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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.

**JEL** Codes: Q40, R14

Keywords: urban simulation, congestion, commuting, gasoline, greenbelt

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# 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.[1] 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.[2] 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 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.[3] In sum, the data generating process that produces cities is very messy

[1] 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.

[2] Some of these papers measure total energy use while others measure determinants of carbon emissions (see Brown, Southworth, and Sarzynski, 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.

[3] 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.

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.[4] 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.[5] 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.[6] 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

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

[5] 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, Duranton, and Gobillon (2012). The similarity is remarkable given their empirical approach to estimating the value versus the simulation approach found in this paper.

[6] 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.

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.

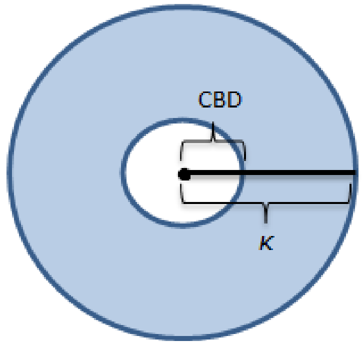
The remainder of this paper is organized as follows. First, the Urban Energy Footprint Model is extended in Section 2. The next section provides parameter assumptions and calibration results for an open city simulation. In Section 4, the specific issues involved in the calibration of energy use equations 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), and 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, Liu, and Yezer (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 $0 < k \leq k_{CBD}$ with only employment, a middle region where $k_{CBD} < k \leq \kappa$ 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.

Figure 1: A simple monocentric city




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.

As is standard practice in nearly all other numerical urban simulation models, all commuting to the CBD in the UEFM is by automobile. Commutes to workplaces outside the CBD are accomplished by walking. Introduction of mass transit would require substantial additional research on a number of fronts and is not considered here. For instance, consider a bus system. Because the UEFM has road congestion, the effects of mixing bus and automobile traffic on urban roads as traffic volumes increased would need to be considered. The relative travel time by bus versus automobile would also need to be modeled as roads became congested, making modal choice between bus and auto use a challenge. Provided these and other similar questions regarding the addition of busses to an urban commuting model were researched and answered, addition of mass transit to a UEFM should certainly be possible.

## 2.1 Employment

Earnings, as well as the level and spatial distribution of city employment, are exogenous. Employment location is divided between the CBD where it is uniformly distributed, and the portion of the city where it shares land use with housing. Hours of work are assumed to be fixed for all workers. In the range where employment exists alongside housing, employment is distributed according to a negative exponential, which McMillen (2004) has demonstrated is a reasonable parameterization of the spatial distribution of employment outside the CBD. This gives total employment as

$$E = E_{CBD} + E_{SRD} = E_{CBD} + \int_{k_{CBD}}^{k_E} E(k_{CBD})e^{-gk}dk \tag{1}$$

Employment in the suburban residential district, $E_{SRD}$, is distributed from the edge of the CBD, $k_{CBD}$, to a maximum employment radius, $k_E$, following a negative exponential with density at the edge of the CBD of $E(k_{CBD})$ and a constant decay rate, $g$. The employment limit, $k_E$, rises in proportion to city size.

When city employment changes, an assumption must be made concerning the distribution of employment changes between CBD and SRD employment. In this model, the ratio of CBD and SRD employment does not change with city size. This is consistent with the empirical result that the employment density gradient does not vary with city size reported in Thurston and Yezer (1994).

## 2.2 Housing Production

Following customary practice in SUM models, housing is produced by developers in a perfectly competitive industry according to a CES production function with constant returns to scale.

$$H = A\left[\alpha_1 S^{\rho} + \alpha_2 L^{\rho}\right]^{1/\rho} \tag{2}$$

where $H$ is housing production, $S$ and $L$ are structure and land inputs, respectively, $\alpha_1$ and $\alpha_2$ are distribution parameters, and the elasticity of substitution is $1/(1-\rho)$. Again, following custom, the elasticity of substitution between structure and land inputs is set at 0.75 and a fixed fraction, $\theta$, of land in each annulus is available for residential development.[7]

## 2.3 Households

The household utility function is assumed to be CES for each of the N households in the city

[7] While the exact elasticity of substitution between structure and land inputs is debatable, it is known to be less than unity because the ratio of structure to land value falls as density rises toward the city center.

$$U = [\beta_1 y^\eta + \beta_2 h^\eta]^{1/\eta} \quad (3)$$

where $h$ is housing consumption, and $y$ is the numeraire consumption good. $\beta_1$ and $\beta_2$ are distribution parameters, and the constant elasticity of substitution between housing and the numeraire is given by $1/(1-\eta)$. Each household inelastically supplies $\epsilon$ workers with combined earnings of $w$.[8] Given values for $E$ and $\epsilon$, this gives the city size in terms of the number of households, $N = E/\epsilon$. A household's budget constraint is

$$w = y(k) + r(k)h(k) + \epsilon T(k) \quad (4)$$

where $T$ is the sum of both time and out-of-pocket commuting cost, $r$ is the rental price of housing services, $h$ is the quantity of housing services consumed, each varying with the distance from the center of the city.[9]

## 2.4 Commuting

All households either commute to the CBD via automobile with commuting costs $T(k)$ or commute costlessly without energy consumption to a job within their annulus in $t_L$ units of time. The no arbitrage equilibrium of urban households requires the standard urban labor market assumption that wages in employment outside the CBD fall with the saving in commuting cost. Thus local households earnings are $w_L(k) = w - \epsilon T(k)$.[10]

The velocity of automobiles commuting through an annulus is a positive function of the land fraction allotted to roads and is inversely related to the number of commuters. The congestion function follows the "Bureau of Public Roads" specification, which is widely adopted in the transportation literature. In this parameterization, velocity is a bounded nonlinear function

[8]In the current analysis, income from capital is ignored. Effectively, all of the housing and land rental payments that are not going towards energy use in the housing unit disappear from the model. This capital income effect would presumably increase energy consumption as housing and land prices rise, suggesting greater energy consumption in larger cities than in the model in this paper.

[9]Structure prices and the price of the numeraire good are assumed constant as city size changes within the simulation. In reality, both will increase with city size as the price of labor and non-tradeables rise, respectively (Balassa, 1964; Samuelson, 1964). The net result of these changes would be to shift the intensity of housing production to land; structure and numeraire good price increases would simply result in a higher wage given the reservation inter-regional utility assumption. On the other hand, larger cities may have a greater consumption amenity through variety (Glaeser, Kolko, and Saiz, 2001). The utility function and budget constraint in this paper implicitly assume that all of these effects are more or less offsetting.

[10]It should be noted that there is no public transportation in the model, the study of which is left for future research.

$$V(k) = \frac{1}{a + bM(k)^c} \tag{5}$$

where $M(k) = (\epsilon(N - N(k)) - E(k))/R(k)$ is the ratio of traffic volume to roads, and $a$, $b$, and $c$ are parameters that reflect the curvature of the function. The parameters $a$ and $b$ are defined such that the velocity at the edge of the CBD is $V(k_{CBD}) = v_{low}$ and the velocity at the edge of the city is $V(\kappa) = v_{high}$, where $v_{low}$ and $v_{high}$ are calibrated parameters. Parameter $c$ is also calibrated. $N(k)$ is the population living inside of radius $k$ and $E(k)$ is employment outside of radius $k$. $R(k)$ is exogenously and uniformly distributed as a constant fraction of land area.

Commuting costs include the fixed costs of owning a vehicle $m_0$, depreciation and maintenance costs related to the length of the commute $m_1 k$, fuel costs of travel, and the opportunity cost of time spent commuting. Miles per gallon, $G(V(k))$, is a function of vehicle velocity, and total fuel cost per mile is given by $p_g/G(V(k))$. The value of time spent commuting is a constant fraction, $\tau$, of household earnings. Therefore, the total cost of commuting from radius $k$ found in Equation 4 can be expressed as the fixed and constant marginal costs of commuting, and the integral of the nonlinear commuting cost of travelling through annulus $i$.

$$T(k) = m_0 + m_1 k + p_g \int_0^k \frac{1}{G(V(M(i)))} di + \tau w \int_0^k \frac{1}{V(M(i))} di \tag{6}$$

Because traffic congestion lowers $V(k)$, it raises commuting cost by increasing both fuel and time costs.

## 2.5 Solving the model

The model is solved numerically following the methods of Muth (1975), Arnott and MacKinnon (1977), Altmann and DeSalvo (1981), and McDonald (2009). Initialized wage and house price values at the edge of the CBD determine a house price gradient as a function of commuting costs. The other gradients for structure density, population density, and land rent follow recursively once commuting costs are determined.[11]

[11] As an illustration of the recursive nature, consider commuting costs at the CBD which are known. Substitution into the indirect utility function gives the house price $r(w - T(k_{CBD}))$. Further substitution into the first order condition of the housing production function gives the land price $p_L(r(w-T(k_{CBD})))$, and the first order condition of the utility function gives housing consumption $h(w-T(k_{CBD}), r(w-T(k_{CBD})))$. The structure/land ratio is then given as $q(p_L(r(w - T(k_{CBD}))), r(w - T(k_{CBD})))$, and population density is simply $D(w - T(k_{CBD})) = q(\cdot)/h(\cdot)$.

The result is a two-equation system of nonlinear differential equations

$$\begin{bmatrix} \frac{dT(k)}{dk} \\ \frac{dN(k)}{dk} \end{bmatrix} = \begin{bmatrix} m_1 + p_g \frac{1}{G(V(M(k)))} + \tau w \frac{1}{V(M(k))} \\ 2\pi\theta k D(T(k)) \end{bmatrix} \tag{7}$$

with initial values

$$\begin{bmatrix} T(k_{CBD}) \\ N(k_{CBD}) \end{bmatrix} = \begin{bmatrix} m_0 + k_{CBD} \left[ m_1 + p_g \frac{1}{G(v_{low})} + \tau w \frac{1}{v_{low}} \right] \\ 0 \end{bmatrix}$$

The first equation in the system gives commuting costs at radius $k$ from the center of the city. The second equation gives $N(k)$, the number of households locating inside radius $k$, where $D(k)$ is the density at $k$.[12] The solution of this system, along with the exogenous employment gradient, gives commuting costs and population for each annulus in the city. Having solved for commuting costs, the rest of the gradients are known.[13]

Two conditions must be met in order for the city to be in equilibrium. First, the price of land at the edge of the city must be equal to the agricultural reservation price of land per acre. This ensures land market equilibrium. If the land price is different than the reservation price, the CBD house price is re-initialized. Second, utility of households, computed based on commuting cost, wages, housing price, and the cost of the composite commodity, must be identical throughout the city and be equal to the exogenous utility level available elsewhere. If the utility of households is different than the regional reservation utility, the wage is re-initialized. If either value is re-initialized, then the entire simulation is re-computed.

## 2.6 Income Changes and Welfare Effects

Because a city size increase raises housing prices and/or commuting costs, the iso-utility condition requires an increase in wages paid by firms. This is a well-known stylized fact and has been modeled in numerical urban simulations by Timothy and Wheaton (2001).[14] In addition to this size effect on income, development policies that influence the cost of commuting and/or price of housing also require changes in earnings paid by firms, holding size constant. These income changes do not alter the utility level of households or the profit

[12] All annuli inside of $k_{CBD}$ have a constant commuting speed equal to $v_{low}$.

[13] The specific solution method for each variable is outlined in Larson, Liu, and Yezer (2012). The differential equations are solved using MATLAB's ODE45 solver.

[14] The model generates an urban wage gradient that falls with the savings in both time and out of pocket cost of commuting to the CBD.

level of firms in an open city because each household receives the inter-regional utility level and each firm receives zero economic profit. Instead, land owners, who own an immobile asset, face welfare effects of various city-level policy and market effects.

Although real income is held constant as city size increases, nominal income changes cause substitution among consumption goods. A standard result of the open city version of the standard urban model is that the price of housing increases while the price of the composite commodity remains constant, with a resulting drop in housing consumption on the Hicksian housing demand curve. This substitution has important implications for energy consumption patterns as city size changes.

Effects of city size changes are presented both under constant utility (necessitating income changes), and constant income (with resulting amenity changes) assumptions. This allows changes to be decomposed into those produced by the compensating variation in income and those that would arise if population were attracted into the larger city by an increase in amenity.

Standard methods for making welfare comparisons among cities have been developed in the literature. Following Sullivan (1985), increases in aggregate land rent and decreases in earnings needed to maintain household utility are counted as surplus for the social planner controlling the city. The change in land rent is based on an area large enough to include the developed area under the largest alternative considered. For example if the urbanized area is smaller under one alternative, then the agricultural land rent in the area not urbanized must be counted.

# 3 Modeling and Calculating Energy Use

Energy use is based on demand by households, and is modeled as three distinct types: (1) commuting energy in the form of gasoline ($E^C$), (2) in the dwelling in the form of electricity ($E^D$), and (3) in all other goods and services, which we term "numeraire" consumption ($E^N$). The UEFM is designed to generate information on commuting time and distance, amount of housing consumed, structure-land ratios, and earnings net of transportation and housing cost, each of which fit within the above energy consumption taxonomy. Energy consumption in each category is measured as the sum of final energy consumption and intermediate energy consumption in production and distribution. For a household at radius $k$, total energy consumption is the sum of each of these three categories.

$$E(k) = E^C(k) + E^D(k) + E^N(k) \tag{8}$$

Households who do not commute to the CBD and instead work locally have $E^C(k) = 0$. Total energy consumption in the city is therefore the integral of the density gradient multiplied by energy consumed by the average household at each annulus. The term $(N(k) - E(k))/N(k)$ is the fraction of households at radius $k$ who commute to the CBD.

$$E = \int_{k_{CBD}}^{\kappa} D(k) \left[ \frac{N(k) - E(k)}{N(k)} E^C(k) + E^D(k) + E^N(k) \right] dk \tag{9}$$

## 3.1 Energy Consumed in Commuting

Energy used in commuting by a household living in annulus $k$ who commutes to the CBD is given by

$$E^C(k) = E_g \int_0^k \frac{1}{G(V(M(i)))} di \tag{10}$$

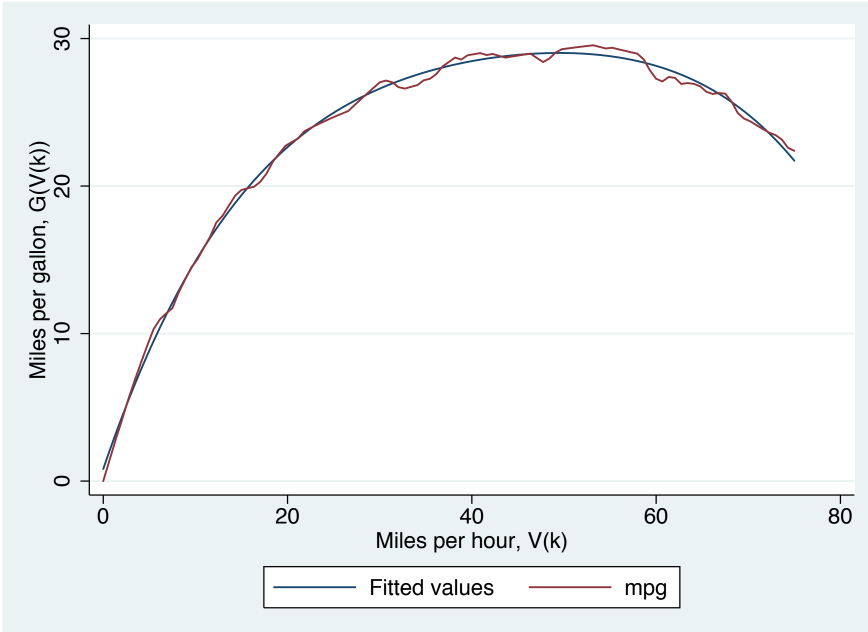
where $G(V(M(i)))$ is the gasoline consumption rate in miles per gallon, a function of vehicle velocity, which is in turn a function of the number of commuters transiting through annulus $i$. $E_g$ is the energy embodied in a gallon of gasoline in BTUs.

The function $G(V)$ is estimated using engineering relations, with the specific form of this function displayed in Figure 3 below.[15] It is assumed that each household in the city owns the same vehicle, and that vehicle is similar to an average vehicle in the U.S. fleet described by West et al. (1999), who conducted an automobile fuel efficiency study at the Fuels, Engines, and Emissions Research Center at the Oak Ridge National Laboratory. Using this fleet, they established the velocity-fuel economy relation shown in Figure 2.[16]

[15] Acceleration/deceleration also affect fuel economy, but for simplification, it is assumed that fuel consumption is only related to velocity.

[16] Anas (2011) also finds that maximum fuel economy is between 40 and 45 miles per hour.

Figure 2: Velocity-Fuel Efficiency Relation




This function maps vehicle velocity to gasoline consumption, and assuming fully petroleum-based gasoline (125,000 BTUs per gallon), gives energy consumed while commuting through each annulus.[17] The Energy Information Administration publishes a petroleum refining and distribution parameter in the Federal Register (2000) that is meant to be multiplied by intermediate energy consumption to arrive at a final use measure: *End Use Energy* = *Total Energy* × *Efficiency Parameter*. Dividing end-use energy consumption by the efficiency parameter gives the total energy consumed in the production, distribution, and final consumption. For gasoline, this parameter is equal to 0.83, giving $E_g = 150,602$ BTUs of energy consumption per gallon.

## 3.2 Energy Consumed in Dwellings

The calculation of dwelling energy consumption is somewhat more complicated. Three major factors determine dwelling energy consumption: income of the household, the square feet

[17] The equation is a 4th degree polynomial:

$$miles\ per\ gallon = .822 + 1.833v - .0486v^2 + .000651v^3 - .00000372v^4$$

of interior space, and structure type.[18] An empirical model of energy demand using the 2005 Residential Energy Consumption Survey (RECS) provides estimates of 0.23 for the partial elasticity of household energy consumption with respect to interior space and 0.07 for the income elasticity. The own-price elasticity of demand for energy is estimated as -0.75. Single-family attached dwellings consume 7% less energy than single-family detached units. Multi-family units lower energy consumption 31% compared to single-family detached (see Larson, Liu, and Yezer, 2012). In the model, structure type is a function of the structure-land ratio $s(q(k))$, where $q(k) = H(k)/L(k)$.[19]

Energy consumption within households comes entirely from electricity. It is known from the RECS that households that have only electricity available consume less energy than those that have access to natural gas, kerosene, and/or heating oil. However, when considering the full chain of production, distribution, and final energy use, the total energy content of electricity generated from fossil fuel is similar to that of fossil fuels consumed in the home.[20] There are two electricity efficiency parameters. The efficiency parameter for fossil fuel electricity production is 0.328, and the efficiency parameter for electricity transmission is 0.924 (Federal Register, 2000). Final electricity demand is multiplied by the inverse of the product of these two measures, $E_e = 1/0.303$ to arrive at total energy consumption in dwellings.

$$E^D(k) = E_e \exp\left[\alpha_1 + \alpha_2 \ln w + \alpha_3 \ln p_e + \alpha_4 \ln h(k) + s(q(k))'\gamma\right] \tag{11}$$

## 3.3 Numeraire Energy Consumption

For the numeraire good, the overall energy intensity of the U.S. economy is used. Energy intensity is defined as the U.S. GDP/energy consumption ratio produced by the Energy Information Administration (2011). This is a rough measure of the energy content of a consumption good, but it serves to represent all intermediate inputs in the production of consumption goods, including raw materials, intermediate product, final production, transportation, distribution, etc. The inverse of the energy intensity gives energy consumed per dollar of GDP, which in 2010 was 7,470. Each dollar of numeraire consumption in the sim-

[18] There are many other factors that affect energy consumption, such as temperature, fuel type, and the age of the housing unit, but housing consumption, income, and structure type are the only variables that change within the energy footprint model.

[19] Structure types represented by values of $q$ are calibrated with respect to the data to give $q_2 = 0.5$, $q_1 = 0.6$, and $q_0 = 0.7$ as cutoffs between single-family detached, single-family attached, 2-4 unit multifamily, and 5+ unit multifamily, respectively.

[20] The obvious exception is non-fossil fuel generated electricity, where efficiency metrics are much different.

ulation model is therefore estimated to be associated with $E_N = 7,470$ BTUs of energy consumption.[21] Numeraire energy at annulus $k$ is therefore equal to earnings net of expenditures on gasoline and electricity multiplied by the inverse energy intensity parameter.

$$E^N(k) = E_N \left( w - p_g E^C(k)/E_g - p_e E^D(k)/E_e \right) \tag{12}$$

# 4 Model Parameter Calibration

The standard method of calibrating a numerical urban simulation model is to first select a city or group of cities as calibration targets. Parameters come from the established literature on housing production and consumption relationships, engineering relationships concerning fuel use and energy content of vehicles at various speeds, and pure calibration when no guidance is given from any of the previous sources.

Because this is the first open city model to attempt to simulate a doubling of city size, there are some special issues of calibration not confronted previously. The model is first calibrated to a city size of 1 million and then allowed to simulate a city of 2 million with the same homogeneous household type. When this is done, it is anticipated, *a priori*, that the simulated city of 2 million will depart in a systematic fashion from an actual city of 2 million.[22]

The most important difference occurs because the relative price of housing rises with city size. Larger cities attract households for which housing consumption is a relatively smaller fraction of total expenditure for two main reasons. First, higher housing prices select smaller households as noted in Black et al. (2002). Second, the fact that the income elasticity of demand for a primary residence is less than unity means that skill intensity of the population (ratio of more to less educated workers) rises with city size. A crucial feature of the simulation is that household type is held constant, because different household types consume energy in different amounts. Therefore, it is anticipated that when city size is doubled in the simulation, the housing consumption increase observed in actual cities will be slightly larger than that which is generated by the simulation where household size and education are held constant.[23] The house price effect on skill intensity also means that the

[21] Expenditures for non-gasoline commuting costs ($m_0 + m_1 k$) and non-energy dwelling costs are assumed to have the same energy content as the numeraire goods for purposes of computing energy consumption.

[22] Rappaport's (2014) results show that a model calibrated to an initial population size of 2 million can, by varying wages paid in the CBD, simulate cities ranging from about 500,000 to 4 million.

[23] The relation between city size, house prices, and skill level is discussed in detail in Kim, Liu, and Yezer (2009).

increase in median income in actual cities will exceed that in the simulation model.

Another difference is that the rise in city radius with size in the simulation will be smaller than the actual increase in simulation. As has been reported in Altmann and DeSalvo (1981), this is also a product of restricting the model to homogenous households. In evaluating the final model calibration exercise, it is important to recall that it is expected *a priori* that maintaining a homogenous household type will cause systematic differences in the relation between the actual effects of doubling city size and the simulated effect of a well calibrated model. However, because this is a first attempt to simulate open cities of different sizes, calibration issues may differ from those encountered previously in the literature.

## 4.1 Calibration Targets

Target outputs from the model are based on a composite of five cities each with population of approximately 1 million and another group of five cities with population of 2 million. Cities are defined as the sum of the principal cities within a CBSA. Principal cities are used instead of CBSAs in order for the simulation to reflect the main urban areas and close suburbs in a city while excluding the outer suburbs and rural satellite counties. Composite cities are used instead of empirical city size relations because of the small number of cities with large enough populations.[24] Cities are selected for geographic diversity in order for the samples to represent a plausible average of a city of a given size. Because there are substantial quality of life differences among cities, cities are selected so that the mean quality of life rank taken from Albouy (2009) for the five smaller cities matches that for the larger cities. Finally, cities with substantial topographical impediments to uniform development are avoided when possible.

Characteristics of the five-city composites for both the 1 million and 2 million population cities can be seen in Table 1. While there is significant diversity among cities of a given size, the average characteristics are consistent with expectation based on the standard urban model of what happens when the population increases from about 1 million to 2 million.[25]

The footprint of the city increases from 369 to 591 square miles, median income rises from 49,000 to 52,000, structures become denser, with the share single-family detached dwellings

[24] In the 2011 American Community Survey (ACS), there are 30 MSAs with a number of principal city households greater than 300,000.

[25] It is difficult to find cities with 2 million people that are not interrupted in some way (e.g. San Francisco and Chicago). This is, in a sense, the *raison d'etre* of the simulation approach in the paper. It may also be possible to calibrate with respect to a smaller basket (e.g. Phoenix and Houston), but a smaller number of calibration targets exacerbates other city-specific attributes. The 5-city average, by chance, ends up quite similar to the city of Phoenix, a city with low development regulation and few topographic interruptions.

falling from 57% to 49%, individual units become smaller, falling from 1,548 to 1,513 square feet, and average commute times rise from 24.4 minutes to 28.5 minutes.[26]

### 4.2 Calibration Parameters

Parameters follow the established literature on cities and numerical urban simulations, as well as from well-established relationships in the physical sciences. Parameter notation, values, and notes are shown in Table 2. Housing production function parameters are all from the literature with the exception of the production technology parameter $A$, which is calibrated to fit the target cities. CES share and elasticity parameters for both the housing production and utility functions are based on Muth (1975) and Altmann and DeSalvo (1981).

The fraction of land used for housing is 25%, which is both common in previous simulation models and very important in this simulation because the floor-area ratio in housing is a major determinant of energy use per square foot of interior space.[27] Land used for employment is based on a fixed ratio of one worker per thousand square feet of land. Three quarters of all employment is located in the CBD. The small-city baseline CBD radius is 1 mile.

Single-family detached units' 90th percentile structure-land area ratio is 0.45 in the 2011 American Housing Survey (AHS). Based on this value, the cutoff for such units in the simulation is set to be 0.5 versus single-family attached. No land measures are given for non-single-family detached units, so cutoff parameters must be calibrated, and are set at 0.6 and 0.7 for 2-4 and 5+ unit apartments, respectively.

### 4.3 Calibration Results

Calibration results obtained by simulating the model to accommodate households totaling 440,000 and 880,000, corresponding to populations of 1 and 2 million respectively, are reported in Tables 1 and 3. The growth in city size for this baseline calibration is assumed to be due exclusively to wage increases because according to the quality of life measures in Albouy (2009), the composite cities used in the calibration are of similar amenity level. The differences between actual and simulated values agree well with expectations. Constraining

[26]This commuting result is consistent with Anas (2011), who find that a doubling of MSA employment results in an increase of commute times of 10%.

[27]It is common to see values ranging from 1/4 to 2/3 of urban land dedicated to housing in the literature. This variation is primarily due to the treatment of roads, which are often included in the fraction of land to housing, and missing land due to interrupted development. Here, land and roads are treated separately.

households to be identical is known to produce a smaller simulated city radius. Because household composition is uniform and constant, actual values for a city of 2 million are expected to depart slightly and systematically from the simulated values. In all cases, these differences are observed. Specifically, the fall in housing unit size is larger and the rise in median income smaller in the simulation than for the actual cities because the skill intensity ratio rises endogenously with city size. For similar reasons, the rise in density of housing in the simulated scenario is larger than observed in reality. This illustrates why use of actual data on changes associated with city size can yield false conclusions regarding the true size effect due to the confounding influence of household composition effects.

The elasticity of time to work with respect to city size in the sample of actual cities is 0.15 and this is slightly smaller than the simulated value of 0.16. However, this is a case in which the sample of actual cities has, for some reason, an unusually high elasticity of travel time. Anas (2011) has recently estimated the elasticity of travel time with respect to size for a large number of U.S. cities at 0.11. It appears that the simulated value of travel time elasticity lies between these two possible standards for the actual value.

Some additional variation between the UEFM simulation and actual cities is to be expected due to the effects of zoning and land use planning which causes actual cities to depart from the unregulated market solution. Despite this and the other potentially confounding factors noted previously, overall, the agreement between the simulated cities and actual mean values for the reference cities is close and the differences are in the direction anticipated for a model in which population is homogeneous as city size increases.

The general spatial characteristics of the simulated city are displayed in Figure 3, which shows baseline simulations for cities of 440,000 and 880,000 households. These functions are consistent with both stylized facts and previous simulation models, with the exception of vehicle velocity, which is a highly non-linear function of distance from the CBD rather than constant as in most other simulations.[28] Increasing city size raises the house price, household density, commuting time, and structure density functions, and lowers the lot size, and housing consumption functions. Density gradients can be parameterized as an exponential function $y(k) = y(0)e^{-\lambda k}$, where $k$ is the distance to the CBD and $\lambda$ is the decay parameter. Estimates of $\lambda$ using simulation output gives $\lambda$s equal to -0.04 for house prices, -0.31 for structure density and -0.34 for population density. Because the model has only one

[28]The fact that employment is distributed outside the CBD does not change the classic form of the house price, land rent, structure density, and population density gradients, because outside the CBD, the density of employment is never greater than the housing density. Therefore, some residents of each annulus outside the CBD commute to the CBD and Muth's equation holds outside the CBD.

income group, density functions are steeper than would be the case with multiple income groups. Nevertheless, the baseline population density gradient is consistent with estimates found in Macauley (1985).

The spatial pattern of energy consumption is displayed in Figure 4. Jumps in the function relating energy use in dwellings are due to the discrete changes in type of unit (single-family detached, to attached, to low-density multifamily, to high-density multi-family) density associated with changes in the structure-land ratio. Both the residential energy use equations estimated to support the UEFM and previous literature, including controlled experiments on households, have demonstrated that the discrete switch from detached to semi-detached to multifamily units is associated with a significant discrete shift in energy use. The gentle positive slope between jumps is due to the effect of increasing unit size on energy consumption. Jumps in consumption of energy due to changes in the numeraire good or composite commodity are due to the implications for the household budget of shifts in energy consumption as structure type changes.

# 5 Simulation Results and Implications

The effects of changing city size, whether due to variation in amenity or wages, are considered in a number of contexts. Simulations are first performed assuming a laissez-faire land market, before moving on to the effects of density limits and greenbelts. Overall, scenarios are designed to isolate the effects of various city attributes on urban form and energy consumption as city size increases.

## 5.1 City Size Effect with Unregulated Density

In this particular scenario, city size is doubled from 440,000 households (approximately 1 million people) to 880,000 households (two million people). The UEFM allows this "pure" size effect on energy consumption to be accomplished in two ways, rising wages or amenity. The consequences of varying the cause of city growth for the relation between city size and per capita energy use as well as other city characteristics are significant.

### 5.1.1 Wage-driven city size increase

The effects of doubling population by raising wages and holding amenity and utility constant are presented in Table 4. It is necessary to increase earnings by 2.4% to attract an additional

440,000 households to the city. Average density rises by 36% with the population increase.[29] The two characteristics most related to energy use, commuting time to work and fraction housed in 5+ unit structures, both rise with city size. Of course these variables have opposite effects on energy consumption and the net effect on energy use is based on the difference in changes associated with size.

Considering only commuting and dwelling energy utilization, there is a 2.6% fall in energy use, for a nominal wage - energy consumption "elasticity" of -1.08.[30] However, the increase in consumption of the numeraire associated with the compensating rise in income net of housing and commuting expenditure implies additional energy consumption of 2.2% (wage elasticity of 0.90). The net effect of these two effects is an increase in energy use of 0.1% (wage elasticity of 0.03), so the energy implication of substituting one city of two million for two cities of one million, when households are fully compensated for the change, is essentially zero. As Table 5 shows, this result is notably robust to changes in simulation parameters. While the level of energy use varies substantially with parameter values, the partial effect of variation in each parameter leaves the simulated city size elasticity of energy use very close to unity.

This finding of no city size effect on per-capita energy consumption when household utility is constant and households are indifferent about the change in city size may appear counterintuitive. One reason that this result is surprising is that energy use other than housing and commuting is usually ignored.

### 5.1.2 Amenity-driven city size increase

The UEFM can also show effects of city growth achieved through an increase in a city-wide, non-spatial amenity. Each household receives the benefits of this amenity equally, and the amenity is expressed as a flow rate in currency units. This amenity effectively lowers the required utility generated by private earnings and consumption. Table 6 contains the results of a scenario in which population doubles by introducing utility from amenities with wages held constant. The city of 1 million is identical to Table 4 and hence the change associated with amenity-driven growth is based on comparing the results for cities of two million. The amount of amenity required to double the city size is $1,061 million per year, or about $1,200 per household per year. Comparing the large city results in Table 6 with those in Table 4 is

[29] Specifically, average density increases from 1,281 to 1,737 households per square mile where households occupy land.

[30] This elasticity is different than the traditional notion of an income elasticity because relative prices and the overall price level in the city change.

facilitated by the final column of Table 6 where differences between city characteristics under amenity-driven growth less those for wage-driven growth are listed. Under amenity-driven growth, the city is more dense, occupies less land area, has shorter commuting time and smaller housing units. Per household energy used in commuting now only rises 16.3% rather than 17.8% while dwelling energy use falls 7.4% rather than 6.4%. Finally the sign of the change in numeraire good consumption is reversed as the higher house prices and unchanged income cause a reduction in non-housing consumption. Accordingly the change in city size is associated with a significant 2.1% fall in per-household energy consumption.

## 5.2 Increasing Density with a Greenbelt

The greenbelt proposal considered here involves prohibiting urban development beyond a given radius. The greenbelt is placed at a radius of nine miles and is binding for both the medium and large cities.[31] This allows analysis of the effects of more or less binding greenbelts as well as issues that could arise as a city grows into an increasingly binding greenbelt restriction.

Before discussing the simulation results it is important to consider market failures in the baseline city. Roads are provided without tolls or fees. Indeed, there is no attempt to relate road capacity to benefits and costs.[32] There is substantial congestion in these cities as evidenced by the travel velocity function. Congestion increases with city size because of rising number and length of commuting trips while land used for highways at any radius is fixed. As first demonstrated by Muth (1975), a system of congestion tolls based on marginal congestion cost would substantially increase urban densities. Accordingly, the greenbelt, by raising residential densities, can be a second best reaction to the market failure caused by the lack of highway pricing in the baseline model.

Comparing the baseline with the greenbelt simulation results for each city size category in Table 7, it is clear that the effects on the larger city are substantial because the greenbelt regulation is more binding.[33] The effect on overall energy consumption in the smaller city is negligible. This is in part due to the compensating variation in income which raises consumption of the numeraire good. Even in the case of the larger city where the greenbelt has

[31] Both the addition of a greenbelt and the implementation of height limits considered in the next section may have a direct effect on the utility of city residents. This direct amenity effect is not included in the welfare calculations presented here.

[32] This may be a fair description of the way urban roads are provided in the real world. In the UEFM simulations, it would be possible to vary road capacity with opportunity cost of the land and benefits from congestion reduction as well as to simulate the effects of congestion charges.

[33] A greenbelt at 9 miles reduces radius about 14% for the smaller city and 30% for the larger city.

a substantial effect on density, housing consumption, and commuting time, the decline in overall per-household energy use is only about 1.1% because the compensating variation in income raises energy consumption embodied in the composite commodity by approximately 0.7%. Taken together, these changes suggest that the effects of a greenbelt on energy consumption, as city size changes, are rather small. On the other hand, the nominal wage - energy consumption elasticities change substantially in the greenbelt scenario. The elasticity with respect to commuting and dwelling energy consumption increases in magnitude to -2.68 compared to -1.08 in the baseline; the elasticity with respect to numeraire energy rises to 1.33 from 0.90; and the elasticity with respect to total energy changes sign and increases in magnitude from 0.03 to -0.40. The economic interpretation of this total wage-energy elasticity in a greenbelt-constrained city is remarkable, suggesting a 10% increase in earnings will cause a 4% drop in per-household energy consumption once the city has grown to its new equilibrium size.

The welfare analysis of the greenbelt policy at the bottom of Table 7 produces what may appear to some to be a remarkable result. For both city sizes, the compensating variation in earnings associated with the greenbelt is positive. However, the rise in land rent, including both developed residential land and the agricultural land included in the greenbelt that would have been developed in the absence of regulation, is substantial. This results in a net welfare change associated with imposition of greenbelt regulation that is positive in the small city but negative in the large city. The amounts are not large, $14 per year per capita for the smaller city and -$26 per year per capita in the large city, but the fact that a greenbelt can increase welfare at all in an otherwise laissez-faire city is worthy of some discussion. Clearly this is a case of the theory of the second best in which, given the failure to price transportation congestion, the baseline city is too large and not sufficiently dense. As the city grows, however, the greenbelt, having a fixed radius, becomes ever more restrictive, tipping the city into welfare loss. Comparing energy use in Tables 4 and 7, the greenbelt has a significant effect on energy consumption per household. Energy use falls 0.5% in the small and 1.7% in the larger city where the greenbelt is more binding.

## 5.3 Decreasing Density with a Height Limit

Effects of the other most common density regulation, a building height, structure density, or floor area ratio regulation, are displayed in Table 8. This type of regulation, sometimes referred to as residential down-zoning, can be imposed anywhere in the city. For purposes of this simulation exercise, the height limit is made uniform across the city and it is only binding in the central area. The limit is identical across city sizes and hence it is more binding in the larger city. Thus, Table 8 gives some insight into the effects of city size and of more or less binding height limits.

Overall, the height limit has negligible effects on the smaller city but consequences for the larger city are significant. A binding height limit or floor area ratio increases city radius and housing consumption, raises housing prices, and increases commuting time versus the baseline simulations in Table 4. Most important, the height limit requires a substantial compensating variation in earnings needed to induce workers to live in the city. Comparing energy consumption in the smaller city with that in the larger city where the height limit is more binding, there is now a small increase in energy consumption associated with city size of 0.4%, with a nominal wage-energy consumption elasticity of 0.14. Holding size constant, imposition of a binding height limit in a large city raises energy consumption in both commuting and dwellings while the numeraire good is essentially constant. Therefore the partial effect of a binding height limit on a city is to increase energy consumption significantly.[34]

Welfare analysis of the height limit for the small and large city shows that there is a substantial compensating variation in earnings required and the rise in rents on urban land is partially offset by the fall in agricultural land as the city spreads. The annualized net welfare effect for the small city where the limit is barely binding is negative but small, -$2 per year per capita, while that for the large city where the limit is significantly binding is substantial, -$11 per year per capita. Given that the height limit has negative welfare effects and raises energy consumption in these simulation results, its economic rationale would necessarily lie in some aesthetic gain from urban form that is omitted from the UEFM.

# 6 Conclusions

The goal of this paper is to demonstrate that an open city simulation model with a single parameterization can simulate cities of different size with homogenous population, industrial composition, topography, and technology. Growth in city size can be generated either by altering wages or changing the city amenity. In addition to usual features, such a model must have endogenous congestion of transportation systems because this is an important characteristic of changing city size. The simulation model holds household preferences and composition constant as city size increases. This is an important advantage of the simulation

[34]These findings echo recent work by Borck (2014), who considers a closed city with no numeraire energy accounting and still finds that under any reasonable case, a height limit increases citywide energy consumption.

because differences in actual cities confound pure effects of size with changes in population characteristics associated with size. Considering this, the model is quite effective in replicating the characteristics of cities over the 1 to 2 million population range. The model has a further advantage of facilitating computation of the welfare implications of alternative patterns of urban development.

While this type of urban simulation model is potentially valuable in studying a variety of issues, the relation between city size and energy consumption is illustrated here. This is a challenging application because energy use varies with vehicle velocity in commuting, so that commuting distance and time are both important, and the precise density of structures matters. Direct empirical estimation of the effect of city size on energy use is hampered by the modest number of large cities available, the quality of data on aggregate energy use, and the substantial heterogeneity of larger cities along a number of dimensions.

The final result of the inquiry into energy implications of city size is surprising and remarkably simple: if growth size is due to wage change, the elasticity of energy consumption with respect to city size is approximately unity but, if the growth is driven by differences in amenity, per capita energy use falls modestly. While these results contrast with much of the empirical literature on density and energy use, there are seeds of them found elsewhere in the literature. For example, Gaigne, Riou, and Thisse (2012) theoretically demonstrate that it is possible for households in larger cities to consume more energy than households in smaller cities, and Glaeser and Kahn (2012) notably express the desire to undertake a full energy accounting of consumption, rather than focusing only on commuting and dwelling energy consumption, but leave this endeavor for further research.

The ability to model both the welfare and energy use implications of specific urban development policies is illustrated by considering greenbelts and residential height limits. First, density increases through a binding greenbelt can achieve very modest reductions in energy use per capita, and perhaps counterintuitively, can increase city welfare, where welfare is defined as the change in aggregate land value minus the total change in the cost of the compensating wage differential. Second, height or density limits raise energy consumption per capita and unambiguously lower welfare.

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Table 1: Calibration Cities

**Calibration: Large Cities**

| CBSA Code | CBSA Name | Area (sq. mi.) | Population | Housing units | Median Income | Units/ sq. mi. | S.F. Detached | S.F. Attached | 2-4 Units | 5+ Units | Avg. Commute | QOL Rank* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19820 | Detroit | 400 | 1,453,257 | 668,183 | 43,409 | 1,671 | 67% | 7% | 9% | 18% | 25.8 | 217 |
| 41860 | San Francisco | 350 | 2,181,589 | 924,550 | 69,248 | 2,639 | 36% | 11% | 16% | 36% | 29.6 | 4 |
| 26420 | Houston | 761 | 2,354,020 | 1,003,954 | 44,269 | 1,319 | 48% | 5% | 6% | 41% | 27.2 | 268 |
| 38060 | Phoenix | 937 | 2,490,498 | 1,079,290 | 51,820 | 1,152 | 60% | 6% | 7% | 27% | 26.2 | 72 |
| 16980 | Chicago | 504 | 3,572,223 | 1,542,968 | 51,264 | 3,060 | 33% | 5% | 27% | 35% | 33.6 | 81 |
| AVERAGE | | 591 | 2,410,317 | 1,043,789 | 52,002 | 1,968 | 49% | 7% | 13% | 31% | 28.5 | 128 |

**Calibration: Small Cities**

| CBSA Code | CBSA Name | Area (sq. mi.) | Population | Housing units | Median Income | Units/ sq. mi. | S.F. Detached | S.F. Attached | 2-4 Units | 5+ Units | Avg. Commute | QOL Rank* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28140 | Kansas City | 515 | 778,945 | 360,109 | 49,001 | 700 | 64% | 7% | 7% | 22% | 22.3 | 184 |
| 38900 | Portland | 223 | 926,981 | 410,431 | 49,682 | 1,845 | 56% | 6% | 10% | 29% | 25.1 | 37 |
| 19740 | Denver | 341 | 981,125 | 439,483 | 48,237 | 1,290 | 50% | 9% | 6% | 36% | 27.0 | 26 |
| 41700 | San Antonio | 505 | 1,385,147 | 547,627 | 43,586 | 1,085 | 66% | 3% | 7% | 24% | 24.6 | 188 |
| 33460 | Minneapolis | 264 | 995,852 | 441,488 | 56,124 | 1,674 | 49% | 8% | 10% | 33% | 23.3 | 174 |
| AVERAGE | | 369 | 1,013,610 | 439,828 | 49,326 | 1,318 | 57% | 6% | 8% | 29% | 24.4 | 121 |

*:Adjusted quality of life from Albouy (2009)

Table 2: Simulation Parameters

| Parameter | Baseline | Description | Source |
|---|---|---|---|
| $1/(1-\rho)$ | 0.75 | Elast. of substitution in the housing prod. function | Altmann and DeSalvo (1981) |
| $\alpha_1$ | 1.1 | Structure share parameter in housing production function | Muth (1975); Altmann and DeSalvo (1981) |
| $\alpha_2$ | 0.9 | Land share parameter in housing production function | Muth (1975); Altmann and DeSalvo (1981) |
| $A$ | 0.32 | Housing production technology parameter | Calibrated |
| $1/(1-\eta)$ | 0.75 | Elasticity of substitution in the utility function | Altmann and DeSalvo (1981) |
| $\beta_1$ | 1 | Numeraire share parameter in utility function | Numeraire |
| $\beta_2$ | 0.1056 | Housing share parameter in utility function | Altmann and DeSalvo (1981) |
| $p_L^a$ | 500 | Reservation agricultural price per acre of land | Bertaud and Brueckner (2005) |
| $\theta$ | 0.25 | Fraction of land used for housing | Muth (1975) |
| $\theta_R$ | 0.25 | Fraction of land used for roads | Muth (1975) |
| $E(k_{CBD})$ | 13000 | Density of employment at the center of the CBD | Calibrated |
| $g$ | 0.4 | Exponential in the employment density gradient | McMillen (2004) |
| $E_{CBD}/E$ | 0.75 | Fraction of households commuting to the CBD | ACS(2011) |
| $k_{CBD}$ | 1 | Small city radius of the CBD | Calibrated |
| $t_L$ | 12 | Time of commute for local workers | ACS (2011) |
| $v_{low}$ | 5 | Minimum commuting speed | Muth (1975) |
| $v_{high}$ | 45 | Maximum commuting speed | Muth (1975) |
| $c$ | 1.75 | Curvature parameter in speed function | Muth (1975) |
| $\tau$ | 0.5 | Time cost of commuting (fraction of wage) | Bertaud and Brueckner (2005) |
| $p_g$ | 3.5 | Gasoline price per gallon | EIA (2011) |
| $p_e$ | 0.12 | Electricity price per kwh | EIA (2011) |
| $m_0$ | 2123 | Fixed cost of commuting | American Automobile Association (2007) |
| $m_1$ | 0.222 | Dollars of depreciation per mile | American Automobile Association (2007) |
| $\bar{U}$ | 15500 | Reservation utility | Calibrated |
| $q_0$ | 0.7 | 5+ unit building floor-area ratio cutoff | Calibrated |
| $q_1$ | 0.6 | 2-4 unit building floor-area ratio cutoff | Calibrated |
| $q_2$ | 0.5 | sf. attached floor-area ratio cutoff | AHS (2011) |

Note: Values are approximate to those from the cited source.

Table 3: Simulation Calibration

| Variable | Small City Actual | Small City Simulated | Large City Actual | Large City Simulated |
|---|---|---|---|---|
| Lot Size (acre) – Occupied Units[1] | 0.278 | 0.190 | 0.250 | 0.183 |
| Unit (square feet) – Occupied Units[1] | 1,548 | 1,560 | 1,513 | 1,514 |
| Area (sq. miles)[2] | 369 | 346 | 591 | 511 |
| Radius (assuming circle)[2] | 10.8 | 10.5 | 13.7 | 12.8 |
| Median Income[2] | $49,326 | $49,924 | $52,002 | $51,147 |
| Total Occupied Units[2] | 439,828 | 440,000 | 1,043,789 | 880,000 |
| Time to work[2] | 24.4 | 23.6 | 28.5 | 27.4 |
| Fraction housed in 1 unit structures[2] | 57% | 54.0% | 49% | 36.4% |
| Fraction housed in 2-4 unit structures[2] | 14% | 21.2% | 20% | 17.0% |
| Fraction housed in 5+ unit structures[2] | 29% | 24.8% | 31% | 46.5% |
| Energy consumed in dwelling, per capita (mmBTUs)[3] | 49.84 | 42.59 | * | 39.85 |

[1] Source for actual values: AHS (2011)

[2] Source for actual values: ACS (2010)

[3] Source for actual values: RECS (2009) households with 100% electricity consumption

* Energy consumption per dwelling is not given in the RECS by city size, so it is presented here only for the small city.

Table 4: Effects of Growth Due to Wage Changes in a Laissez-Faire City

| Variable | Small City | Large City | Difference | Size Elasticity |
|---|---|---|---|---|
| *Urban Form* | | | | |
| Total Occupied Units | 440,000 | 880,000 | 440,000 | |
| Lot Size (acre) – Detached Units | 0.190 | 0.183 | -0.007 | -0.036 |
| Unit (square feet) – All Units | 1,560 | 1,514 | -46 | -0.030 |
| City Area (sq. miles) | 346 | 511 | 165 | 0.475 |
| City Radius (assuming circle) | 10.5 | 12.8 | 2.3 | 0.214 |
| Residential Struct./Land ratio (CBD) | 1.20 | 1.69 | 0.49 | 0.405 |
| Residential Density (hh per sq. mile) | 1,281 | 1,737 | 456 | 0.356 |
| Time to work | 23.6 | 27.4 | 3.9 | 0.164 |
| Fraction housed in 1 unit structures | 54.0% | 36.4% | -17.6% | -0.326 |
| Fraction housed in 2-4 unit structures | 21.2% | 17.0% | -4.1% | -0.195 |
| Fraction housed in 5+ unit structures | 24.8% | 46.5% | 21.7% | 0.875 |
| *Income/Expenditure Accounting* | | | | |
| Base Income | $ 49,924 | $ 51,147 | $ 1,223 | 0.024 |
| Numeraire Expenditure | $ 36,782 | $ 37,212 | $ 430 | 0.012 |
| Housing Services Expenditure | $ 9,885 | $ 10,113 | $ 228 | 0.023 |
| Housing Expenditure | $ 8,387 | $ 8,712 | $ 324 | 0.039 |
| Dwelling Energy Expenditure | $ 1,498 | $ 1,401 | $ -96 | -0.064 |
| Commuting Gasoline Expenditure | $ 758 | $ 893 | $ 135 | 0.178 |
| Income Reductions* | $ 2,499 | $ 2,929 | $ 430 | 0.172 |
| *Total Energy Consumption (billion BTUs)* | | | | |
| Commuting | 11,478 | 27,045 | 15,567 | 1.356 |
| Dwelling | 61,831 | 115,706 | 53,874 | 0.871 |
| Commuting and Dwelling | 73,310 | 142,751 | 69,441 | 0.947 |
| Numeraire | 94,181 | 192,499 | 98,318 | 1.044 |
| Total | 167,491 | 335,250 | 167,760 | 1.002 |
| *Energy Consumption per Household (million BTUs)* | | | | |
| Commuting | 26.1 | 30.7 | 4.6 | 0.178 |
| Dwelling | 140.5 | 131.5 | -9.0 | -0.064 |
| Commuting and Dwelling | 166.6 | 162.2 | -4.4 | -0.026 |
| Numeraire | 214.0 | 218.8 | 4.7 | 0.022 |
| Total | 380.7 | 381.0 | 0.3 | 0.001 |
| *Welfare Accounting* | | | | |
| Total Wages ($m) (-) | $ 21,966 | $ 45,009 | $ 23,043 | 1.049 |
| Residential Land Rent ($m) (+) | $ 438 | $ 1,003 | $ 565 | 1.292 |
| Agriculture Land Rent ($m) (+)** | $ 115 | $ 63 | $ -53 | -0.457 |

* Consists of time-cost of commuting and reduced income from non-CBD employment
** Measured up to a 15 mile radius

Table 5: Parameter Sensitivity of Wage Change Effects in Laissez-Faire City

**Baseline Per-Capita Energy Estimate (million BTUs):** Small: 380.75; Large: 381.06; Elasticity: 1.0008

| Parameter | Baseline | Description | *Per-capita energy use when parameter in row is increased by 10%* | | |
|---|---|---|---|---|---|
| | | | Small City | Large City | Elasticity |
| $1(1-\rho)$ | 0.75 | Elast. of substitution in the housing prod. function | 393.37 | 393.16 | 0.9995 |
| $\alpha_1$ | 1.1 | Structure share parameter in housing production function | 393.35 | 393.84 | 1.0012 |
| $\alpha_2$ | 0.9 | Land share parameter in housing production function | 384.93 | 385.34 | 1.0011 |
| $A$ | 0.32 | Housing production technology parameter | 375.37 | 375.83 | 1.0012 |
| $1/(1-\eta)$ | 0.75 | Elasticity of substitution in the utility function | 567.75 | 569.52 | 1.0031 |
| $\beta_1$ | 1 | Numeraire share parameter in utility function | - | - | - |
| $\beta_2$ | 0.1056 | Housing share parameter in utility function | 399.46 | 399.89 | 1.0011 |
| $p_L^a$ | 500 | Reservation agricultural price per acre of land | 380.67 | 380.99 | 1.0008 |
| $\theta$ | 0.25 | Fraction of land used for housing | 381.07 | 381.17 | 1.0003 |
| $\theta_R$ | 0.25 | Fraction of land used for roads | 382.58 | 383.23 | 1.0017 |
| $E(k_{CBD})$ | 13000 | Density of employment at the center of the CBD | 380.74 | 381.08 | 1.0009 |
| $g$ | 0.4 | Exponential in the employment density gradient | 380.72 | 381.05 | 1.0009 |
| $E_{CBD}/E$ | 0.75 | Fraction of households commuting to the CBD | 380.69 | 381.02 | 1.0009 |
| $k_{CBD}$ | 1 | Small city radius of the CBD | 381.82 | 382.27 | 1.0012 |
| $t_L$ | 12 | Time of commute for local workers | 380.75 | 381.06 | 1.0008 |
| $v_{low}$ | 5 | Minimum commuting speed | 379.69 | 379.79 | 1.0003 |
| $v_{high}$ | 45 | Maximum commuting speed | 381.55 | 381.76 | 1.0006 |
| $c$ | 1.75 | Curvature parameter in speed function | 380.55 | 380.78 | 1.0006 |
| $\tau$ | 0.5 | Time cost of commuting (fraction of wage) | 379.79 | 380.18 | 1.0010 |
| $p_g$ | 3.5 | Gasoline price per gallon | 380.33 | 380.65 | 1.0009 |
| $m_0$ | 2123 | Fixed cost of commuting | 380.78 | 381.09 | 1.0008 |
| $m_1$ | 0.222 | Dollars of depreciation per mile | 379.96 | 380.34 | 1.0010 |
| $\bar{U}$ | 15500 | Reservation utility | 410.65 | 411.03 | 1.0009 |
| $q_0$ | 0.7 | 5+ unit building floor-area ratio cutoff | 382.08 | 382.29 | 1.0005 |
| $q_1$ | 0.6 | 2-4 unit building floor-area ratio cutoff | 380.75 | 381.06 | 1.0008 |
| $q_2$ | 0.5 | sf. attached floor-area ratio cutoff | 381.20 | 381.41 | 1.0005 |

Note: Baseline parameter values are those used in the baseline simulation shown in Table 4 and Figures 3 and 4. The elasticity column shows the elasticity of energy use with respect to city size under the parameter in the row multiplied by 1.1. The elasticity of elasticity column shows the elasticity of the city size elasticity with respect to the parameter in the row.

Table 6: Effects of Growth Due to Amenity Changes in a Laissez-Faire City

| Variable | Small City | Large City | Difference | Size Elasticity | Large City Δ vs. baseline |
|---|---|---|---|---|---|
| *Urban Form* | | | | | |
| Total Occupied Units | 440,000 | 880,000 | 440,000 | | |
| Lot Size (acre) – Detached Units | 0.190 | 0.178 | -0.012 | -0.063 | -0.0052 |
| Unit (square feet) – All Units | 1,560 | 1,471 | -89 | -0.057 | -43 |
| City Area (sq. miles) | 346 | 491 | 145 | 0.418 | -20 |
| City Radius (assuming circle) | 10.5 | 12.5 | 2.0 | 0.191 | -0.25 |
| Residential Struct./Land ratio (CBD) | 1.20 | 1.71 | 0.51 | 0.422 | 0.02 |
| Residential Density (hh per sq. mile) | 1,281 | 1,807 | 526 | 0.410 | 70.21 |
| Time to work | 23.6 | 27.3 | 3.7 | 0.156 | -0.2 |
| Fraction housed in 1 unit structures | 54.0% | 35.8% | -18.2% | -0.336 | -0.6% |
| Fraction housed in 2-4 unit structures | 21.2% | 16.8% | -4.3% | -0.204 | -0.2% |
| Fraction housed in 5+ unit structures | 24.8% | 47.3% | 22.5% | 0.906 | 0.8% |
| *Income/Expenditure Accounting* | | | | | |
| Base Income | $ 49,924 | $ 49,924 | $ 0 | 0.000 | $ -1,223 |
| Numeraire Expenditure | $ 36,782 | $ 36,282 | $ -499 | -0.014 | $ -929 |
| Housing Services Expenditure | $ 9,885 | $ 9,847 | $ -38 | -0.004 | $ -266 |
| Housing Expenditure | $ 8,387 | $ 8,461 | $ 73 | 0.009 | $ -251 |
| Dwelling Energy Expenditure | $ 1,498 | $ 1,387 | $ -111 | -0.074 | $ -15 |
| Commuting Gasoline Expenditure | $ 758 | $ 881 | $ 124 | 0.163 | $ -11 |
| Income Reductions* | $ 2,499 | $ 2,913 | $ 414 | 0.165 | $ -17 |
| *Total Energy Consumption (billion BTUs)* | | | | | |
| Commuting | 11,478 | 26,700 | 15,222 | 1.326 | -345 |
| Dwelling | 61,831 | 114,493 | 52,662 | 0.852 | -1,212 |
| Commuting and Dwelling | 73,310 | 141,193 | 67,884 | 0.926 | -1,557 |
| Numeraire | 94,181 | 186,840 | 92,659 | 0.984 | -5,659 |
| Total | 167,491 | 328,034 | 160,543 | 0.959 | -7,216 |
| *Energy Consumption per Household (million BTUs)* | | | | | |
| Commuting | 26.1 | 30.3 | 4.3 | 0.163 | -0.4 |
| Dwelling | 140.5 | 130.1 | -10.4 | -0.074 | -1.4 |
| Commuting and Dwelling | 166.6 | 160.4 | -6.2 | -0.037 | -1.8 |
| Numeraire | 214.0 | 212.3 | -1.7 | -0.008 | -6.4 |
| Total | 380.7 | 372.8 | -7.9 | -0.021 | -8.2 |
| *Welfare Accounting* | | | | | |
| Total Wages ($m) (-) | $ 21,966 | $ 43,933 | $ 21,966 | 1.000 | $ -1,076 |
| Residential Land Rent ($m) (+) | $ 438 | $ 981 | $ 543 | 1.242 | $ -22 |
| Agriculture Land Rent ($m) (+)** | $ 115 | $ 69 | $ -46 | -0.402 | $ 6 |
| Household Amenity ($m) (+) | $ 0 | $ 1,061 | $ 1,061 | - | $1,061 |

* Consists of time-cost of commuting and reduced income from non-CBD employment

** Measured up to a 15 mile radius

Table 7: Effects of Land Use Planning: Greenbelt

| Variable | Small City | Large City | Difference | Size Elasticity | Small City Δ vs. baseline | Large City Δ vs. baseline |
|---|---|---|---|---|---|---|
| *Urban Form* | | | | | | |
| Total Occupied Units | 440,000 | 880,000 | 440,000 | | | |
| Lot Size (acre) – Detached Units | 0.139 | 0.087 | -0.052 | -0.371 | -0.051 | -0.096 |
| Unit (square feet) – All Units | 1,542 | 1,461 | -81 | -0.052 | -19 | -53 |
| City Area (sq. miles) | 254 | 254 | 0 | 0.000 | -92 | -257 |
| City Radius (assuming circle) | 9.0 | 9.0 | 0.0 | 0.000 | -1.5 | -3.8 |
| Residential Struct./Land ratio (CBD) | 1.25 | 1.87 | 0.62 | 0.497 | 0.05 | 0.18 |
| Residential Density (hh per sq. mile) | 1,751 | 3,520 | 1,770 | 1.011 | 469.22 | 1,783.30 |
| Time to work | 23.2 | 26.3 | 3.1 | 0.133 | -0.4 | -1.2 |
| Fraction housed in 1 unit structures | 48.1% | 16.0% | -32.1% | -0.668 | -5.9% | -20.4% |
| Fraction housed in 2-4 unit structures | 22.5% | 19.2% | -3.3% | -0.148 | 1.3% | 2.1% |
| Fraction housed in 5+ unit structures | 29.4% | 64.8% | 35.4% | 1.205 | 4.6% | 18.3% |
| *Income/Expenditure Accounting* | | | | | | |
| Base Income | $ 50,012 | $ 51,431 | $ 1,419 | 0.028 | $ 88 | $ 284 |
| Numeraire Expenditure | $ 36,846 | $ 37,421 | $ 574 | 0.016 | $ 65 | $ 209 |
| Housing Services Expenditure | $ 9,967 | $ 10,367 | $ 399 | 0.040 | $ 82 | $ 254 |
| Housing Expenditure | $ 8,495 | $ 9,058 | $ 563 | 0.066 | $ 108 | $ 346 |
| Dwelling Energy Expenditure | $ 1,472 | $ 1,309 | $ -164 | -0.111 | $ -25 | $ -93 |
| Commuting Gasoline Expenditure | $ 731 | $ 816 | $ 85 | 0.116 | $ -27 | $ -77 |
| Income Reductions* | $ 2,467 | $ 2,828 | $ 361 | 0.146 | $ -32 | $ -101 |
| *Total Energy Consumption (billion BTUs)* | | | | | | |
| Commuting | 11,069 | 24,710 | 13,641 | 1.232 | -409 | -2,335 |
| Dwelling | 60,783 | 108,057 | 47,274 | 0.778 | -1,048 | -7,649 |
| Commuting and Dwelling | 71,852 | 132,768 | 60,916 | 0.848 | -1,458 | -9,983 |
| Numeraire | 94,828 | 196,790 | 101,961 | 1.075 | 647 | 4,290 |
| Total | 166,680 | 329,557 | 162,877 | 0.977 | -810 | -5,693 |
| *Energy Consumption per Household (million BTUs)* | | | | | | |
| Commuting | 25.2 | 28.1 | 2.9 | 0.116 | -0.9 | -2.7 |
| Dwelling | 138.1 | 122.8 | -15.3 | -0.111 | -2.4 | -8.7 |
| Commuting and Dwelling | 163.3 | 150.9 | -12.4 | -0.076 | -3.3 | -11.3 |
| Numeraire | 215.5 | 223.6 | 8.1 | 0.038 | 1.5 | 4.9 |
| Total | 378.8 | 374.5 | -4.3 | -0.011 | -1.8 | -6.5 |
| *Welfare Accounting* | | | | | | |
| Total Wages ($m) (-) | $ 22,005 | $ 45,259 | $ 23,254 | 1.057 | $ 39 | $ 250 |
| Residential Land Rent ($m) (+) | $ 460 | $ 1,145 | $ 685 | 1.487 | $ 23 | $ 142 |
| Agriculture Land Rent ($m) (+)** | $ 145 | $ 145 | $ 0 | 0.000 | $ 29 | $ 82 |
| Total Surplus ($m, vs. Baseline) | | | | | $ 14 | $ -26 |

* Consists of time-cost of commuting and reduced income from non-CBD employment
** Measured up to a 15 mile radius

Table 8: Effects of Land Use Planning: Height Limit

| Variable | Small City | Large City | Difference | Size Elasticity | Small City Δ vs. baseline | Large City Δ vs. baseline |
|---|---|---|---|---|---|---|
| *Urban Form* | | | | | | |
| Total Occupied Units | 440,000 | 880,000 | 440,000 | | | |
| Lot Size (acre) – Detached Units | 0.190 | 0.183 | -0.007 | -0.038 | 0.0000 | -0.0004 |
| Unit (square feet) – All Units | 1,561 | 1,517 | -44 | -0.028 | 0 | 3 |
| City Area (sq. miles) | 347 | 526 | 178 | 0.514 | 1 | 15 |
| City Radius (assuming circle) | 10.5 | 12.9 | 2.4 | 0.230 | 0.01 | 0.18 |
| Residential Struct./Land ratio (CBD) | 1.00 | 1.00 | 0.00 | 0.000 | -0.20 | -0.69 |
| Residential Density (hh per sq. mile) | 1,279 | 1,689 | 410 | 0.321 | -2.70 | -48.42 |
| Time to work | 23.6 | 28.0 | 4.4 | 0.186 | 0.1 | 0.6 |
| Fraction housed in 1 unit structures | 54.1% | 37.2% | -16.9% | -0.313 | 0.1% | 0.8% |
| Fraction housed in 2-4 unit structures | 21.2% | 17.5% | -3.7% | -0.174 | 0.0% | 0.5% |
| Fraction housed in 5+ unit structures | 24.7% | 45.3% | 20.6% | 0.835 | -0.1% | -1.2% |
| *Income/Expenditure Accounting* | | | | | | |
| Base Income | $ 49,933 | $ 51,228 | $ 1,295 | 0.026 | $ 9 | $ 81 |
| Numeraire Expenditure | $ 36,783 | $ 37,236 | $ 453 | 0.012 | $ 2 | $ 25 |
| Housing Services Expenditure | $ 9,884 | $ 10,097 | $ 213 | 0.022 | $ -1 | $ -16 |
| Housing Expenditure | $ 8,386 | $ 8,690 | $ 304 | 0.036 | $ -2 | $ -22 |
| Dwelling Energy Expenditure | $ 1,499 | $ 1,407 | $ -91 | -0.061 | $ 1 | $ 6 |
| Commuting Gasoline Expenditure | $ 760 | $ 922 | $ 162 | 0.213 | $ 2 | $ 29 |
| Income Reductions* | $ 2,505 | $ 2,973 | $ 468 | 0.187 | $ 6 | $ 44 |
| *Total Energy Consumption (billion BTUs)* | | | | | | |
| Commuting | 11,513 | 27,924 | 16,411 | 1.425 | 35 | 879 |
| Dwelling | 61,857 | 116,170 | 54,313 | 0.878 | 26 | 464 |
| Commuting and Dwelling | 73,371 | 144,094 | 70,723 | 0.964 | 61 | 1,343 |
| Numeraire | 94,170 | 192,235 | 98,065 | 1.041 | -11 | -264 |
| Total | 167,541 | 336,329 | 168,788 | 1.007 | 51 | 1,079 |
| *Energy Consumption per Household (million BTUs)* | | | | | | |
| Commuting | 26.2 | 31.7 | 5.6 | 0.213 | 0.08 | 1.0 |
| Dwelling | 140.6 | 132.0 | -8.6 | -0.061 | 0.06 | 0.5 |
| Commuting and Dwelling | 166.7 | 163.7 | -3.0 | -0.018 | 0.14 | 1.5 |
| Numeraire | 214.0 | 218.4 | 4.4 | 0.021 | -0.03 | -0.3 |
| Total | 380.8 | 382.2 | 1.4 | 0.004 | 0.11 | 1.2 |
| *Welfare Accounting* | | | | | | |
| Total Wages ($m) (-) | $ 21,970 | $ 45,081 | $ 23,110 | 1.052 | $ 4 | $ 71 |
| Residential Land Rent ($m) (+) | $ 440 | $ 1,068 | $ 628 | 1.428 | $ 2 | $ 65 |
| Agriculture Land Rent ($m) (+)** | $ 115 | $ 58 | $ -57 | -0.496 | $ -0.2 | $ -5 |
| Total Surplus ($m, vs. Baseline) | | | | | $ -2 | $ -11 |

* Consists of time-cost of commuting and reduced income from non-CBD employment

** Measured up to a 15 mile radius

Figure 3: Wage Changes in a Laissez-Faire City: Urban Form

Dotted line: 440,000 household city

Solid line: 880,000 household city

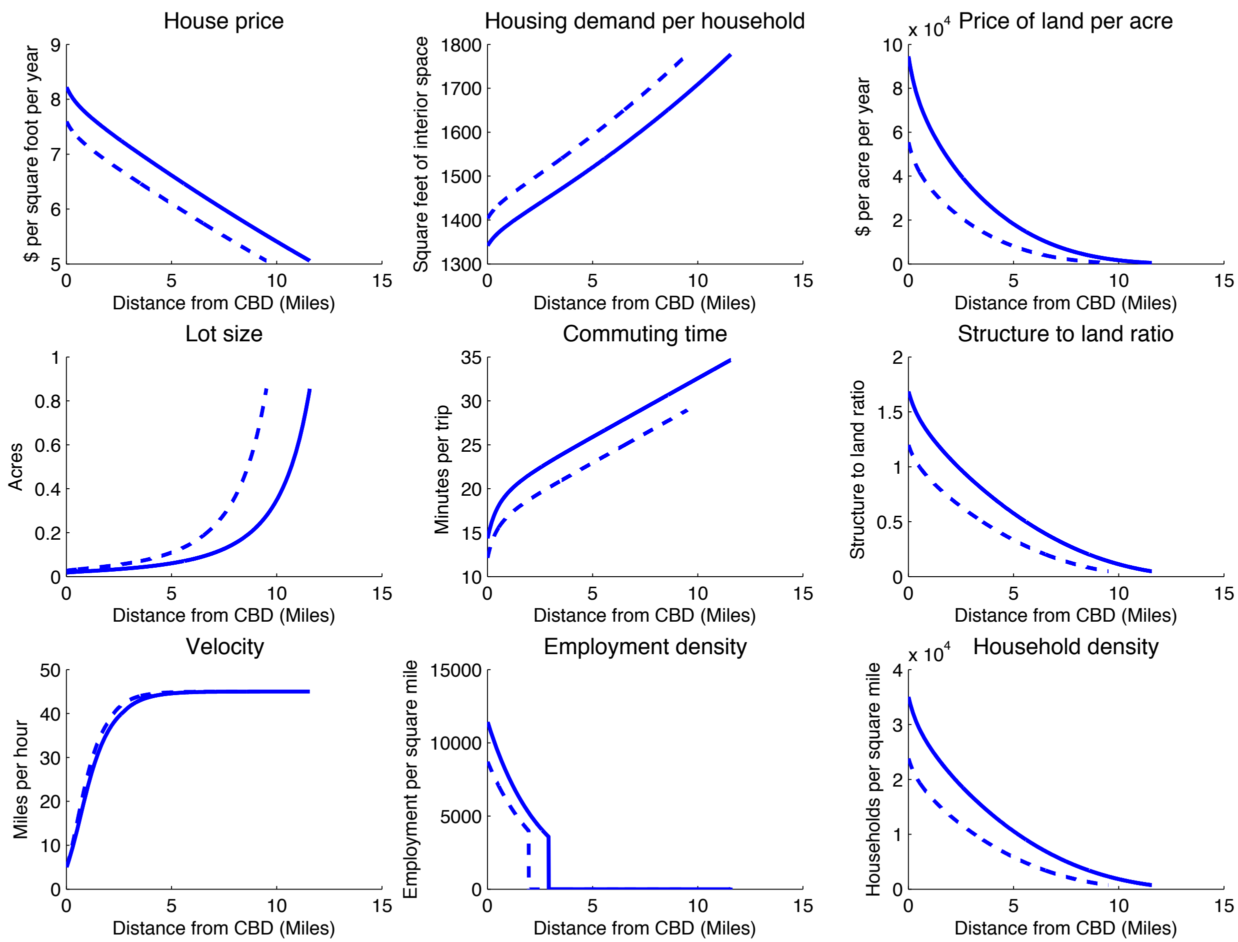

Figure 4: Wage Changes in a Laissez-Faire City: Energy Consumption

Dotted line: 440,000 household city
Solid line: 880,000 household city