan population growth to urban, suburban, and rural census tracts based on 1980–1990 Portland growth shares. Allocate 2010–2020 growth to urban, suburban, and rural census tracts based on 1990–2000 Portland growth
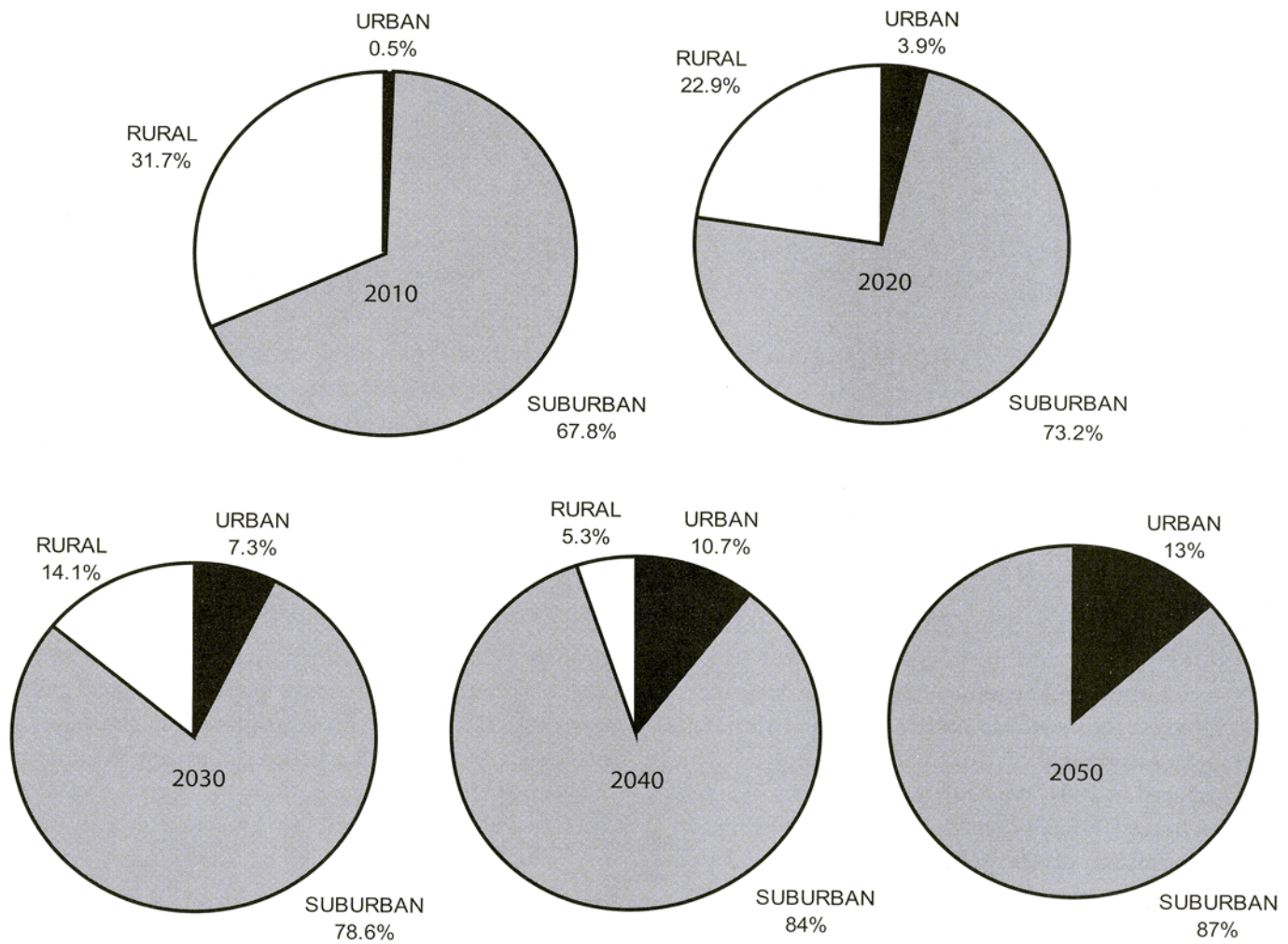

Figure 1. Shares of MSA population growth assumed for future decades.

Note:
The 2010 assumptions are the same as Portland, Oregon growth shares for the period from 1980 to 1990. The 2020 assumptions are the same as Portland growth shares for the period from 1990 to 2000.

shares.[3] Within each community type, allocate new population to individual census tracts through a constant share routine.[4]

3. Compute the share of growth going to each community type in each Midwestern MSA for the years 2030, 2040, and 2050 as a linear extrapolation of the change in Portland community type growth shares between the 1980–1990 and 1990–2000 periods. This step recognizes that the share of growth urban and suburban tracts receive should increase as rural land becomes less available within the growth boundary.[5] Figure 1 shows the growth shares we used for each community type for each decade.

This simple modeling process yields a new set of population estimates for urban, suburban, and rural census tracts within each Midwestern MSA, without altering the MSA-level BAU population projections for future years. In addition to adjusting the tract-level population estimates, we modified the number of households and mean-vehicles-per-household variables to reflect trends experienced in Portland between 1980 and 2000. We assume that each MSA's average household size remains what it was in 2000, meaning that the number of households will vary with changes in tract population.[6] We adjusted tract-level vehicle ownership rates based on the historical difference between the annual percentage change in vehicles per household in Portland and those in each Midwestern MSA, according to community type.[7]

Vehicle Activity Modeling

The core of our research approach is a framework for associating future land use and demographic change with vehicle travel. We extend a "transferability" framework, developed by researchers at the Oak Ridge National Laboratory (ORNL) to support the derivation of census-tract-level travel statistics from national travel survey data, and use it to project future vehicle activity based on a small set of demographic variables.

Developed in 2001, the Nationwide Personal Transportation Survey (NPTS) transferability framework supports the estimation of vehicle trip generation and miles of travel at the census tract level in response to three census variables: income, vehicle ownership, and employment rate, plus the urban-rural community type classification discussed above.[8] Identified in the transportation literature as significant predictors of vehicle travel (Bento et al., 2005; Heanue, 1998; Holzclaw et al., 2002), these variables can be used to identify clusters of census tracts hypothesized to share similar travel characteristics. Once tracts are grouped

into these homogenous clusters, average daily vehicle trips and miles of travel per household are derived from the national travel survey responses in each cluster and used to estimate tract-level vehicle travel based on the number of households per tract (Reuscher, Schmoyer, & Hue, 2002).

As detailed in Figure 2, the Federal Highway administration (FHWA) transferability framework creates clusters of similar census tracts in three steps. In the first step, census tracts characterized by very high or very low median incomes are combined into separate clusters. In the second step, the remaining census tracts are divided into urban, suburban, and rural clusters on the basis of density, as described earlier. In the final step, each density-based cluster is further subdivided into clusters with high, medium, and low median household incomes, employment rates, and mean vehicles owned.

Once the various clusters have been formed, an average rate of vehicle miles of travel is calculated from the national travel survey respondents captured within each cluster. As noted above, this average may be multiplied by the number of households in any census tract from the same cluster type to derive an estimate of total daily vehicle miles of travel for that tract. Figure 3 shows the average daily household VMT associated with each type of cluster in the framework.

We make use of the transferability project framework described above to estimate future year vehicle travel based on forecast changes over time in the four variables used to construct the census tract clusters. We assume that as these characteristics of a tract change over time, its average household VMT will change correspondingly. For example, if the population of a census tract in the "suburban-high" cluster (tracts characterized by suburban densities and high levels of income, employment, and vehicle ownership) increases over time, it may cross the density threshold to become an "urban-high" tract (characterized by high density and high levels of income, employment, and vehicle ownership), with the corresponding average household VMT. Through this process we forecast changes in daily household VMT[9] based on other forecast changes. The process is referred to as the "cluster-migration" routine and is illustrated in the bottom portion of Figure 2.

The FHWA's transferability framework is a good basis for modeling the effects of land use change on vehicle travel over time for two reasons. First, as the framework is based on census variables, it allows estimating vehicle travel for small geographic units (census tracts) across the entire United States. This enables for the first time a detailed assessment of land use, travel behavior, and air quality across a multistate region, a scale that more completely captures pollution formation and transport processes. Second, the transferability framework estimates vehicle

A Classification of Census Tracts

All Census Tracts with Population > 0
and Number of Vehicles > 0 (59,236 Tracts)

Split by Income

| very low income tracts (1,634) | *All Tracts Except Very Low and Very High Income Tracts (55,798 Tracts)* | very high income tracts (1,804) |

Split by Area Type

| *Urban (10,238 tracts)* | *Suburban and Second City (21,564 tracts)* | *Rural and Town (23,996 tracts)* |

Split by Cluster Analysis Based on Income, Employment Rate, and Numbers of Vehicles

2000

| Low Cluster (3,059 Tracts) | Medium Cluster (4,565 Tracts) | High Cluster (2,614 Tracts) | Low Cluster (5,136 Tracts) | Medium Cluster (9,865 Tracts) | High Cluster (6,563 Tracts) | Low Cluster (6,604 Tracts) | Medium Cluster (11,722 Tracts) | High Cluster (5,670 Tracts) |

2050

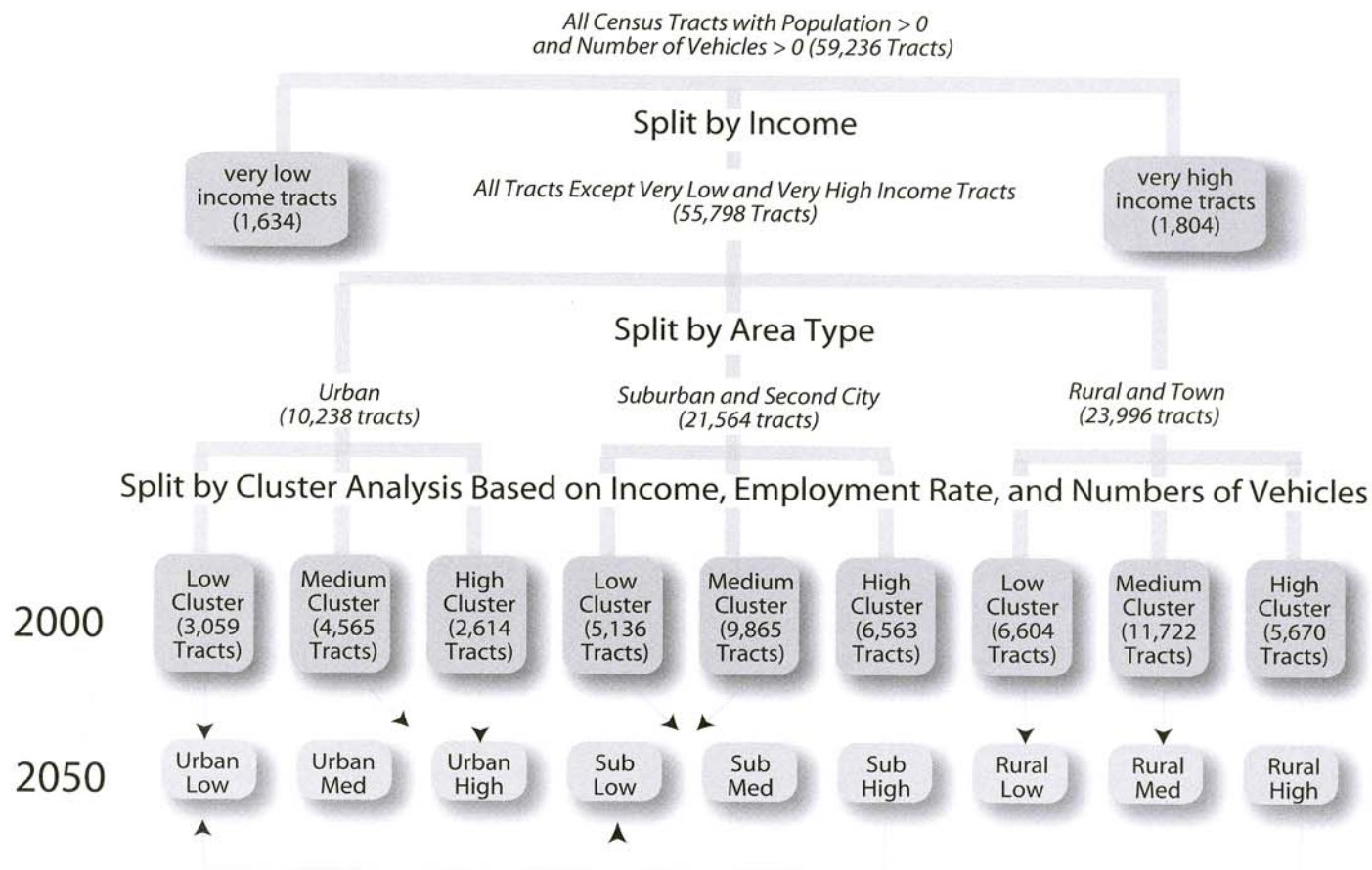| Urban Low | Urban Med | Urban High | Sub Low | Sub Med | Sub High | Rural Low | Rural Med | Rural High |

Figure 2. Federal Highway Administration's transferability framework.

Note:

The arrows illustrate potential tract migrations from one cluster to another with changes in contextual density, income, employment rate, and vehicle ownership between 2000 and 2050.

Source: Adapted from Reuscher et al., 2002.

travel quite accurately. Reuscher et al. (2002) compared VMT projected using the transferability framework and observed travel data obtained through three independent travel surveys conducted in New York, Massachusetts, and Oklahoma, finding the transferability framework to estimate VMT at the metropolitan and state levels with a mean error rate of approximately 3.1%.

Vehicle Emissions Modeling

We used EPA's MOBILE6 emissions factor model to estimate vehicle emissions of carbon monoxide (CO), nitrogen oxides (NOx), fine particulate matter (PM2.5), and volatile organic compounds (VOC) associated with

both current and future VMT over the study area. MOBILE6 calculates average emissions factors in grams per mile for each pollutant based on input parameters detailing the composite characteristics of the vehicle fleet, engine mode of operation (coldstart, hotstart, or stabilized operating modes), a set of climate variables, and mean travel speeds, among other variables.[10] These average emissions factors may then be multiplied by the tract-level estimates of VMT to derive emissions of each major vehicle pollutant for each tract.[11] In addition, we derived estimates of average travel speeds and vehicle fuel efficiencies by community type to estimate total emissions of carbon dioxide (CO_2), a principle greenhouse gas, for each scenario.
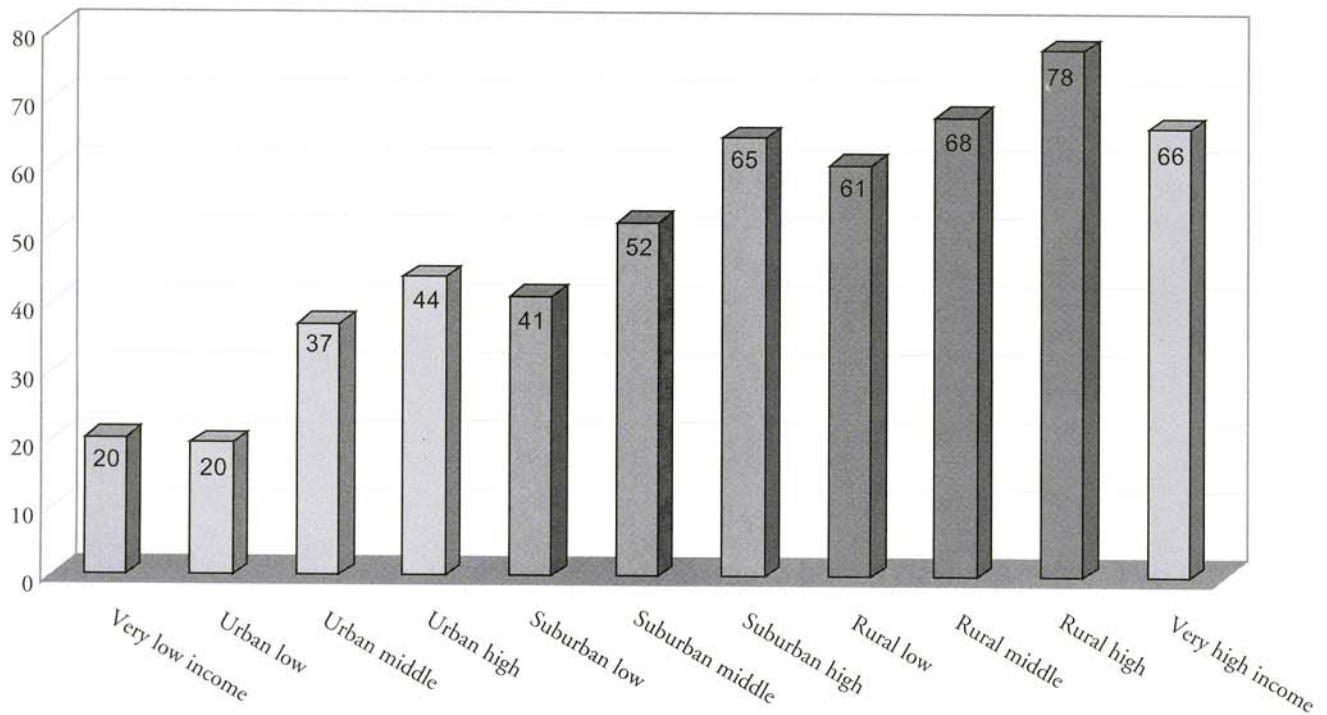
Figure 3. Average daily household vehicle miles of travel by tract cluster type.

Study Results

The following section describes the differences we found in population density, vehicle miles of travel, and tailpipe emissions between the BAU and CG scenarios in 2050. We report our study results for the 11 MSAs in the study region that had populations exceeding 500,000 in 2000. A map of these metropolitan areas is provided in Figure 4.

Population Density

One of our key assumptions is that under the CG scenario Midwestern MSAs will experience development trends like those documented in Portland since 1980, causing population density to increase faster than under the BAU scenario. While the share of growth received by urban census tracts in Portland in the 1980s was quite small (see Figure 1), as this share increases and rural growth diminishes over time, average tract population densities in urban and suburban zones should increase as well, resulting in a migration for some tracts to VMT clusters with lower rates of daily household vehicle travel.

Figure 5 shows population density in the Columbus, Ohio, metropolitan area in the base year and under the BAU and CG scenarios in 2050. As the three panels illustrate, the BAU and CG scenarios differ significantly in the extent of low-density urban expansion into peripheral rural census tracts by 2050. The CG scenario for Columbus predicts most population growth will occur in census tracts that were already urbanized in 2000, much as if a growth boundary were in place, and increases average tract-level population density by 9.2% over the BAU scenario by 2050. Across the 11 large MSAs in the study region, the mean tract-level population densities under the CG scenario ranged from 6.6% to 26.8% greater than BAU, with a median increase of 14.4% relative to the BAU scenario.

Vehicle Miles of Travel

The observed difference in mean tract population density by MSA is important due to the relationship between density and the average daily household vehicle travel rates presented in Figure 3. If compact development patterns serve to significantly increase the density of the average census tract, the household vehicle travel rate associated with these tracts is likely to decrease. Figure 6 bears out this logic, with our model estimating fewer vehicle miles of travel under the CG scenario than under the BAU scenario in 2050 in 10 of 11 major Midwestern MSAs. Figure 6 shows two measures of these differences in VMT: one averaged across all MSA residents, and one only considering new households who arrived since 2000. As discussed below, these differences result from differences in
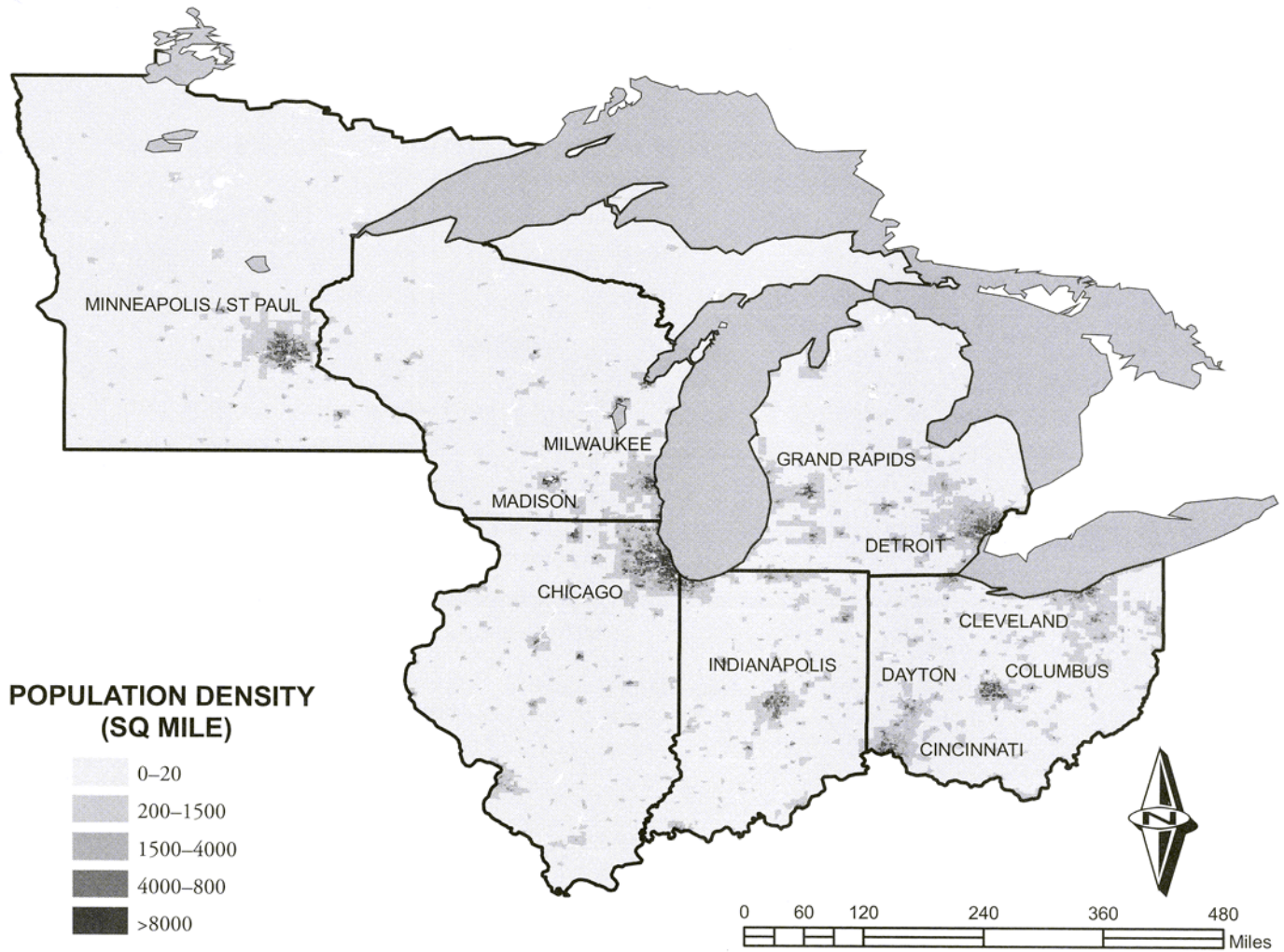
Figure 4. Population densities in the upper Midwest study region, naming metropolitan areas with populations greater than 500,000.

MSA growth rates. Compact growth may have only a minimal impact on metro-wide VMT in MSAs experiencing low rates of population growth, where a large percentage of the population will live at the same residential density under both scenarios. However, it can have a significant impact on the travel patterns of the small numbers of new residents if they would have chosen rural locations under BAU, but under CG instead locate in suburban or urban census tracts.

The model indicates the median VMT across the 11 MSAs to be 6.0% lower under the CG scenario than under the BAU scenario by 2050. For a few large metros, total VMT is nearly 10% lower under the CG scenario, though Chicago's VMT are actually higher (by less than 1%) under the CG scenario. The difference in VMT among new residents generally tracks that of all households in the MSA, but the magnitude of the effect is greater. New

residents experience a median VMT that is 11.1% lower under CG, ranging between being 4.4% higher for Chicago and 39.6% lower for Dayton, Ohio.

The differences between VMT under the CG and BAU scenarios for particular MSAs result principally from two characteristics unique to each metropolitan region. The first of these is the urban share change. As illustrated in Figure 6, the urban share change is a measure of the difference in the percentage of the 2050 MSA population residing in urban census tracts under the BAU and CG scenarios, and can be conceptualized as an index of the dissimilarity between historical growth patterns of Portland and those of each Midwestern MSA. A large urban share change suggests that the CG scenario significantly changed the distribution of new population growth relative to the historical trends extrapolated through the BAU scenario. For example, the percentage of the 2050 MSA population residing

2000   **BAU 2050**   **CG 2050**

Population Density (sq. mile)

☐ 1–200
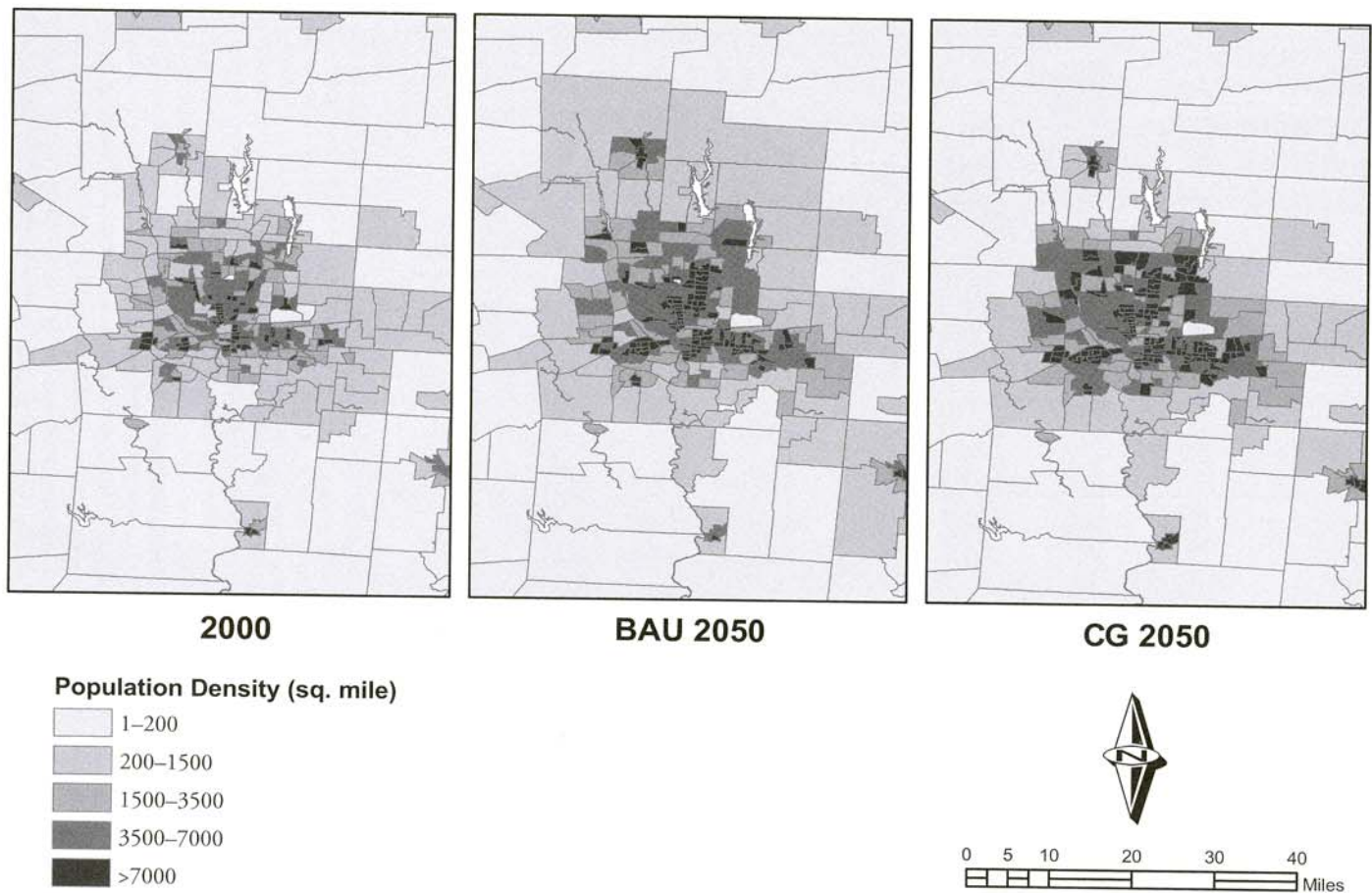☐ 200–1500
☐ 1500–3500
☐ 3500–7000
☐ >7000

Figure 5. Residential density of Columbus, Ohio in 2000 and under the BAU and CG scenarios in 2050.

in urban census tracts in Indianapolis, Indiana is about 10% under the BAU scenario, compared to about 35% under the CG scenario. The application of Portland-based growth shares to BAU trends in this MSA substantially changed the historic pattern of urban growth extrapolated in the BAU scenario. At the other end of the continuum, Chicago had fewer new residents in urban tracts under the CG scenario than under the BAU scenario, indicating that Chicago's own historic growth trend exceeds the rate of urbanization in Portland.

The second regional characteristic affecting the differences in VMT between the scenarios is the rate of population growth at the MSA level. For some cities, the projected rate of population growth under the BAU scenario is very low. Dayton, for example, is projected to experience only a 1.2% gain in its metropolitan population between 2000 and 2050. As a result, regardless of the share of new population growth captured by urban census tracts in Dayton, the difference between the averages of all census tract densities in the MSA for the BAU and CG scenarios will

be modest due to the low rate of growth overall. This indicates that, like other growth-oriented planning strategies, compact growth requires a healthy increase in regional population over time to be effective.

In combination, the change in the urban share of MSA resident population and the population growth rate explain average VMT change for entire MSAs and for new residents in each region. At the high end of the continuum, our model predicts Indianapolis would have large differences in its urban share of total population under CG (indicating that Indianapolis's historic growth trends were very dissimilar from those of Portland), and one of the highest rates of modeled future population growth. This combination redirects a large number of new residents away from rural census tracts and toward suburban and urban census tracts, subsequently increasing the population density of these tracts and lowering the household VMT rate. Chicago's lesser share of the population in urban and suburban tracts under CG, combined with a modest growth rate, results in higher VMT under CG than under BAU.
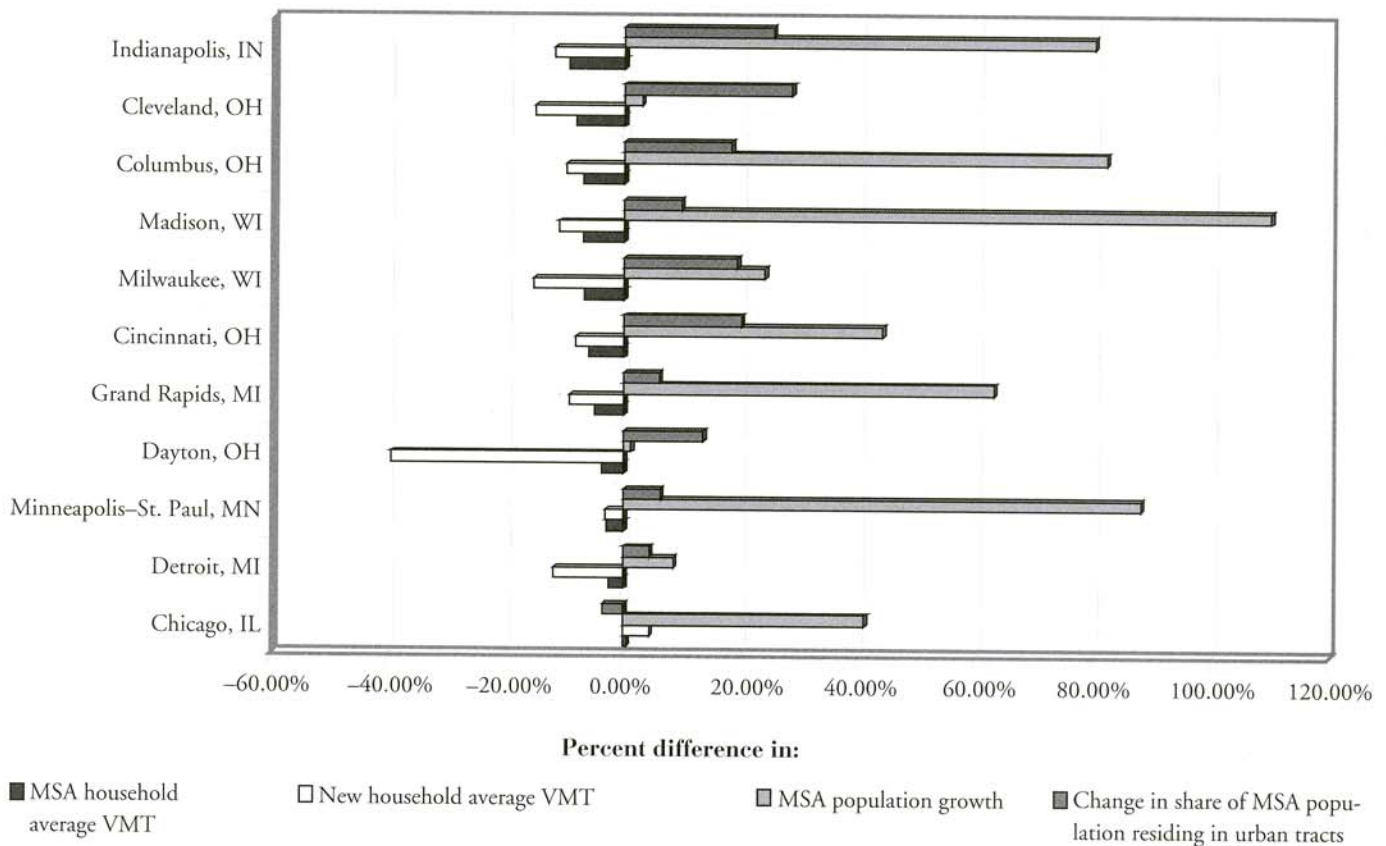
Figure 6. Percentage that the CG scenario differs from the BAU scenario in 2050 on measures of VMT and growth in Midwestern MSAs.

Vehicle Emissions

While trends in vehicle emissions should be expected generally to mirror those of vehicle miles of travel, two characteristics of vehicle travel behavior related to community type can create a divergence between VMT and emissions patterns: travel speeds and the distribution of coldstarts. To estimate the vehicle emissions of trips originating in different zones of each MSA, we used national travel survey data obtained in the six-state study region to derive average vehicle travel speeds for all trips taken by households in urban, suburban, and rural zones of the region. Because trip speeds tend to be inversely related to density, we found higher average travel speeds in rural zones and lower speeds in urban zones. Lower average speeds within the range recorded in the travel survey diaries tend to be associated with higher levels of pollutant emissions per mile of travel. Thus, while higher density was generally associated with lower levels of VMT, the emissions per mile of travel tend to be marginally greater in urban zones, serving to diminish the benefits of compactness for air quality.

A second important mechanism through which land use can influence vehicle emissions is the spatial distribu-

tion of coldstart trips. Our analysis of NPTS data for the six-state study region found the frequency of coldstart trips to be higher in urban than in suburban or rural zones, because suburban and rural residents tend to combine or "chain" trips more than urban residents (Ewing, Haliyur & Page, 1994; Kumar & Levinson, 1995). The chaining of vehicle trips can reduce the cool-down period between each trip and reduce coldstarts. We account for this spatial variation in coldstart frequency by applying separate coldstart and noncoldstart emissions factors to the percentage of VMT associated with each trip type. Thus, the average travel speed and coldstart trips associated with urban zones together offset some of the air quality benefits resulting from lower VMT in higher density zones.

The results of our emissions analysis are presented in Figure 7. As expected, emissions differences between the CG and BAU scenarios across large MSAs in the study region are closely correlated with, although marginally lower than, VMT differences. Median differences vary by pollutant, with the CG scenario producing 6.0% less PM$_{2.5}$, and 5.6%, 5.6%, and 5.2%, less, respectively, of NOx, CO and VOC. The variance in emissions differences

is primarily attributable to more coldstart trips in urban census tracts when these areas experience greater growth under the CG scenario. As particulate matter is not controlled by catalytic converters, reductions in particulates are directly proportional to VMT reductions. In contrast, VOC, the pollutant most effectively controlled by catalytic converters, exhibits the smallest difference between scenarios, while CO and NOx differences are slightly higher due to the variable sensitivity of these pollutants to coldstarts and travel speeds. Based on an average rate of CO_2 emissions per gallon of gasoline consumed and for differences in fuel economy by community type, we found the median reduction in CO_2 emissions under the CG scenario to be 5.1%.

Discussion

The results of our study suggest that compact development patterns, when instituted over a significant period of time, can measurably reduce vehicle travel and pollutant emissions at the scale of the metropolitan region. These findings provide a basis for assessing three principal issues pertaining to long-range land use, transportation, and air quality planning at the metropolitan level: the elasticity of vehicle travel with respect to density change, the strategic direction of new growth, and the significance of growth to "smart" growth planning.

The Elasticity of Vehicle Travel with Respect to Density Change

More important than the estimated difference in vehicle travel and emissions between the CG and BAU scenarios for each MSA in our analysis is the average rate of change in these variables associated with changes in density. As we cannot assume that the adoption of Portland-like growth management policies in Midwestern MSAs would actually result in Portland-like growth, we do not claim to forecast the influence of such policies on future growth in the upper Midwest. Rather, we aim to gauge the reduction in vehicle travel and emissions likely to be associated with specified increases in population density. For example, if a metropolitan area can increase average population densities by 20% with any combination of
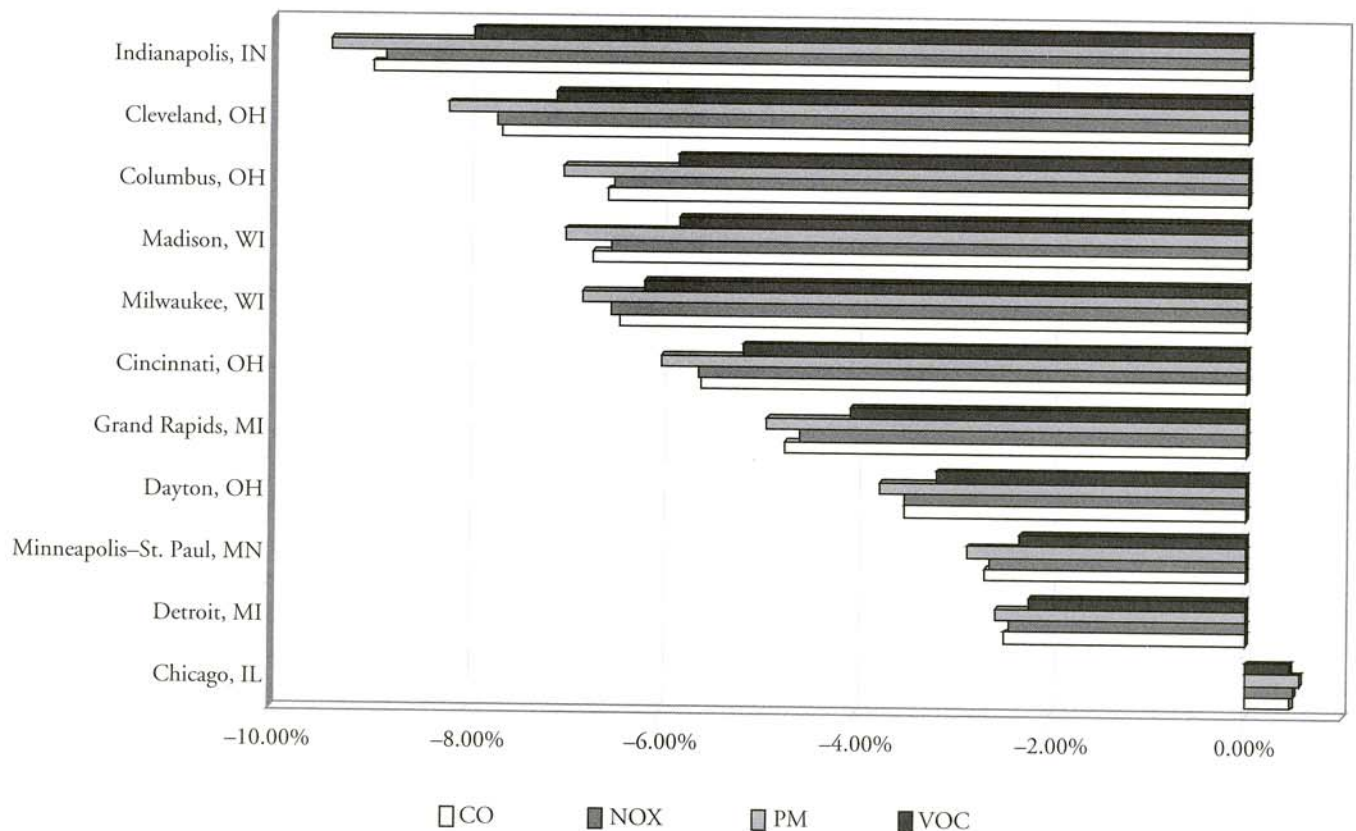

Figure 7. Percentage of difference in vehicle emissions under the CG scenario compared to the BAU scenario in 2050.

planning policies, what consequences for vehicle travel and emissions can reasonably be anticipated?

We address this question by using our model to measure the elasticity of vehicular travel with respect to density, measured as the ratio of the percent change in household VMT to the associated percent change in population density for different community types or for metropolitan areas. We find in Indianapolis, for example, that the mean 2050 population density of all census tracts is about 27% higher under the CG scenario than under the BAU scenario. And the household VMT rate for all census tracts is 9% less under the CG scenario than under the BAU scenario. The vehicle travel elasticity in Indianapolis is thus about −0.33, indicating that a 10% increase in density due to population growth is associated with a 3.3% reduction in VMT per household, on average. The median vehicle travel elasticity across the 11 large metros was found to be −0.35.

The implications of this finding for planning policy are two-fold. First, the median vehicle travel elasticity found here is considerably higher than that reported in previous work (Ewing & Cervero, 2001), and suggests that compact growth may play an important role in reducing vehicle travel and emissions relative to historical trends when instituted over a long planning horizon.[12] Second, if compact growth alone is to effect a significant reduction in vehicle travel and emissions over the next half century, metropolitan rates of densification will need to surpass those achieved in Portland during the 1980s and 1990s. At the median, five decades of Portland-like growth patterns in the 11 large metropolitan areas we studied increased mean tract-level population densities by about 14% over what they would be if historic growth trajectories continued, resulting in only a modest reduction in vehicle travel and emissions beyond what would occur without controlled growth.

The Inequality of Density

The results of our study further suggest that density has a variable effect on vehicle travel and emissions by community type. Our approach emphasized shifting expected population growth from rural zones to suburban and urban zones. We addressed whether densifying suburban zones or urban zones would more effectively reduce vehicle travel and emissions by computing vehicle travel elasticities for urban and suburban census tracts only, rather than for each MSA as a whole. We find the median vehicle travel elasticities of urban and suburban zones across the 11 MSAs to be −0.43 and −0.19, respectively, indicating that densifying urban tracts is more effective in reducing vehicle travel than suburban densification by a factor of 2.3.

This finding suggests compact growth strategies should favor urban over suburban population growth. While we found the densification of both urban and suburban census tracts to be associated with lower average daily household VMT rates, we found urban growth to be more effective in reducing vehicle travel due to its role in density maintenance. Under the BAU scenario, a significant number of urban census tracts continue a pattern of historical population loss, which serves to reduce densities and raise household vehicle travel rates, a trend that the CG scenario reverses.

Maintaining urban densities is important. A nonlinear association between density and travel behavior noted in previous studies (e.g., Frank & Pivo, 1994) may result from transit and other nonauto modes of travel requiring some minimum threshold density to become viable. Density changes within urban zones have been shown to have a more pronounced effect on vehicle travel than comparable density changes within nonurban zones, evidenced in this study through the higher vehicle travel elasticity in urban zones. In light of this finding, policies designed to give priority to increasing the densification of the more heavily urbanized zones of metropolitan regions may be warranted.

The Paradox of Smart Growth

The results of our analysis highlight an important paradox inherent in "smart" growth planning programs that emphasize compact development patterns: Those cities found to exhibit the greatest difference between the CG and BAU scenarios were also projected to experience the greatest future increase in total regional VMT and emissions over base year levels. For example, while we found the level of regional VMT in Indianapolis under the CG scenario to be almost 10% lower that that of the BAU scenario in 2050, this level of VMT was still 71% greater than the region's total in 2000. At the other end of the continuum, in Dayton levels of vehicle travel under CG were a meager 4% lower than the BAU trend, but VMT only increased by 8% between 2000 and 2050, resulting in a much lower growth in total vehicle travel and pollutant emissions than in Indianapolis. As illustrated in Figure 6, a principal distinction between these two metropolitan areas is the rate of population growth over time. While the distribution of future growth in Indianapolis can be smarter, it is still growth; and all growth entails costs for the environment.

The chief implication of this paradox is that redistributing population growth in the absence of overall growth controls or disincentives to auto use is likely to achieve only limited reductions in vehicle travel and emissions. It is for this reason that the most effective approach to regional

air quality management in rapidly growing cities will be to integrate land use and technological strategies. The appeal of technological emissions controls is that such strategies hold the potential to reduce emissions from both existing and new vehicles within a relatively short period of time. The introduction of reformulated fuels, for example, has measurably improved air quality in some regions within a few weeks or even days. The effects of land use strategies, by contrast, tend to be limited principally to those residents who live or work within zones targeted for new development. As a large percentage of the area that will be urbanized in 2050 is already built up in most cities, contemporary patterns of land use and transport are likely to dominate travel behavior for decades to come.

Conclusions

Is compact growth good for air quality? Our findings suggest the answer to this question to be a qualified "yes." Across the Midwestern MSAs examined in this study we found a median vehicle travel elasticity with respect to density of −0.35, indicating a 10% increase in mean tract level density to be associated with a 3.5% reduction in vehicle travel. Thus, we found increased compactness to reduce vehicle travel more than had been discovered in previous studies. This suggests land use change can play a measurable role in improving regional air quality over time.

Importantly, we found that where this higher density development occurs is critical. Our model showed the densification of urban zones to be more than twice as effective in reducing VMT and emissions as the densification of suburban zones. Our findings in the Chicago MSA were instructive on this point, since redirecting Chicago's population growth from urban to suburban zones under the CG scenario increased overall VMT relative to the BAU scenario, despite an increase in average MSA-wide tract densities. Our findings thus suggest compact growth to be better for air quality than continuing historical patterns of growth when priority is given to densifying urban over nonurban zones.

In evaluating the results of this study, a few important limitations of our work should be considered. The first of these pertains to the use of Portland-based growth shares in our scenario modeling, which may result in growth patterns that are more or less compact than what may be attainable over time in each target MSA. While intended to empirically ground our analysis in the development trends of a region in which comprehensive growth management policies have actually been adopted, Portland's experience

in the 1980s and 1990s may fall short of what some MSAs might achieve with an aggressive suite of policies tailored to the Midwest and specifically designed to enhance urban densities and reduce vehicle travel, as opposed to protecting peripheral resource lands. As a sensitivity analysis, our work seeks only to gauge the responsiveness of vehicle travel and emissions to potential changes in urban form, rather than to accurately forecast such changes themselves. While we expect a more aggressive approach to regional growth management would send a greater share of growth to urban zones and would lower rates of household vehicle travel below those reported here, we find no evidence to suggest higher growth in urban zones would be associated with higher vehicle travel elasticities.

A second limitation of our approach, related to the first, is our implicit extrapolation of economic and environmental conditions that prevailed in U.S. cities during the study's historical period to future time periods. The urban growth shares observed in Portland and our Midwestern cities during the 1980s and 1990s directly reflect that period's fuel prices, land values, and a host of other factors with important implications for travel behavior. Had the costs of vehicle travel been higher during this period, it is quite likely that the urban growth shares extrapolated in both the BAU and CG scenarios would have been greater, resulting in more compact growth over time. In the context of growing constraints on the global oil supply and increasing evidence of global climate change, it is also reasonable to expect that vehicular travel in future time periods will respond more to urban form than was observed during the late 20th century. If that is true, the vehicle travel elasticities documented through this study are more likely to constitute a floor than a ceiling on the sensitivity of vehicle travel and emissions to land use change over time.

Finally, the results of this analysis support the conclusion that more compact development strategies, while serving to diminish rates of vehicle travel and emissions over time, are likely to be insufficient as a sole mechanism for combating the problems of congestion and poor air quality in large cities. Ultimately, the most effective options for reducing the impacts of increased vehicle usage include either limitations on regional population growth or a combination of growth management strategies with technological and infrastructure improvements, including a greater reliance on regional transit services. The allure of more compact growth lies in its potential to advance both of these latter sets of strategies: first, by reducing the demand for vehicle travel, and, second, through enhancing the potential for nonvehicle modes to meet a greater share of our travel needs. Through ongoing work we hope to

better illuminate the potential for both land use and technological approaches to improve urban air quality over time.

Notes

1. Elasticity measures the percent change in the affected factor (vehicle miles of travel in this case) per percent change in the influencing factor. Thus, a −0.05 elasticity of VMT with respect to density means that VMT declines by 0.5% for every 10% increase in density.

2. The urban, suburban, and rural community type classifications are derived from a measure of "contextual density" developed by the economic forecasting firm, Claritas, Inc. This measure is based on the aggregate density of a geographic unit and its adjacent units, or "neighborhood." The distinction between rural tracts and urban/suburban tracts is based solely on contextual density. The distinction between urban and suburban tracts is based on a combination of a tract's contextual density and that of its nearest regional population center. For more information on the community type classifications used in this study, see Reuscher et al. (2002).

3. In some cases, the share of a Midwestern MSA's growth locating in urban and suburban tracts under the BAU scenario was higher, or the rural share was found to be lower, than predicted by the Portland example. In these instances we retained the BAU growth shares in the CG scenario.

4. We allocated population growth to individual census tracts based on a constant share approach so that the percentage of the total urban, suburban, or rural population each tract captured in the base year of the analysis, 2000, remained the same throughout the analysis period.

5. The application of this growth share increment assumes that future expansions of Portland's growth boundary will be consistent with those that occurred during the historical period.

6. We kept average household sizes as they were in 2000 because we used average daily VMT per household based on average household sizes in 2000.

7. For each community type (urban, suburban, and rural), we subtracted Portland's historic annual percentage change in household vehicle ownership from the corresponding change in each of the Midwestern MSAs. Where the resulting differences were negative, we added them to BAU-projected annual percentage changes at the individual tract level, thereby reducing projected vehicle ownership per household. We used the same median household income and employment rates for the BAU and CG scenarios. Theory and empirical evidence is insufficient to indicate how growth management policies might influence these variables.

8. The relatively small number of NPTS survey respondents recruited per state is insufficient to derive statistically significant statistics for geographic areas smaller than multistate census divisions. Since many state, municipal, and county agencies would like to use this national travel survey data for transportation planning, the FHWA sponsored development of the ORNL method to address this issue.

9. As our scenario modeling framework does not use different tract level median household income estimates for the BAU and CG scenarios, the "very high" and "very low income" clusters are not employed in developing VMT estimates for future time periods.

10. We assume a coldstart occurs following any period of vehicle rest of 60 minutes or more. Coldstart trips generate higher emissions per mile because catalytic converters (emission control devices designed to reduce emissions of CO, VOC, and, in newer cars, NOx) are less effective when engine temperatures are low. To isolate the influence of land use on future air quality, we kept the vehicle fleet characteristics constant throughout the time period analyzed. However, as hybrid-electric vehicles and other emerging technologies become more widespread, they should greatly diminish emissions per mile of travel.

11. We analyzed NPTS data for the six-state region to obtain average travel speeds and coldstart trip rates by community type, and used these rates to model vehicle emissions with MOBILE6 for the entire analysis period.

12. As the contextual density measure employed in this study reflects both local and surrounding "neighborhood" densities, the elasticities reported here may not be directly comparable to those associated with other density measures.

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