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The influence of urban form on GHG emissions in the U.S. household sector

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HIGHLIGHTS

- We examine how urban form influences household CO_2 emissions using a multilevel SEM.
- Doubling population-weighted density is associated with a 48% reduction in CO_2 emissions from household travel.
- Doubling population-weighted density is associated with a 35% reduction in CO_2 emissions from residential energy use.
- Doubling per capita transit subsidy is associated with a 46% lower VMT and 18% reduction in transportation CO_2 emissions.
- Smart growth policies should be a crucial part of any strategic efforts to mitigate GHG emissions and stabilize climate.

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ABSTRACT

To better understand the role of sustainable urban development in greenhouse gas (GHG) mitigation, this study examines the paths by which urban form influences an individual household's carbon dioxide emissions in the 125 largest urbanized areas in the U.S. Our multilevel SEM analyses show that doubling population-weighted density is associated with a reduction in CO_2 emissions from household travel and residential energy consumption by 48% and 35%, respectively. Centralized population and polycentric structures have only a moderate impact in our analyses. Given that household travel and residential energy use account for 42% of total U.S. carbon dioxide emissions, these findings highlight the importance of smart growth policies to build more compact and transit friendly cities as a crucial part of any strategic efforts to mitigate GHG emissions and to stabilize climate.

1. Introduction

Experts widely agree that the global mean temperature (GMT) should be kept within a maximum of 2 °C above preindustrial levels to prevent potentially catastrophic consequences for human society and natural ecosystems (Smith et al., 2009). In response to “the 2 °C guardrail” endorsed by the Copenhagen Climate Summit (Richardson et al., 2009; UNFCCC, 2009), the U.S. federal government set a goal of reducing greenhouse gas (GHG) emissions by 17% below 2005 levels in 2020 and by 83% in 2050 (U.S. Department of State, 2010). Most of the current and proposed policy measures to meet the climate stabilizing GHG reduction target in the U.S. rely on technology and pricing solutions: stricter fuel economy standards, promoting low-carbon fuels, and cap and trade systems or carbon taxes (Chapman, 2007; Ewing et al., 2008a; Pacala and Socolow, 2004). Many studies, however, show that technology and market solutions alone, without moderating energy demand, cannot achieve these GHG reduction goals (Boies et al., 2009; Grazi and Van den Bergh, 2008; Johansson, 2009; Kromer et al., 2010; Morrow et al., 2010). Moreover, technology may not develop at a sufficient rate to meet the challenge (Johansson, 2009), and the potential GHG savings from improved energy efficiency are likely to be (at least partially) offset by ‘rebounded’ energy consumption (Greening et al., 2000; Sorrell et al., 2009).

To fill this gap, additional steps are needed. Reducing individual energy consumption through shifts in behavior represents one opportunity to mitigate GHG emissions. This option is compelling given that households, as an end-user sector, account for 42% of total U.S. carbon dioxide emissions from fossil fuel combustion, combining emissions from residential buildings (22%) and passenger travel (20%) (U.S. Environmental Protection Agency, 2012). While various factors such as energy price, income, and weather affect household energy consumption, a growing body of literature has linked compact urban development to more carbon-efficient lifestyles, including less driving and more energy efficient housing

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choices (Ewing et al., 2008a, 2008b). Nevertheless, researchers disagree about the magnitude of urban form effects. Some argue that more sustainable urban form and transportation network can more effectively reduce carbon emissions than replacing all gasoline with corn ethanol (Marshall, 2008). Others question whether urban form matters at all (Echenique et al., 2012). Therefore, more empirical research is necessary to systematically assess the potential of smart growth policies to mitigate household sector carbon emissions.

This study investigates the paths by which urban form influences household sector carbon dioxide emissions in the 125 largest urbanized areas (UAs) in the U.S. We estimate individual household carbon emissions from travel and home energy use by processing household surveys, including the census and quantify spatial structure of urbanized areas in several dimensions beyond a simple population density measure. Using this data, combined with a multilevel structural equation model (SEM), we demonstrate that shifting toward more compact urban form can significantly reduce energy consumption and CO_2 emissions in the household sector. Our analysis shows that increasing population-weighted density by 10% leads to a reduction in CO_2 emissions by 4.8% and 3.5% from household travel and residential building energy use, respectively. The effects of other spatial variables are estimated to be small.

2. Urban form and GHG emissions

Connections between urban form and GHG emissions have been studied in the fields of transportation and building energy research. In the transportation sector, research has typically focused on the influence of the built environment on travel demand, often measured in vehicle miles traveled (VMT). In the absence of adequate emissions data at individual and even urban area levels, emissions are often assumed to be a function of VMT, given the current or a target fuel efficiency and fuel carbon content (Mui et al., 2007). Despite earlier skepticism (Boarnet and Crane, 2001; Boarnet and Sarmiento, 1998), many recent empirical studies have found that urban form variables significantly influence travel behavior, including mode choice, trip frequency, trip distance, and, ultimately, VMT. These variables include density, land use diversity, street design (3Ds; Cervero and Kockelman, 1997), destination accessibility, and distance to transit (additional 2Ds; Cervero et al., 2009). A growing body of literature shows that residents in more compact and transit-friendly neighborhoods drive considerably less than those living in sprawling neighborhoods. Moreover, the travel impacts of neighborhood characteristics are found to be significant, even after controlling for the effects of residential self-sorting by preferences and environmental attitudes (Cao et al., 2009; Mokhtarian and Cao, 2008).

However, research on urban form and travel connections mostly focuses on neighborhood level effects, despite the continually reported significance of urban area level spatial structure. Several studies show that variables such as job accessibility (the 4th D) and distance to downtown have larger impacts on VMT reduction (with a typical elasticity of -0.2) than neighborhood level attributes, whose elasticities typically range between -0.04 and -0.12 (Cervero and Duncan, 2006; Ewing and Cervero, 2010; Kockelman, 1997; Naess, 2005; Sun et al., 1998). These results suggest that the location and distribution of developments within a metropolitan region may be more important determinants of travel behavior than neighborhood level density and land use mix at given locations. Nonetheless, few studies have examined the impacts of urbanized or metropolitan area level spatial form (Bento et al., 2005; Cervero and Murakami, 2010; Ewing et al., 2003), primarily due to the lack of appropriate measures of urban area level spatial structure.

Some research has extended urban form and travel connections to study the impacts on energy consumption and GHG emissions. A study of California households finds that 40% higher residential density is associated with a 5.5% fuel use reduction, with 3.8% coming from less driving and 1.7% derived from vehicle choice (Brownstone and Golob, 2009). Other studies show that households in denser urban areas are less likely to own and drive low fuel-efficiency vehicles such as SUVs and pickup trucks (Bhat and Sen, 2006; Bhat et al., 2009; Fang, 2008; Liu and Shen, 2011). These findings suggest that vehicle choice in terms of fuel-efficiency, as well as VMT, should also be taken into account when measuring the effects of urban form on GHG emissions from household travel.

Urban form also affects energy consumption, and hence GHG emissions in residential buildings, through two paths: housing choices – sizes and types – and, potentially, urban heat island (UHI) effects. Households in multifamily housing units, characterized by shared walls and typically smaller floor space, consume less energy for space heating, cooling, and all other purposes than do households in detached single-family homes, when controlling for the age of housing structures as a proxy of construction technology (Brown and Southworth, 2005; Holden and Norland, 2005; Myors et al., 2005; Perkins et al., 2009). An analysis of the U.S. Residential Energy Consumption Survey (RECS) data shows that single-family home residents consume 54% more energy for home heating and 26% more energy for home cooling than do comparable multifamily housing units (Ewing and Rong, 2008). The same study also shows that doubling home size is associated with the use of 16% more energy for heating and 13% more energy for cooling. However, research in this area is still too thin to derive a generalizable elasticity between residential energy use and development density.

UHI effects, another potential path between urban form and residential energy use, are known to raise surface temperatures by 0.5 to 5 °C in urban areas, compared with surrounding rural regions (Navigant Consulting, 2009; Rosenfeld et al., 1995; Stone, 2007). Thus, UHI effects significantly affect the energy demand for home cooling and heating by changing the number of cooling degree days (CDDs) and heating degree days (HDDs) in large urban areas. While many studies indeed show the negative consequence of UHI effects in sun-belt cities such as Phoenix, AZ (Baker et al., 2002; Guhathakurta and Gober, 2007), potential heating energy savings in the winter, especially in frost-belt cities, remain understudied. A national scale study is needed to adequately assess this potential trade-off. The potential relationship between the intensity of UHI effects and urban development patterns also require further research.

Although UHI intensity is found to increase with urban population size (Arnfield, 2003; Oke, 1973), little is known about the effects of urban form – including population density and polycentric structure – on heat island formation. Because increased heat storage capacity and limited evapotranspiration of constructed urban fabrics are the main causes of UHI (Oke et al., 1991), urban form would affect UHI intensity to the extent that it alters the thermal properties of urban surfaces. A study of the Atlanta (GA) region shows that lower density residential areas with large lots generate more radiant heat energy than do higher density developments (Stone and Rodgers, 2001). On the contrary, a county level cross-sectional study shows that the UHI effect is more intense in compact counties, with increased CDDs and decreased HDDs (Ewing and Rong, 2008). Further empirical studies are therefore necessary.

Researchers have recently begun to take a more comprehensive and systematic approach to inventorying metropolitan carbon footprints. They associate the variation in newly estimated metropolitan