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The energy implications of city size and density

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ABSTRACT

This paper develops a new open-city urban simulation model capable of showing the urban form and energy consumption effects of variation in city size. The model is able to consider city size differences caused by wage and amenity differentials, both with and without housing and land use regulation. The surprising conclusion is that per-capita energy use is relatively invariant to city size when growth is driven by wages but falls modestly with growth induced by rising amenity. Common land use policies, specifically density limits and greenbelts, can positively or negatively affect both city welfare and energy use.

1. Introduction

Since its introduction by Muth (1975), various versions of the urban simulation model have been used to understand the spatial structure of cities. Virtually all of these applications have involved closed cities with exogenous population, a single type of structure, and exogenous urban transportation costs. None of these efforts has attempted to simulate the effects of variation in city size. The model formulated and solved here is, along with Rappaport (2014), the first urban simulation model of an open city with endogenous population, housing supply and demand, and highway use and congestion.[4] This model is calibrated with respect to the characteristics of a city with one million people, and is quite successful in accounting for the effects of doubling city size on city characteristics.

The model is then used to determine the effect of city size and density on energy use, an important policy question that has been the object of recent empirical research. This empirical research begins with the stylized fact that the rise in house prices with city size causes increases in residential density.[5] As the logic goes, the energy efficiency of multifamily dwellings results in reduced energy consumption in larger, denser cities. Offsetting some of these energy savings are longer and more congested commuting trips. Despite the ambiguity in the magnitudes of these countervailing effects, the prevailing view appears to be that there are net savings in per capita energy use associated with city size.

Why is it necessary to rely on a theoretical model of cities to determine the relation between changes in city size and energy use? Even if precise city-level estimates of energy use in housing and commuting were available, it would be difficult to determine the relation between size and energy use using data from actual cities. First, there is substantial heterogeneity in population and industrial structure of cities. Second, the current spatial form, housing, transportation, and technology in cities are functions of

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[4] Rappaport (2014) has independently developed another simulation model of an open city with endogenous population, housing supply and demand, and highway use and congestion. The model calibration and simulation results in this paper are remarkably similar to the model developed here.

[5] Some of these papers measure total energy use while others measure determinants of carbon emissions (see Brown et al., 2008 and Glaeser and Kahn, 2010 for two recent examples). Generally, they are concerned with some rate of energy use, either energy per capita, energy per household, or energy per unit gross domestic product.

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the historical path of development. Third, climate and topography have major effects on energy use. Finally, fragmented political systems and land use regulations have important implications for urban form and energy use.[6] In sum, the data generating process that produces cities is very messy and the natural experiment of doubling city size holding other factors constant is never close to being performed.

Rather than attempting to correct for the effects of all these factors that confound empirical estimation of the partial relation between an exogenous change in city size and energy consumption, a simulation model creates a city which holds technology, topography, planning, climate, industrial structure, and population characteristics and preferences constant while size is shifted by wages or amenities. It is also possible to study the interaction between a change in size generated by an exogenous shift in one variable and the regulations in place governing land use. Robustness checks within the simulation model allow the partial effects of variation in both model parameterization and city characteristics on energy consumption to be evaluated.

In the simulation with the amenity-driven city size increase, there is a net fall in per capita energy consumption of about 3.7%. However, there is evidence that much of the observed increase in city size in the United States is driven by wage increases caused by agglomeration economies, and as such, the amenity basis for city size increases may be rare.[7] Rather, it is likely that compensating wage differentials drive much of the variation in city size, following the long quality-of-life literature beginning with Roback (1982), and more recently, Desmet and Rossi-Hansberg (2013). This compensating variation in income associated with a doubling of size is simulated to be 2.4% and this has two effects on energy consumption.[8] First, it mitigates the fall in housing consumption due to the price increase. Second, the rise in income results in greater expenditure on the numeraire consumption good.[9] When both these effects are considered, per capital energy consumption actually increases by 0.1% with city size. Thus, doubling city size by increasing the city amenity significantly lowers per capita energy consumption while the same size effect achieved by increasing wages leaves per capita energy consumption essentially unchanged.

Finally, the simulation model can be used to investigate the effects of land use planning policies on both energy use and urban welfare in the case when wages drive city size increases. Because the model relies on an inter-regional equilibrium for both firms (zero profits) and households (a reservation utility level), welfare is measured following Sullivan (1985) as the change in aggregate land value minus the total cost of any compensating wage differential needed to maintain city size. Two common planning policies are examined. First, a residential building height limit is found to exacerbate sprawl, causing both an energy consumption increase and a welfare reduction for any city where the limit is binding. These effects grow larger as city size increases. Second, a greenbelt is simulated with rather different results. If the greenbelt is not severely binding, it can produce lower energy use and higher welfare than the laissez-faire city. Potential welfare gains associated with the greenbelt appear to arise because it functions as a second-best response to unpriced highway congestion. This is consistent with Wheaton's (1998) theoretical demonstration of the effects of failing to price congestion.

The remainder of this paper is organized as follows. First, the Urban Energy Footprint Model is extended in Section 2. The next section provides parameter assumptions and calibration results for an open city simulation. In Section 4, the specific issues involved in the calibration of energy use equations are discussed. Section 5 presents the simulation results and reports on the main findings in the paper.

2. The Urban Energy Footprint Model (UEFM)

The standard urban model (SUM) was developed by Alonso (1964), Mills (1967), Muth (1969), Wheaton (1974), and was summarized nicely by Brueckner (1987). The Urban Energy Footprint Model (UEFM) layers commuting and dwelling energy consumption parameters onto the SUM, building on the closed-city model of Larson et al. (2012).

The UEFM follows the SUM in that it is monocentric and homogenous at a given radius k from the center with a constant fraction of land at each radius available for development. The city has three regions, the Central Business District (CBD) ranging from $0 < k \leqslant k_{CBD}$ with only employment, a middle region where $k_{CBD} < k \leqslant \kappa$ with both employment and housing, and an agricultural hinterland with neither employment nor housing where $k > \kappa$. Households are homogenous and paid an exogenous wage in the CBD which declines with distance beyond the CBD based on commuting cost (see Fig. 1).

The UEFM has a number of features that differ from the standard SUM because it is designed to model energy consumption in housing and commuting. First, the UEFM has employment distributed outside the CBD, a characteristic that is uncommon in the SUM. Second, commuting travel on roads is subject to congestion. Third, housing density is related to structure characteristics with multifamily, single family attached, and single family detached housing distinguished. Fourth, the UEFM is an "open city" model with households able to move at zero cost to achieve identical utility at any location within and outside the city, whereas the SUM often assumes a "closed city" where households cannot migrate between cities.

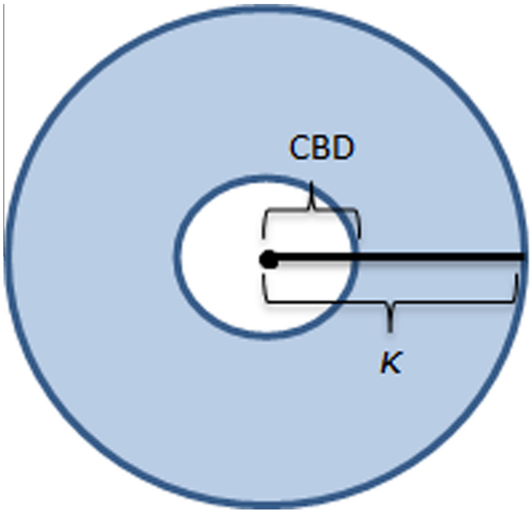

Fig. 1. A simple monocentric city.

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[6] For example, Duranton and Turner (2011) find that the process of adding highways is sufficiently problematic that new road capacity has virtually no effect on congestion in U.S. cities.

[7] See Helsley and Strange (1990), Ellison and Glaeser (1997), and Glaeser and Gottlieb (2009).

[8] The simulated compensating variation of 2.4% is similar to recent estimates of the urban cost elasticities with respect to city size of 1.6–4.6% (depending on various assumptions) in French cities found by Combes et al. (2012). The similarity is remarkable given their empirical approach to estimating the value versus the simulation approach found in this paper.

[9] Another major issue in current empirical studies is the failure to account for the energy embodied in consumption of the numeraire good. This includes Glaeser and Kahn (2010), who acknowledge their inability to produce a full energy accounting, and Borck (2014), who produces a closed city simulation model and shows that a height limit can lower energy consumption without accounting for the numeraire good.