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Energy footprint of the city: Effects of urban land use and transportation policies

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ABSTRACT

Urban land use and transportation policies have dramatic effects on the density and spatial distribution of residences in large cities. Effects of these policies have been analyzed using numerical urban simulation models. At the same time, the US Energy Information Administration's Residential Energy Consumption Survey has allowed researchers to investigate the relation between household energy consumption and characteristics of housing units.

This paper links these two lines of inquiry by demonstrating how simulation results on the implications of land use and transportation policies for the spatial form of cities can be used to compute implications for energy consumption. The resulting Urban Energy Footprint Model, "UEFM," allows one to trace the implications of a change in land use zoning or transportation policy through its effects on housing markets and residential location to the resulting changes in energy use for residential and commuting purposes – i.e. to understand the energy footprint of transportation, housing, and land use policies. Accordingly, the UEFM provides, perhaps for the first time, a link between urban and energy economics, and can allow measurement of rebound effects of energy policies in a more general equilibrium context.

1. Introduction

There is substantial interest in understanding and controlling the use of energy in the residential and transportation sectors of the US economy. Recent studies have attempted to measure energy consumption and/or carbon footprints for residents of cities around the world. Substantial differences in energy use across cities have been reported. For example, independent studies estimated the carbon footprint per capita for Washington, DC to be from 2.1 to 2.8 times that of New York City.[1] The most obvious difference between these two cities is the land use policies regulating the density of real estate development.[2] This suggests that urban land use and transportation policies may have a significant influence on the carbon footprint of the city. Few empirical studies have investigated the relation between patterns of urban development and energy use. Recently, Brownstone and Golob (2009) have shown that residential density is inversely related to vehicle energy consumption and Glaeser and Kahn (2010) report that older, denser cities have lower carbon dioxide emissions. Research on this topic has been limited by the lack of a model relating urban planning and development policies to energy use in cities. The urban energy footprint model (UEFM) developed in this paper is designed to fill that intellectual gap.

Ever since their introduction by Muth (1975), numerical urban simulation models have been used to project the effects of urban land use and transportation policies on spatial patterns of housing within cities.[3] Altmann and DeSalvo (1981) demonstrated that these models could replicate the spatial form and stylized facts characteristic of housing in moderate-sized US cities. Sullivan (1985) pioneered models in which employment was moved out of the central business district. Bertaud and Brueckner (2005) used a numerical urban simulation model to study the effects of planning policies, including the effects of limits on floor area ratios in cities. Bento et al. (2006) model the effects of some of the policies consid-

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[1] See Brown et al. (2008) and Dodman (2009) for sample estimates. There are many difficulties measuring total energy use and carbon emissions, but the reported differences between Washington and New York in both studies are larger than any likely measurement error. Note that both cities have well developed mass transit systems and simple statistical analysis of the cross-section of US cities in the first report ruled out the influence of climate or city size as the cause of differences in carbon footprint per capita.

[2] In addition to binding height and floor area ratio limits, significant portions of the District of Columbia have been declared historic. This limits both density and energy efficiency of the structures.

[3] For many purposes, it is possible to exclude housing supply and have urban land directly enter the household utility function. Many of the most important simulation models, particularly those dealing with optimal transportation investment in cities, have followed this "Mills and de Ferranti" approach and ignored housing supply. However, modeling the effects on energy use of a full range of housing and land use policies requires explicit consideration of the housing production function.

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ered here on urban sprawl using a similar model. Overall, there is a significant research tradition which "fits" numerical urban simulation models to cities and then traces the consequences of planning, land use, and transportation policies for the spatial pattern and density of development.

Given recent attention to issues of energy consumption, as well as rapid changes in the price of energy, research on the connection between urban form and energy consumption seems appropriate. The contribution of this paper is to make a formal connection between the outputs of a numerical urban simulation model and the consequences for energy consumption by residences and commuters. In order to make that connection, the UEFM includes features like multiple income groups, employment decentralized outside the CBD, and endogenous commuting congestion that have not been combined in previous urban simulation models. Incorporating highway congestion is crucial because it affects fuel consumption. Generating the energy cost of commuting as a function of vehicle velocity and distance traveled is relatively straightforward. Household energy consumption equations are obtained by estimating a model of residential energy consumption using the Residential Energy Consumption Survey.[4] Energy use in production, by the public sector, and in non-commuting trips is not considered in this model.

The next two sections of this paper briefly describe the numerical urban simulation model with two income groups and endogenous congestion in urban transportation. Then the residential energy consumption estimation is presented. Finally the model is simulated and the energy footprint implications of some stylized land use and energy policies are generated. The results indicate that the interaction between energy cost and the spatial form of the city is significant and should be considered when evaluating land use and energy initiatives.

2. The energy footprint urban simulation model

The basic form of the numerical simulation model follows the literature discussed above. It is calibrated to replicate the spatial housing pattern of a composite of five moderate-sized cities.[5] The household's utility function is assumed to be CES:

$$V = [\beta_1 y^\eta + \beta_2 h^\eta]^{1/\eta} \tag{1}$$

where h is housing consumption, and y represents all other goods, β_1 and β_2 are distribution parameters, and the constant elasticity of substitution between housing and all other goods is given by $1/(1-\eta)$. The household budget constraint is $I = y + rh + T$, where I is household income, T is the sum of both time and out-of-pocket commuting cost, r is the rental price of housing and h is the quantity of housing services consumed.[6] The price of y is normalized to unity. All other variables vary with distance from the edge of the central business district (CBD) where most employment is concentrated. There are two household types, low and high income. An iso-utility condition for each household type ensures that Muth's equation,

$$\frac{dr}{dk} = -\frac{dT}{dK}\frac{1}{h} \tag{2}$$

where k is distance from the center, holds.[7] Altmann and DeSalvo (1981) demonstrated that models with a single income group tend to generate cities that are too small and dense. To the extent that the UEFM is used for policy evaluation, effects on different income groups could be an attractive feature. For these reasons, households have been divided into low and high income groups.

Housing is produced by a perfectly competitive constant returns industry according to a CES production function:

$$H = [\alpha_1 S^\rho + \alpha_2 L^\rho]^{1/\rho} \tag{3}$$

where H is housing production, S and L are structure and land inputs, respectively, α_1 and α_2 are distribution parameters and the elasticity of substitution is $1/(1-\rho)$. As noted above, all this is common in the literature on simulation models which include explicit housing production.

All workers are either employed where they live or commute by automobile to the central business district.[8] A fixed proportion of land at each distance is used for highways. The road system is subject to congestion based on the number of workers commuting by automobile at any distance. Following Muth (1975) and Sullivan (1985), a version of what is commonly referred to as the Bureau of Public Roads congestion function is used in which commuting speed at a given location is inversely related to traffic volume according to:

$$v(k) = \frac{1}{a + bV(k)^c} \tag{4}$$

where $v(k)$ is the commuting speed at distance from the CBD, $V(k)$ is the traffic volume through location k, and a, b, and c are parameters that reflect the severity of the traffic congestion function. This particular formula is chosen to allow some level of flexibility in modeling the relation between commuting speed and traffic volume. As opposed to previous studies, the implications of vehicle velocity for time and out-of-pocket cost are considered separately because fuel efficiency and gasoline tax policies can change one without changing the other.

Most simulation models have all employment concentrated in a CBD. Sullivan (1985) has both a CBD and suburban business district. Because commuting distance is so important for energy use, the approach adopted is slightly different in that it follows McDonald (2009) in imposing on the city an exogenous employment density function of the form estimated by McMillen (2004). In a closed city model, total employment is always exogenous but assumption of a constant employment density function means that the location of firms does not respond to changes in the spatial distribution of households.[9] Overall, the UEFM closely resembles in the literature, particularly those models, like McDonald (2009) and Altmann and DeSalvo (1981), where the goal is to replicate the spatial pattern of housing density in actual cities. This density replication is important for understanding the energy footprint of cities because household energy use is very sensitive to structure type, i.e, single family detached versus multifamily, etc., as discussed in the next section on calibration. A more detailed discussion of the distinctive features of the UEFM and its solution is given in Appendix A.

The model is solved by imposing three fundamental equilibrium or no arbitrage conditions. First, for both low and high income households, utility must be equal at any location where they live

[4] US Department of Energy, Energy Information Agency, collects these data in a survey of households and utilities taken every four years. This paper relies on the 2005 data set which is the most recent survey available.

[5] The five cities are Charlotte, Kansas City, Denver, San Antonio, and Sacramento. These cities are similar in size and commuting times but differ in climate.

[6] There is one worker per household who must commute to work 5 days per week and work 8 h per day. Commuting time is deducted from leisure and valued at 40% of the wage rate, following guidelines stated in US Department of Transportation (2009). This follows the general convention in the urban simulation model literature.

[7] In the model calibration, the lower income households live closer to the city center. Muth's equation holds within the areas occupied by each income group. House prices and land rent are continuous functions but structure size is discontinuous at the boundary between income groups.

[8] If this model were applied to a city with significant mass transit, particularly a fixed rail system, some commuters could easily be allocated to that system using a modal choice model but it would also be necessary to estimate the energy used by this alternative mode.

[9] Thurston and Yezer (1994) provide empirical evidence that this is a good assumption for all major employment sectors except retail and services.