Telework: Urban Form, Energy Consumption, and Greenhouse Gas Implications

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November 2, 2015

Abstract

A primary motivation of telework policy is to reduce energy consumption and greenhouse gas emissions. Using a numerical simulation of the standard urban model, we show telework causes sprawl, calling into question the idea that telework decreases energy consumption. Overall effects depend on wage changes due to telework, land use regulation such as height limits or greenbelts, and the telework participation rate. While energy consumption increases in some scenarios, emissions may fall due to changes in the energy mix between gasoline and other sources.

JEL Codes: R11, R28, C60

Keywords: energy consumption, urban simulation, modal choice, standard urban model

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[*] The authors would like to thank Leah Brooks, Paul Carrillo, Tony Yezer, and seminar participants at the Federal Reserve Bank of Richmond's Regional Economics Workshop, the Urban Economic Association's 2015 annual meeting, and the AREUEA session at the 2016 ASSA meeting.

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1 Introduction

It is increasingly common for employees with offices in the central business district (CBD) to work in the home, a practice often referred to as "telework." Between 2005 and 2013, the share of majority-teleworking employees in the United States increased from 1.8 million to 3.5 million, an increase of 11% per year (Figure 1).[1] Teleworkers tend to be employed in occupations relating to management, business, science, and the arts, with a 10 percentage point increase in a county's employment share in these occupations associated with a 0.67 percentage point increase in the fraction of teleworkers.[2] Telework is most prevalent in the least and most dense counties U.S. but otherwise has no clear geographic concentration. According to Bureau of Labor Statistics data analyzed by Matthews and Williams (2005), up to 45% of all jobs in the United States are compatible with at least part-time telework. Increasing rates and high potential levels of telework adoption portend major changes to household and firm-level bargaining and workplace location decisions, thus warranting attention from researchers and policymakers on how best to harness the potential efficiency gains of a mobile workforce.

Some of the effects of telework are clear, based on experiments such as the "Ecommute" pilot program established by the U.S. National Telecommuting and Air Quality Act of 1999. These include a reduction in number of commuting trips for teleworkers and lower levels of traffic congestion for remaining commuters (Nelson, Safirova and Walls, 2007). Generally positive findings from this and other programs have led to an increased policy focus on encouraging telework as a part of efforts to improve employee welfare and reduce energy consumption and emissions. Since the early 2000s, the European Framework Agreement on Telework of 2002 in the E.U, the Telework Enhancement Act of 2010 in the U.S., and discussions of tying emissions credits in the European Union and under the Kyoto Protocol (Nelson, 2004) reflect a general view that telework has a number of benefits to workers, firms,

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[1] Source: American Community Survey, 1-year estimates. This statistic includes all workers who report working from home a majority of the time, excluding the *self-employed in own incorporated business workers*, *self-employed in own not incorporated business workers*, and *unpaid family workers* categories.

[2] The sample consists of all central counties in MSAs according to 2013 definitions. Data are from the 5-year sample of the 2013 American Community Survey. The model

$$telework\ share = \alpha + \beta \times occupation\ share + \epsilon$$

is estimated over $N = 728$ observations, with $\hat{\beta} = 6.7(0.5)$

and the environment.[3]

The major issue with research on telework thus far is the inability to estimate long-run general equilibrium effects within cities and regions. The fall in transportation costs for both teleworkers and non-teleworkers reduces incentives to live near the CBD where housing costs are high, causing sprawl. This sprawl effect of telework lowers structure density while increasing average home size and the length of the average commute. Each of these indirect, general equilibrium effects tend to increase energy consumption, making the overall energy and greenhouse gas effects of telework uncertain.

Long-run effects of telework on the urban form and energy consumption of cities are difficult to identify using empirical methods. First, telework has existed over a short time period and cities take time to adjust to changes in transportation costs. Second, adoption of telework is likely an endogenous response to commuting conditions in the city.[4] Finally, cities face path dependence in development, with the commuting patterns in a city often determined by technologies and land use decisions from prior centuries. It is therefore extremely difficult to find a proper experiment that can be used to estimate the effects of telework on long run commuting, living, and working patterns in a city.

Rather than attempting to account for all the issues with empirical estimation, there is another line of research that uses the standard urban model to generate predictions regarding changes to transportation costs, following the long tradition of Alonso (1964), Mills (1967), and Muth (1969). This model treats the city as an endogenous system of households, housing producers, and employers who determine the location and density of economic activity. It is able to model both direct and indirect effects of changes to transportation costs on house prices, density, commuting patterns, and energy consumption. Due to the complexity of the model, numerical solution methods are often preferred, following Muth (1975), Arnott and MacKinnon (1977), Altmann and DeSalvo (1981), Sullivan (1985), Bertaud and Brueckner (2005), Rappaport (2014), and others. Importantly, the simulation approach easily allows

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[3] Research has also found some favorable effects on productivity and employee morale associated with telework. Bloom, Liang, Roberts, and Ying (2015) found call center employees who started teleworking experienced a 13% increase in productivity and 50% fall in turnover. Dutcher (2012) reported that productivity of workers performing "creative" tasks rose relative to those performing "dull" tasks.

[4] There have been some other notable policy experiments, including Mokhtarian, Collantes, and Gertz (2004) who examine 218 workers in California from 1988 to 1998, and find that teleworkers tend to live further from their main job site, yet fail to find any causality in the suburbanization of households due to telework. Similarly, Ory and Mokhtarian (2006) and Muhammad et al. (2007) each find that, controlling for demographics and other socioeconomic characteristics, telework does not cause changes in household location. While these studies are informative, especially regarding the main issues and stylized facts of telework, the data available are much too limited to determine the long-run effects (a shortcoming noted by Ory and Mokhtarian, 2006).

true counterfactual experimentation by holding all other aspects of a city constant.

This paper extends the standard urban model to include households who telework. The model is calibrated to four American cities with low regulation and few topographic interruptions (according to the Wharton Residential Land Use Regulatory Index [Gyourko, Saiz, and Summers, 2008] and the Saiz [2010], topography index, respectively) to give a baseline city. Counterfactual telework scenarios are then simulated in order to answer several main questions regarding the effects of telework. These include adoption and expansion of telework along intensive versus extensive margins, differences in the dimensions (utility, wages, or migration) over which the urban area adjusts to a new equilibrium, and interactions of telework with common urban form regulations including height limits and greenbelts. Overall, these counterfactual scenarios are able generate estimates of the long-run effects of telework on the city.

All simulations agree on some effects of telework. In every case, the city's density gradient flattens with the total land area expanding. The average lot size increases as does the average square feet of interior space. Commuting expenditures fall, leading to increases in various welfare measures.

Other effects are uncertain and depend on model assumptions. If teleworkers are able to maintain their prior wage and population in the city does not change, household expenditures shift from commuting to other expenses, including housing, which is relatively energy-intensive. The consequence of telework in this "wage constant" scenario is to cause a net increase in energy consumed by households. On the other hand, in the "wage discount" scenario, employers are able to capture all the gains from telework and reduce wages to a point where utility is as it was before telework was adopted. In this case, expenditures fall on all goods and services relative to the wage constant scenario, causing a fall in density and reduced overall energy consumption. In both cases, however, CO_2 emissions fall as the energy mix shifts from gasoline to other, cleaner sources used in electricity generation. Finally, in the "migration" scenario, income is constant but rather than current residents benefitting, in-migration results because of the utility differential with the region. In this case, the population increases to the point where roads are just as congested as they were before households teleworked, causing the city to be nearly equal in all other respects, only larger.[5]

The model also has implications for the distribution of telework. When the city has both

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[5] This result is similar to the result in Duranton and Turner (2011), who find more roads do not necessarily lead to lower long-run congestion.

teleworking and non-teleworking households, sorting results due to differences in bid-rent gradients, with non-teleworkers occupying land near the CBD. Both types of households are better off because teleworkers do not have to commute as often and non-teleworkers' trips to the CBD face less congested roads. Interestingly, expansion of telework along the intensive margin results in greater welfare gains and lower energy consumption for the city than expansion along the extensive margin. This occurs because an unequal distribution of telework provides opportunity for location-based sorting, with those who commute most frequently living the closest to the CBD. On the other hand, when commute trips are more uniformly distributed throughout the city, sorting cannot occur, causing commutes to the CBD to be, on average, longer.

Finally, telework has interactions with two common urban form regulations in the city: greenbelts (also called urban growth boundaries), such as in Portland, OR, and London, UK, and building height limits such as those found in Washington, DC, and Bangalore, India. Telework adoption in a city with an already binding greenbelt causes lower welfare gains, denser structure types, and lower energy consumption, relative to an unregulated city, due to the prohibition of sprawl. In a city with a binding height limit, telework reduces the inefficiency caused by the regulation, as the density gradient rotates causing the height limit to be less binding.

The rest of the paper is organized as follows. First, the model structure and solution method is described in detail, including a discussion of model closing conditions and their relevance to the question of the urban form and energy implications of telework. Next, the calibration of the model with respect to a composite American city is considered, along with results of the calibration. Counterfactual scenarios are then simulated, with each isolating a particular aspect of the effects of telework on the city. Finally, these results and some potential implications, caveats, and extensions are discussed, and the paper is concluded.

2 Model Structure

The standard urban model (SUM) of Alonso (1964), Mills (1967), and Muth (1969) considers the relation between commuting, housing consumption, and the location of households in a city. One of the key results from this literature is the inverse relation between commuting costs and sprawl, and the positive relation between sprawl and housing consumption. Using the standard urban model, Larson, Liu, and Yezer (2012) and Larson and Yezer (forthcoming) demonstrate how each of these outcomes is related to the consumption of energy based on established engineering functions governing gasoline consumption in automobiles and empirical models characterizing energy consumption in buildings. Layering these energy consumption relations onto standard simulation outputs enables aggregate city-level energy consumption to be calculated for commuting, dwellings, and the numeraire consumption good.

2.1 The Standard Urban Model with Telework

The city lies on a featureless plane, with no geological or regulatory features that would inhibit development. Firms occupy the Central Business District (CBD), and they exogenously demand E identical workers, which provide the impetus for households to locate and remain in the city. An agricultural hinterland determines the reservation land rent at the edge of the city. Between the CBD and the hinterland reside the workers who commute to the CBD. Housing producers and households receive a reservation profit and level of utility, respectively, at every location inside the city. In some applications, there is also an inter-regional reservation utility condition, but this is not required in the model. The city is putty-putty – none of the city solutions between the CBD and the hinterland are static or constrained – so the model is to be interpreted as a long-run equilibrium solution.[6] The city is uniform at every radius, allowing characteristics to be expressed in radial terms as a function of the distance from the CBD.

Telework in this model is implemented in a straightforward and simple manner: by eliminating some number of commuting trips to the CBD. This has the direct effect of reducing commuting costs for teleworkers, and the indirect effect of removing drivers from the road, thereby reducing congestion for those who commute to the CBD. There are several potential effects of telework that this model does not consider. First, the model implicitly assumes telework does not affect the productivity of workers. If telework increases/decreases productivity, this might affect the wage firms are willing to pay.[7] Second, the model assumes that there are no changes in office space location associated with telework. Because teleworkers use their home office more intensely than non-teleworkers, presumably they would demand more interior space. Similarly, firms in the CBD would demand less office space as the intensity of usage falls. This leads to a third mechanism that is not considered, energy

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[6] Adjustment paths are an interesting extension worthy of further research, but are outside the scope of the present paper.

[7] This effect could be either positive or negative. Bloom et. al (2015) find telework increases productivity, and Dutcher (2012) finds that workers who perform "creative" tasks have higher productivity when teleworking, whereas those with "dull" tasks have lower productivity.

efficiency of CBD versus home offices. It is likely home offices are less efficient from an engineering standpoint because they exist within less dense structures. Despite these simplifying assumptions, the model generates many interesting predictions. Other potential effects are left for further research.

Housing Production

Housing H at distance k from the CBD, is produced by combining structure S and land inputs L under a constant returns to scale technology according to a CES production function with an elasticity of substitution of $1/(1-\rho)$.

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

Structure inputs are perfectly elastically supplied, but aggregate land input is fixed at each radius as the fraction of land available for residential development, θ.[8]

Households

All households are identical and consume two goods, rental housing h and a numeraire consumption good y, under a CES utility function.

$$U = \left[\beta_1 y^\eta + \beta_2 h^\eta\right]^{1/\eta} \tag{2}$$

β_1 and β_2 are related to consumption shares between the two arguments, and $1/(1-\eta)$ represents the constant elasticity of substitution between housing and the numeraire good. Household expenditure is divided among the numeraire good, $y(k)$, housing purchases, $r(k)h(k)$, and total transportation costs given by the product of workers per household, ϵ, and transportation costs per worker, $T(k)$.

$$w = y(k) + r(k)h(k) + \epsilon T(k) \tag{3}$$

Households maximize utility by choosing how much transportation cost they are willing to bear and how much numeraire and housing to consume, all of which vary by location.

The number of households in the city is N, which is equal to the integral of the density of households from the CBD to the edge of the city at radius $\bar{k}$.

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[8] This model ignores the role of maintenance, rehabilitation and durability of structures in housing production.

$$N = \int_{k_{CBD}}^{\bar{k}} 2\pi\theta k D(k) dk \tag{4}$$

Cost of Commuting

Annual commuting costs for a household living at radius k include fixed costs of owning an operating an automobile m_0 (e.g. insurance, licensing), variable costs related to distance traveled (e.g. vehicle depreciation), nonlinear gasoline costs with price per gallon of p_g, and non-linear time-cost of commuting which is τ fraction of the wage rate. All workers either costlessly telework from home or commute to the CBD via automobile. The fraction of days teleworked for households living at radius k is denoted $\delta(k)$.

$$T(k) = m_0 + (1 - \delta(k)) \left[m_1 k + p_g \int_0^k \frac{1}{G(V(M(\kappa)))} d\kappa + \tau W \int_0^k \frac{1}{V(M(\kappa))} d\kappa \right] \tag{5}$$

Both fuel and time cost is related to the velocity of the automobile at various locations in the city, which is in turn related to the ratio of traffic volume to roads. Following "Bureau of Public Roads" specification, velocity can be expressed as

$$V(k) = \frac{1}{a + bM(k)^c} \tag{6}$$

where $M(k) = \overrightarrow{N}(k)/R(k)$, and a, b, and c are congestion parameters and $\overrightarrow{N}(k)/R(k)$ is the ratio of traffic passing through annulus k to roads. It is assumed that fraction of land area allocated to roads is uniform, therefore $R(k)$ is a constant fraction of land area in each annulus. The traffic volume at radius k, $\overrightarrow{N}(k)$, is calculated as the sum of the commuting workers living at or beyond radius k.

$$\overrightarrow{N}(k) = \int_k^{\bar{k}} \epsilon(1 - \delta(\kappa)) 2\pi\theta k D(\kappa) d\kappa \tag{7}$$

Note that the telework fraction δ reduces per-worker transportation costs directly in Equation 5, but also indirectly by reducing the traffic volume in Equation 7.

2.2 Model Solution

The solution method follows Muth (1975), Arnott and MacKinnon (1977), Altmann and DeSalvo (1981), and McDonald (2009). The system of equations described above can be solved and reduced to one with two simultaneous differential equations with initial values. After a solution is obtained, the remaining gradients can be found recursively. The two-equation system of nonlinear differential equations includes marginal commuting costs and the household density at radius k.

$$\begin{bmatrix} \frac{dT(k)}{dk} \\ \frac{dN(k)}{dk} \end{bmatrix} = \begin{bmatrix} (1-\delta(k))\left[(m_1 + p_g \frac{1}{G(V(M(k)))} + \tau w \frac{1}{V(M(k))})\right] \\ 2\pi\theta k D(T(k)) \end{bmatrix} \tag{8}$$

with initial values

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

After solving this system, it is possible to derive house prices, housing demand, land prices and structure/land ratios as a function of commuting costs and housing unit density, following Altmann and DeSalvo (1981).

There are two conditions that then must be met. First, the land price at the edge of the city must be equal to the agricultural land rent $p_L(\bar{k}) = p_L^a$, and second, the number of workers in the city must be equal to the number of jobs available $\epsilon N = E$. If either of these equilibrium conditions is not met, the simulation is re-initialized and simulated again until subsequent iterations achieve an equilibrium solution.

2.3 Alternative Equilibrium Conditions

The model just described sets an exogenous wage w and number of households $N = E/\epsilon$, implicitly allowing city-wide utility U to vary if parameters are altered. This is referred to as a "closed city" in the literature because no net migration occurs between cities. Alternatively, it is also possible to construct the model holding exogenous any two of these three variables. For instance, holding w and U constant gives an "open city," where the fixed U is interpreted as a reservation utility, and perfectly competitive firms produce output subject to constant returns to scale. Changes to model parameters then bring about changes to population. Similarly, in a fixed U and fixed N model, households are free to relocate across cities, but choose not to because w adjusts endogenously to achieve the reservation utility.

These alternative closing conditions are useful to consider because they represent the extremes of potential behaviors in response to changes in city characteristics. A short-hand description of these conditions is presented in Table 1 for reference. In a model with fixed wages and population, a change in the telework parameter may represent a scenario of nation-wide telework adoption so that utility rises by the same amount in every city and there is no incentive for households to relocate to a different city. The fixed wage suggests bargaining power between workers and employers over returns to this innovation resides completely with the workers. In this case, the fall in commuting costs is captured entirely by the workers with no fall in the wage. Models with this closing are labeled "wage constant" simulations. Empirically, Oettinger (2011) finds that there is no wage discount from telework, suggesting simulations fixing w and allowing U or N to vary may be realistic. Similarly, there is an intuitive interpretation for the simulation where population and utility are held constant. In this city, telework does not help workers from a utility perspective because firms reduce wages to the point where utility is the same as the level before telework was adopted. This is termed the "wage discount" case. Finally, the case where wages and utility are constant is called the "migration" case because workers flow into the city and raise house prices and commuting cost until utility is maintained at its initial level. In general, because the importance of each of these effects is unknown, it is prudent to simulate all three, thus bounding the magnitudes of the implications of telework.

2.4 Simulating energy demand

Having simulated relevant expenditure, housing consumption, and commuting gradients, it is now possible to calculate the effects of each of these factors on energy consumption. Total energy consumption, $E(k)$, can be categorized into three main types: electricity in dwellings, $E^D(k)$, gasoline while commuting, $E^C(k)$, and numeraire, which embodies all other forms of consumption, $E^N(k)$. All energy is measured including costs of production and transmission.[9]

$$E(k) = E^C(k) + E^D(k) + E^N(k) \tag{9}$$

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[9] Different types of energy consumption may carry with them different types of externalities, and these are not considered. For instance, fossil fuels burned miles away from a city in a power plant may produce less particulate matter and volatile organic compounds that harm households versus those burned within the city in the form of gasoline. The simulation model in this paper does not consider these nor other local environment or climate-related externalities.

Total energy consumption in the city is the integral of this function over the city area. Teleworkers have $E^C(k) = 0$ for the days they telework, as represented by the $1 - \delta(k)$ term.

$$E = \int_{k_{CBD}}^{\bar{k}} D(k) \left[(1 - \delta(k))E^C(k) + E^D(k) + E^N(k)\right] dk \tag{10}$$

Engineering relationships govern the use of gasoline while commuting. Using data gathered by West et al. (1999) for an average vehicle in the U.S. fleet, $G(V(k))$ in Equation 5 is estimated by Larson, Liu, and Yezer (2012) using the 4th degree polynomial.[10] This gives about 14 miles per gallon at 10 miles per hour, up to a maximum of 29 miles per gallon at 50 miles per hour, falling to about 25 miles per gallon at 70 miles per hour. Under the assumptions that each worker in the city owns the same vehicle as the average vehicle in the U.S. fleet, this function gives an appropriate representation of commuting fuel use in the simulation.

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

$$E^C(k) = E_g \int_0^k \frac{1}{G(V(M(\kappa)))} d\kappa \tag{11}$$

where $G(V(M(\kappa)))$ is gasoline consumption in miles per gallon, a function of speed, which is in turn a function of the commuters/roads ratio. E_g is the energy embodied in a gallon of gasoline in BTUs. The energy in gasoline begins with the 125,000 BTUs contained in a gallon of 100% petroleum-based gasoline. Additionally, according to the Federal Register (2000) published by the Energy Information Administration, in order to produce 1 gallon of gasoline with 125,000 BTUs, 150,602 BTUs of total energy are actually expended in the process of production, distribution and final consumption. This value is multiplied by the amount of fuel consumed to arrive at the value for commuting energy consumption.

Dwelling energy consumption is determined by three major factors: income of the household, the square feet of interior space, and structure type. Larson, Liu, and Yezer (2012) also estimate residential energy demand parameters using the 2005 Residential Energy Consumption Survey (RECS). They find the partial elasticity of household energy consumption with respect to interior space is 0.23 and the estimated income elasticity is 0.07. Compared with the energy consumption in single-family detached units, single-family attached dwellings con-

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[10] The fitted model gives the following velocity-fuel efficiency relation:

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

sume 7% less energy and multi-family units consume 31% less energy. In the simulation, the structure type can be determined by structure to land ratio, defined as the ratio of housing square footage over lot size, denoted $q = H/L$. The critical value of q for each structure type are calibrated. The structure type is single-family detached if $q \in [0, 0.6]$, single-family attached if $q \in (0.6, 0.7]$, 2-4 unit multifamily if $q \in (0.7, 0.8]$ and 5+ unit multifamily when q is above 0.8.

For simplicity, it is assumed all energy consumed in the dwelling is electricity.[11] Each kilowatt hour of electricity consists of 3,412 BTUs of energy. As with gasoline, there is also energy embodied in production and distribution. The total energy consumed in the production, distribution and final dwelling energy use can be calculated by dividing final dwelling energy use by electricity efficiency parameter 0.303, which is the product of the efficiency parameter for fossil fuel electricity production 0.328 and efficiency parameter for electricity transmission 0.924 (Federal Register, 2000). This gives the function for dwelling electricity as

$$E^D(k) = E_e \exp\left[\alpha_1 + \alpha_2 \ln w + \alpha_3 \ln p_e + \alpha_4 \ln h(k) + s(q(k))'\gamma\right] \tag{12}$$

The energy embodied in \$1 of numeraire consumption is estimated to be $E_N = 7,470$ BTUs, which is the average energy intensity of the U.S. economy (Energy Information Administration, 2011). Energy intensity is used for this measure because it implicitly includes all energy in the raw materials, intermediate input production, final production, and transportation of the goods and services. Numeraire energy at annulus k is set equal to earnings net of expenditures on gasoline and electricity multiplied by the inverse energy intensity parameter.[12]

$$E^N(k) = E_N \left(w - p_g E^C(k)/E_g - p_e E^D(k)/E_e\right) \tag{13}$$

Greenhouse gas emissions are calculated based on energy consumption in the three categories, each multiplied by a carbon dioxide (CO_2) emissions coefficient reported by the Energy Information Administration.[13] The combustion of one gallon of gasoline results in 19.6 pounds of CO_2, or 157 pounds of CO_2 per million BTUs. Electricity is produced using

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[11] Electricity-only consumption is associated with lower per-household energy use compared to homes with natural gas, wood, or oil, according to the RECS. Therefore, estimates in this paper serve as the lower bound of energy consumed in the home.

[12] 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 good for purposes of computing energy consumption.

[13] CO_2 is the only greenhouse gas considered. Other greenhouse gases include methane (CH_4), hydrofluorocarbons (HFC), and nitrous oxide (N_2O). These are omitted because together, they account for less than 5% of all greenhouse gas emissions from gasoline consumption and electricity generation.

a number of methods in the United States, and carbon emissions from electricity consumption is therefore averaged over each of the major sources. In 2014, coal produced 39% of all electricity generated, with an average of about 215 pounds per million BTUs over each of the types of coal consumed. Natural gas produced 27% of all electricity, at 117 pounds of CO_2 emissions per million BTUs. The remaining sources include nuclear, hydroelectric, biomass, solar, and wind, which together make up 34% of all energy production. These sources are assumed to result in zero net emissions in the production of electricity. The weighted average of the U.S. electricity production basket from these three main categories is 103 pounds of CO_2 per million BTUs. Both numeraire and dwelling energy is assumed to be produced using this basket. Because gasoline and the other sources of energy have different emissions coefficients, CO_2 emissions can change when energy consumption does not if the share of energy source is changing.

3 Calibration

The calibration of numerical urban simulation models is evaluated by comparing simulation outputs to characteristics of a selected group of cities. In this case, cities are selected based on the Wharton Residential Land Use Regulatory Index (WRLURI; Gyourko, Saiz, and Summers, 2008) and the absence of topographical constraints according to GIS analysis by Saiz (2010). Cities chosen have over 90% of nearby area topographically available for development, are below the median level of land use regulation, and have between 300,000 and 700,000 housing units in principal cities. Based on these criteria, our calibration target values are from the average of the principal cities of Charlotte, Indianapolis, Kansas City, and San Antonio.[14]

Parameter calibration is performed following the literature on numerical urban simulations. These parameter values are shown in Table 3. The housing and utility parameters are close to those found in Altmann and DeSalvo (1981), which gives elasticities of substitution between structure and land inputs in the housing production function, and housing and the numeraire consumption good, of 0.75 in both equations. Land shares to housing and roads are similar to Muth (1975), as well as the speed parameters in the congestion function. Fixed and marginal commuting costs are from the American Automobile Association. The time cost of commuting is from Bertaud and Brueckner (2005), and set to 50% of the wage. The

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[14] Suburbs are not included in the tabulation because the simulation is focused on areas nearest to the center of cities where gradients are closest to being monotonic.

reservation agricultural rental price per acre per year is \$500, which corresponds to \$10,000 per acre at a 5% capitalization rate.

Results of the simulation calibration are shown in the final column of Table 2. The baseline city consists of 450,000 households, with an assumed CBD radius of 1 mile, and a total developed radius, including the CBD, of 9.8 miles–slightly lower than the composite city average of 12.2 (assuming a circular city, given the land area). Median income is about \$49,000 per year in the simulation, compared to about \$47,500. Commutes are slightly longer in the simulation, at 24 minutes per trip compared to composite city average of 23 minutes. The baseline simulation has 0% telework which is close to the city average of 2.3%.[15] Average unit size is about 1,520 sq. ft. compared to 1,600 in the composite, with an average single-family lot size of 0.16 acres in the simulation versus 0.28 in the composite. Generally, the simulation fits the composite city quite well, with the exception of the land area. However, it is well-known in the urban simulation literature that simulations with only one income group tend to produce cities with a smaller land area than those in the real-world (Altmann and DeSalvo, 1981).

The simulated urban form and spatial distribution of some key variables are shown in Figure 2. The figures show the distance from the CBD on the horizontal axis with the variable in the title on the vertical axis. Simulation results are consistent with past simulations in the literature and with intuition. House prices, land prices, traffic volume, and density are highest closest to the CBD and fall with distance. Housing demand, lot size, and commuting speed each increase with distance from the CBD.

Energy consumption is shown in Figure 3. The positive slope of the housing consumption gradient from Figure 2 leads to a positive slope of the dwelling energy consumption gradient. The jumps in this gradient are due to structure type changes based on the structure-land ratio, from large multifamily (5+ units), to small multifamily (2-4 units) to single-family structures, which are of decreasing energy efficiency. Commuting distance is positively related to commuting energy consumption, though at a decreasing rate because of the higher velocity as a function of the distance to the CBD. Because households further from the CBD spend more of their incomes on housing and commuting, numeraire good consumption falls with distance from the CBD, counteracting some of this sprawl effect on energy consumption. Overall, after summing these three effects, energy consumption rises with distance from the

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[15] We believe this assumption is tenable for two reasons. First, most counterfactual scenarios considered have 10% to 20% of the city teleworking, making the 2.3% figure relatively small in comparison. Second, telework has only recently gained attention, so it is unlikely to have significantly reshaped the long-run urban form of the city.

CBD.

4 Scenario Design and Results

This section uses the calibrated simulation model to perform various counterfactual experiments by altering model parameters. Scenarios are designed to uncover the effects of widespread telework adoption, changes to the distribution of telework days among workers in the city, and interactions of telework with urban form regulation. Combined, these scenarios provide rich predictions regarding the commuting, urban form, and energy effects of telework, while maintaining consistency with the stylized facts posed in the introduction regarding telework and its correlation with larger populations and longer commutes.

4.1 Effects of Widespread Telework Adoption

The first city with telework is simulated by setting $\delta = 0.2$ in Equation 5, which represents a city where every worker teleworks 1 day per week, or 20% of the time. While in reality, it is unlikely that every worker in a city will telework, this scenario is useful to consider precisely because of the limited nature of the change from the baseline city. This scenario gives the pure effects of telework without considering heterogenity in telework frequency, regulatory interactions, or other effects.

The results of this counterfactual scenario are shown graphically compared to the baseline in Figures 4 and 5 and in Table 4. The direct effect of universal telework is to reduce transportation costs by 20%. Because telework removes traffic volume, commute times and transportation costs fall further than the direct effect would indicate. This total fall in transportation costs causes a rotation of the house price gradient, which causes greater dispersion of the population and a larger footprint of the city with larger and lower density housing units. These effects combine to increase dwelling energy consumption, decrease commuting energy consumption, and have an ambiguous effect on numeraire energy consumption. The net effects are often of ambiguous sign and are dependent on the chosen endogenous model closing variable described in Section 2.3: endogenous wage, fixed population and utility (wage discount), endogenous utility, fixed population and wage (wage constant) and endogenous population, fixed wage and utility (migration).

Model Closing Condition 1: Wage Discount

Columns 3 and 4 of Table 4 report the results relative to the baseline of a simulation where utility is fixed and the wage rate is set endogenously in order to achieve the desired number of households. As discussed in Section 2.3, this set of assumptions corresponds to a city where employers are able to capture gains of telework.[16] Households are no better or worse off, having achieved the same utility as in the no-telework scenario. Rather, all benefits go to firms.

The fall in transportation costs causes house prices to fall and housing consumption to rise in spite of the fall in income. As a result, energy consumption in dwellings actually increases 4.3%. Commuting energy falls by 24.0%, suggesting a fall that is greater than the direct effect of telework, which is 20% for this scenario.[17] The overall commuting and dwelling energy effect is a net 0.1% increase. The fall in the nominal wage rate of 2.9% leads to a fall in numeraire expenditures of 4.0%. This elasticity is greater than one because the relative price of the numeraire good rises with a fall in house prices. It is assumed that commuting and dwelling expenditures that are not directly related to the consumption of energy (electricity, gasoline, etc.) have the energy content of the numeraire good. These items are added to the numeraire good itself, and with these included, numeraire energy consumption falls by only 2.9%. The net result of all of these effects is a -2.0% effect of telework on citywide household energy consumption. CO_2 emissions fall by 2.5%, which is greater than the overall energy consumption because the basket of energy products shifts away from gasoline toward electricity.

Model Closing Condition 2: Wage Constant

The next scenario allows households to capture the gains from telework by maintaining their wage as before, but allowing utility to increase. Closed city models assume that the same change is implemented in all cities, and the regional reservation utility adjusts at the same rate as the city-level utility, thus the city population remains stable. In this scenario, household welfare rises by 3.2%. The city takes up a larger area than in the previous telework scenario, with larger homes, larger lots, and longer average commuting distance.

Commuting, numeraire, and dwelling expenditures increase relative to the wage discount

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[16] This scenario is also consistent with the case where worker productivity falls as a result of telework with a corresponding fall in wages. In either case, the wage rate falls 2.9%.

[17] This 4% gap is made up of several effects, including a sprawl effect, an income effect, and a congestion effect.

scenario. The result is that commuting energy falls by only 23% (vs 24%), dwelling energy rises by 5.3% (vs 0.1%), and numeraire energy rises by 0.1% (vs -2.9%). The net result of these effects is to increase energy consumption by 0.4% versus the -2.0% effect from the prior scenario. Thus the energy implications of universal telework adoption appear to depend on who captures any efficiency gains that may be associated with telework. On the other hand, because the energy basket contains less gasoline and more electricity, greenhouse gasses actually falls by 0.1%.

Model Closing Condition 3: Migration

This city could arise if it is the only city in the region to adopt telework, with the efficiency gains inducing in-migration. The closing condition allows for endogenous population, and represents an open city. This scenario requires assumptions about the nature of center-city production because the number of workers in the city changes, so for simplicity, it is assumed that production is constant returns to scale in labor and land, and that households are able to capture all of the gains from telework.

In this city, 20% universal telework adoption causes the in-migration of 201,591 households, or an additional 44% versus the baseline. This city shares the rotation of the house price gradient of the previously simulated cities, but also a shift up as new households immigrate. The interesting implication of this scenario is that the average household is nearly identical to the average household in the baseline. No expenditure share changes by more than 0.6%, and no energy share increases by more than 0.6% (with the exception of the time cost of commuting line item in the numeraire category). One interpretation of this effect comes from the "System of Cities" literature, which considers the distribution of the sizes and types of cities (see Henderson, 1974, and Abdel-Rahman and Anas, 2004). This model suggests that a fall in the marginal cost of urbanization, in the form of lower transportation costs, results in a smaller number of larger cities. The simulation results of the open city migration case are logically consistent with this model and the population is presumably concentrated in a smaller number of cities.

This simulation is also consistent with the work of Duranton and Turner (2011), who posit a "Fundamental Law of Road Congestion," which suggests that commuters are willing to bear a certain amount of commute time, and therefore road construction–and by extension, telework–will not affect long-run commute times or congestion. Under this interpretation, as with the Systems of Cities model, rather than increasing welfare by reducing congestion, telework simply allows for a larger city in which energy use per capita is approximately unchanged.

Assessing the Linearity of Telework Effects

In order to consider the effects of telework along the intensive margin, cities with closing conditions 1 through 3 are simulated with workers teleworking an increasing number of days per week. Table 5 presents results of simulations of these cities. In the wage constant and wage discount scenarios, the partial welfare elasticity of telework decreases as the fraction of days teleworked increases. Welfare in the wage constant city is measured using utility, which rises by 3.2% when the city goes from 0 to 1 telework day per week. This does not quite double with the second telework day, which increases utility by an additional 2.6%. Similarly, in the wage discount city, the earnings required to induce residence falls by 3.0% when the city goes from 0 to 1 day of telework per week, and by 2.4% when going from 1 to 2 days. In these cases, welfare returns to telework are decreasing along the intensive margin. Density is similar, with the floor/area ratio at the CBD falling from 1.68, 1.20, and 0.82 under 0, 1 and 2 days of telework, respectively, in both the wage constant and wage discount case. Energy results are similar to the welfare results in that they exhibit decreasing returns. Based on these combined results, it appears that increasing telework intensity affects energy consumption at a decreasing rate.

One interesting corner case is where the entire city teleworks 100% of the time. There is no longer any reason to locate near the CBD for commuting purposes, and it must therefore be assumed that households continue to live near the CBD for some other reason such as an amenity or infrastructure. This city has no solution in the migration case because there is no marginal cost of distance from the CBD which would cause population increases, reducing utility. In the wage constant and wage discount scenarios, density is uniformly distributed and determined by the wage rate and exogenous structure and agricultural land prices, with the edge of the city determined by the exogenous population level imposed on the city combined with the uniform density.

In the migration scenario, 1 day of telework per week induces an additional 201,591 households to live in the city, while the 2 day scenario causes the city to more than double in population, attracting an additional 598,896 households. This is presumably due to the fact that the area of the city increases at a rate of the radius squared, making the city able to support increasingly larger populations with a constant rate of increase of telework adoption. This case suggests increasing welfare returns to telework adoption. CBD density increases with telework intensity, rising by 1.1% and 1.7% when going from 0 to 1 day and 0 to 2 days of telework, respectively. Similarly, per capita energy consumption rises by 0.2% comparing the baseline to the 1 day telework city and 0.4% when comparing the baseline to the 2 day telework city. Evaluated together, the three cases suggest different returns to scale in welfare and energy depending on the margins over which firms and households adjust to telework.

4.2 Implications of the Distribution of Telework

A changing distribution of telework is implemented by fixing the number of telework days throughout the population to be equal to the universal 1-day per week scenario, and concentrating these days on differently-sized worker populations. The teleworker and non-teleworker populations are treated differently, and may have different levels of utility, but within a particular group, utility is held constant regardless of the location in the city where they reside. Existing research on telework suggests that teleworking households tend to live towards the edge of the city. This is confirmed in Figure 6, which shows the differential slopes of the bid-rent curves for households who telework, versus those who do not, when 50% of the population teleworks 2 days per week and the other half does not telework.

Results in Table 6 suggest that it is slightly better, both from a welfare and an energy consumption perspective, to have a more uneven distribution of a fixed number of telework days.[18] In the wage discount city with universal 1 day telework, a wage reduction of 3.0% per household was enough to maintain the population equilibrium, versus the scenario where 50% of the population commutes 2 days per week, which allows a reduction in average wage of 3.4% per household. Energy consumption among teleworkers is kept low because of the falling compensating income differential, but falls further with a decrease in the fraction of teleworkers who telework with higher intensity. All firms employing workers are better off, as wages required to induce residence fall for both groups. In this case, even those firms hiring workers who do not telework benefit due to the reduced congestion in the city, though they benefit less when the distribution of telework is less equal.

The wage constant city gives similar results. In this city, utility rises by 3.2% in the universal 1-day per week scenario, increasing to 3.8% per household (5.4% for teleworkers; 2.1% for non-teleworkers) and indicating that both types of households–even those that do not telework–are better off by having some households in the city telework. Other results are qualitatively similar to the wage discount scenario. An uneven distribution of a constant number of telework days results in the greatest welfare gains and reduction in energy

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[18] There is no migration scenario because a model with a fixed fraction of teleworkers, combined with an endogenous population, has no solution.

consumption.

4.3 Interactions of Telework with Urban Form Regulation

Because telework affects the density and the area of an unregulated city, it is natural to consider the effects of telework under regulatory regimes that are designed to affect the city along these dimensions. Two regulations are considered here, a height limit (also referred to as a floor/area ratio limit) and a greenbelt (also referred to as an urban growth boundary). These regulations have been considered using simulation models in non-telework contexts, including Bertaud and Brueckner (2005), Brueckner (2007), and Borck (2014). Findings generally suggest that both greenbelts and height limits lower welfare, but height limits increase energy consumption and and greenbelts decrease energy consumption.[19] Simulations in this section show that under a height limit, the welfare effects of telework are higher, and under a greenbelt, they are lower. In both cases, telework reduces energy consumption.

The height limit in the simulation is set at 0.8, which is the approximate floor/area ratio of a neighborhood of single-family attached units (also known as row-houses). The greenbelt is set at a radius of 9 miles (8 miles from the edge of the CBD), and is binding under baseline parameter values with no telework. Results from these scenarios under a wage constant, universal 20% telework scenario are presented in Table 7, with urban form changes shown in Figure 7.

A baseline city with a height limit has more sprawl, with a city radius that is 0.2 miles larger. This results in longer commutes, larger homes, and less numeraire consumption, leading to higher overall energy consumption and lower welfare relative to the no-height limit baseline. Under telework, the height limit is still binding, but less so. As Column 8 shows, the rotation of the density gradient caused by telework results in a regulated city that more closely resemble the unregulated city compared to before telework was introduced. Under telework, the welfare difference falls from -0.24% to -0.05% and the energy consumption difference falls from 1.68% to 0.75%. Overall, telework reduces the distortion to the urban form of the city caused by a height limit.

In contrast to the height limit city, the greenbelt city area is smaller than the baseline with no telework. When telework is introduced, the greenbelt becomes increasingly binding. The commuting expenditure savings from telework causes numeraire and housing consumption to increase relative to the unregulated city. The density increase offsets the increase in

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[19] Brueckner (2007) finds that a greenbelt that is only slightly binding may act as a second-best policy solution to unpriced traffic congestion and actually increase welfare.

housing consumption so that dwelling energy consumption is actually lower in the greenbelt scenario. Combined with the commuting effect, the greenbelt city ends up denser and with lower energy consumption compared to the laissez faire city. On the other hand, because the greenbelt is more severely binding under telework, welfare increases by much less than in the unregulated city. In sum, in the greenbelt case, telework exacerbates distortions to the urban form of the city.

4.4 Telework, Greenhouse Gas Emissions, and Energy Sources

Thus far, the energy mix for the numeraire and housing good has been assumed to follow 2014 United States electricity generation mix of 39% coal, 27% natural gas, and 34% "green" (i.e. without substantial CO_2 emissions). For commuting, all of the energy was produced using gasoline. Each of these different types of energy inputs produces different quantities of CO_2 emissions for each unit of energy created. Because the energy shares of commuting, numeraire, and housing change with the adoption of telework, telework may have a different effect on greenhouse gas emissions compared to overall energy consumption. This is demonstrated by considering four different energy mixes for the numeraire and housing good, while holding overall energy production and the commuting energy source (gasoline) constant: (1) the 2014 U.S. average, (2) a region in which energy is produced using 100% coal, (3) a region in which energy is produced using 100% natural gas, and (4), a "future green" scenario with less coal (25% total) and more green energy production (50%). Table 8 considers the 1 day per week, universal telework, constant wage scenario under each of these four energy production baskets.

The 2014 U.S. mix was presented earlier in Table 4, and shows a small reduction of -0.14% in overall greenhouse gasses from telework despite the overall increase in energy consumption of +0.4%. In the coal region, total emissions without telework are twice as high as under U.S. mix. With telework, this increases a further 0.71%, which is the opposite sign of the effect of telework under the U.S. mix. The natural gas region has a slightly higher level of emissions than the U.S. average, and the effect of telework is close to neutral in terms of CO_2 emissions, with an 0.03% increase. In the future green scenario, the level of total emissions is 19% lower than the U.S. mix. Under telework, these emissions fall a further 0.54%

Overall, these scenarios suggest an interaction between telework and changes to the energy input mix. The rotation in the density gradient caused by telework shifts energy consumption from gasoline to other energy sources. The change in emissions due to telework is therefore different depending on the sum of the changes in emissions from each energy category. If a large fraction of residential and numeraire energy generation comes from fossil fuels, telework increases CO_2. On the other hand, as the energy mix shifts towards renewable energy sources, such as is the goal under the Kyoto protocol and other international climate goals, telework decreases greenhouse gas emissions.

5 Discussion and Conclusion

According to Bureau of Labor Statistics data analyzed by Matthews and Williams (2005), at least 45% of the U.S. workforce holds a job that is compatible with at least part-time telework. Combined with the steady increase in telework adoption of about 0.1% per year, according to the American Community Survey, it is clear that telework will play an increasing role in the future of workers, employers, and cities. Local, national, and international policies designed to encourage telework have been implemented and are beginning to take effect. Accordingly, it is therefore important to understand the potential commuting, urban form, and energy implications of telework in cities, both for those who telework and those who do not.

The numerical simulation model presented in this paper, while limited to the analysis of homes and commutes, establishes rich predictions that are not intuitive at first glance. While telework increases the welfare of those who telework, it also makes those who do not telework better off through reduced congestion. Household utility effects depend on whether employers are able to reduce the wage paid in response to telework adoption, or if households can maintain their prior wage rate. An interesting case is the migration scenario, where telework induces new households to migrate to the city, giving a result that is consistent with Turner and Duranton's (2011) "Fundamental Law of Road Congestion." In this case, at least initially, households benefit from telework because wages are held constant and transportation costs fall due to the lower congestion. However, this utility differential induces in-migration until congestion and utility return to pre-telework levels. The end result is a city that is larger in size but with utility and earnings at the same level as before. In a nation with a fixed population in a Systems of Cities Model (Henderson, 1974), telework would thus result in a smaller number of larger cities.

For a given number of telework days per household in a city, a more uneven distribution of telework is more desirable from a welfare standpoint, and in some cases, from an energy consumption standpoint. This is because commutes to the CBD originate, on average, closer to the CBD than under a more uniform distribution of telework. On the other hand, under higher telework concentrations, the footprint of the city increases, as households with a greater share of days teleworking are less bound to the CBD.

The overall energy implications of telework are, perhaps surprisingly, uncertain. All cities experience increases in land area, housing unit size, and dwelling energy consumption. Commuting energy per worker falls in all cities except for the migration case, where it is flat. Only when firms capture the gains from telework through a reduction in the wage, or the city is constrained by a greenbelt, does telework reliably decrease overall per-capita energy consumption. Under the other scenarios, where workers are able to both telework and maintain their prior wage rate, total energy consumption per household increases.

However, because the energy mix shifts from gasoline to other sources under telework, greenhouse gas emissions tend to fall even when energy consumption rises. This result hinges on the energy source for the numeraire and housing good. If the source is mostly fossil fuels, then telework may increase greenhouse gas emissions. On the other hand, if the mix includes carbon-neutral sources, including nuclear, hydroelectric, solar, and wind, then telework can result in substantial greenhouse gas emissions reductions even when overall energy consumption increases.

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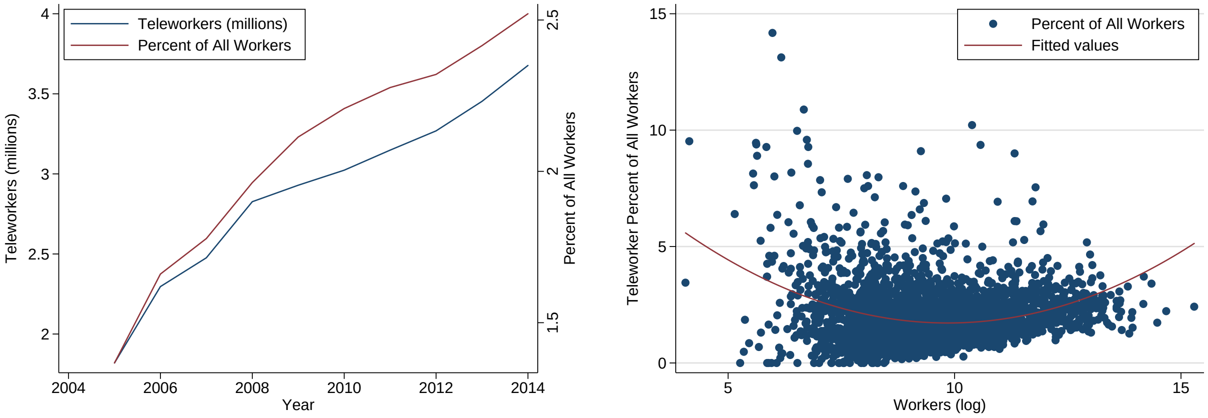
Figure 1: Telework Stylized Facts

(a) Adoption in the United States

(b) County Size



(c) Commute Time

(d) Telework Occupations

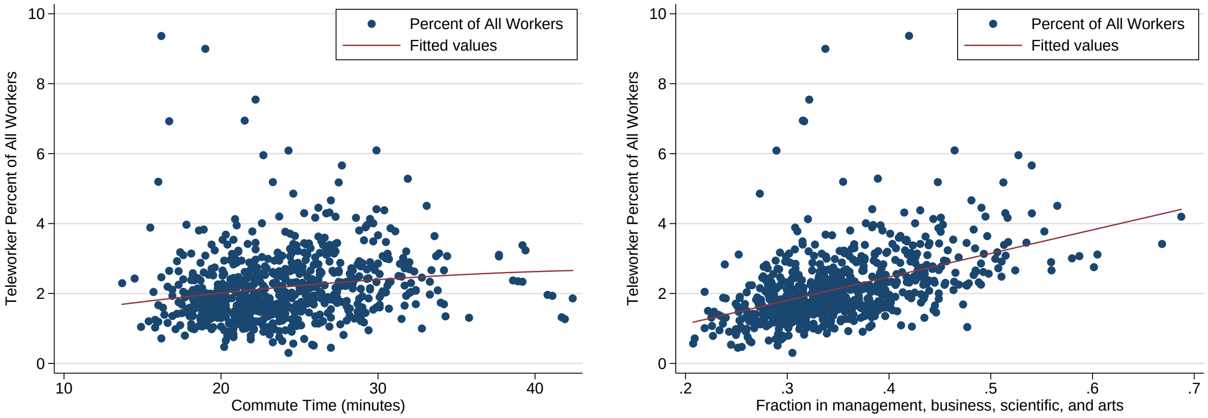


Figure 2: Baseline Simulation - Urban Form

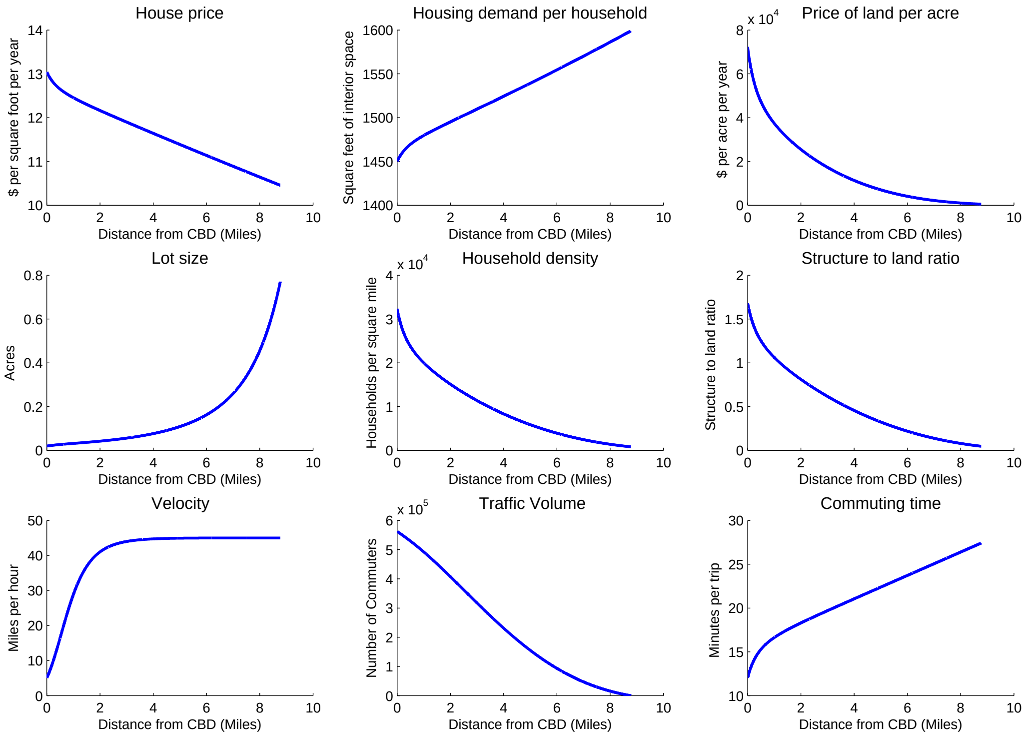


Figure 3: Baseline Simulation - Energy Consumption

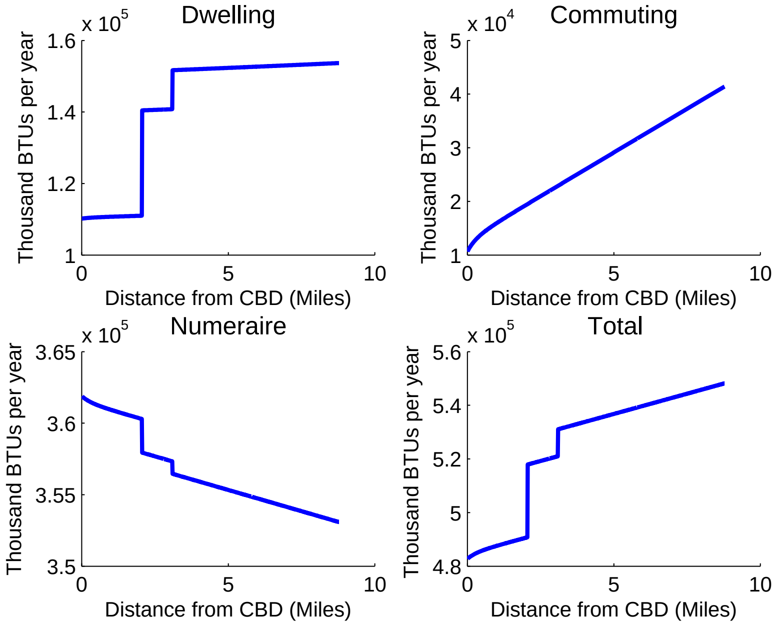


Figure 4: Baseline and Universal 20% Telework Simulations (Wage Constant) - Urban Form

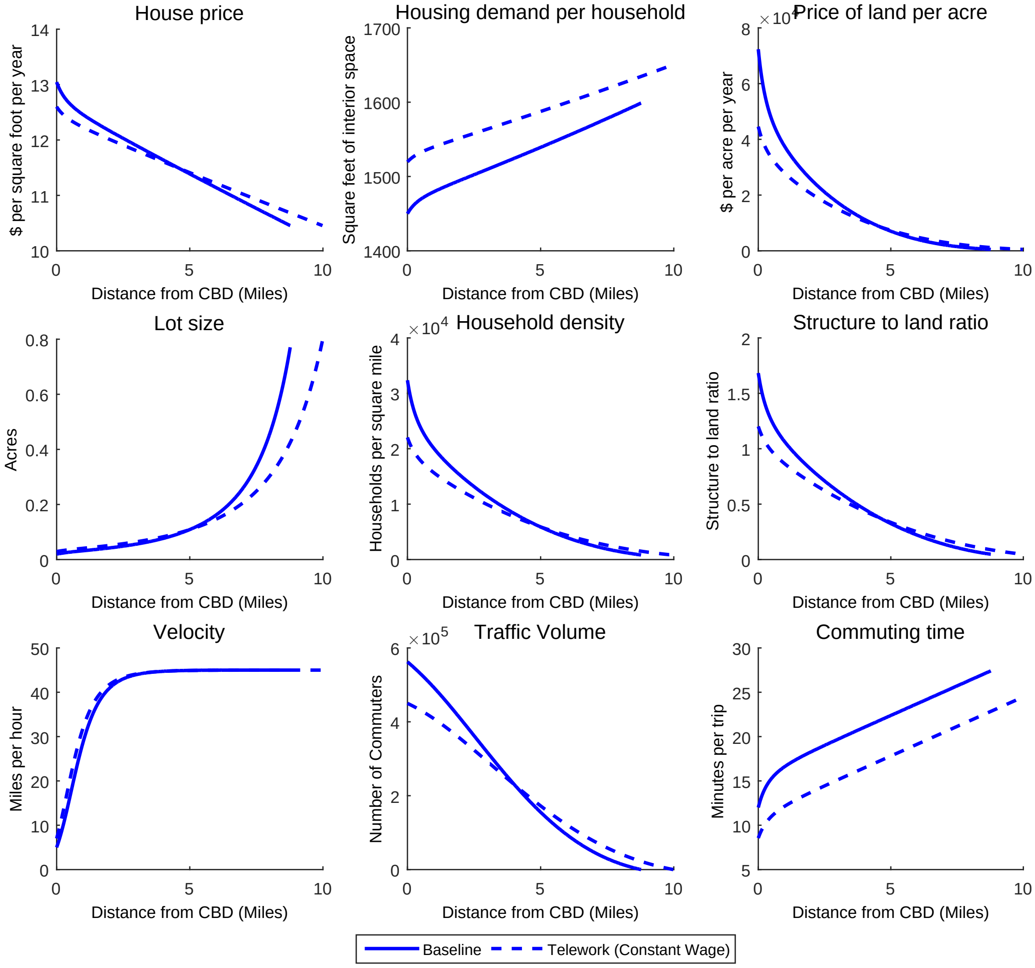


Figure 5: Baseline and Universal 20% Telework Simulations (Wage Constant) - Energy Consumption

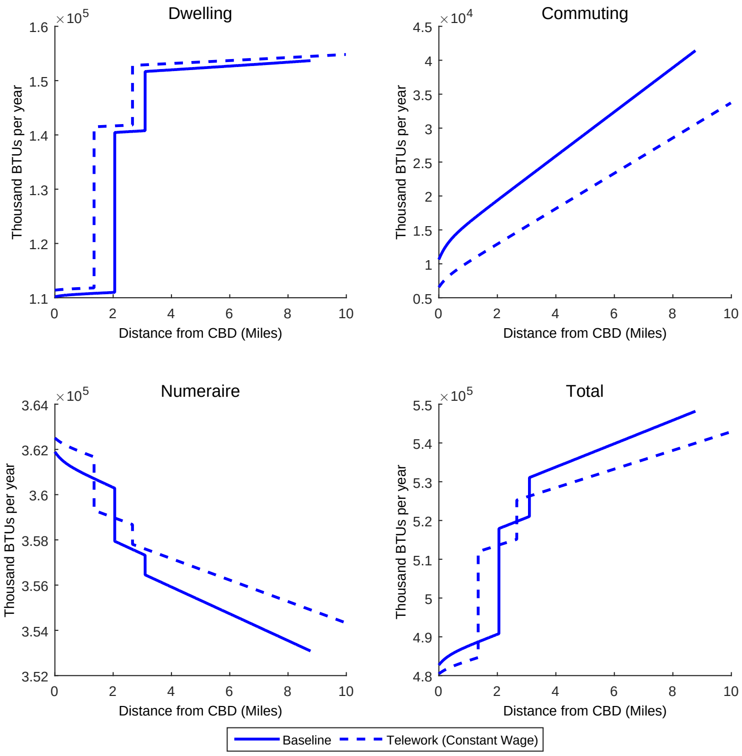


Figure 6: Bid-Rent Curves (Wage Discount)

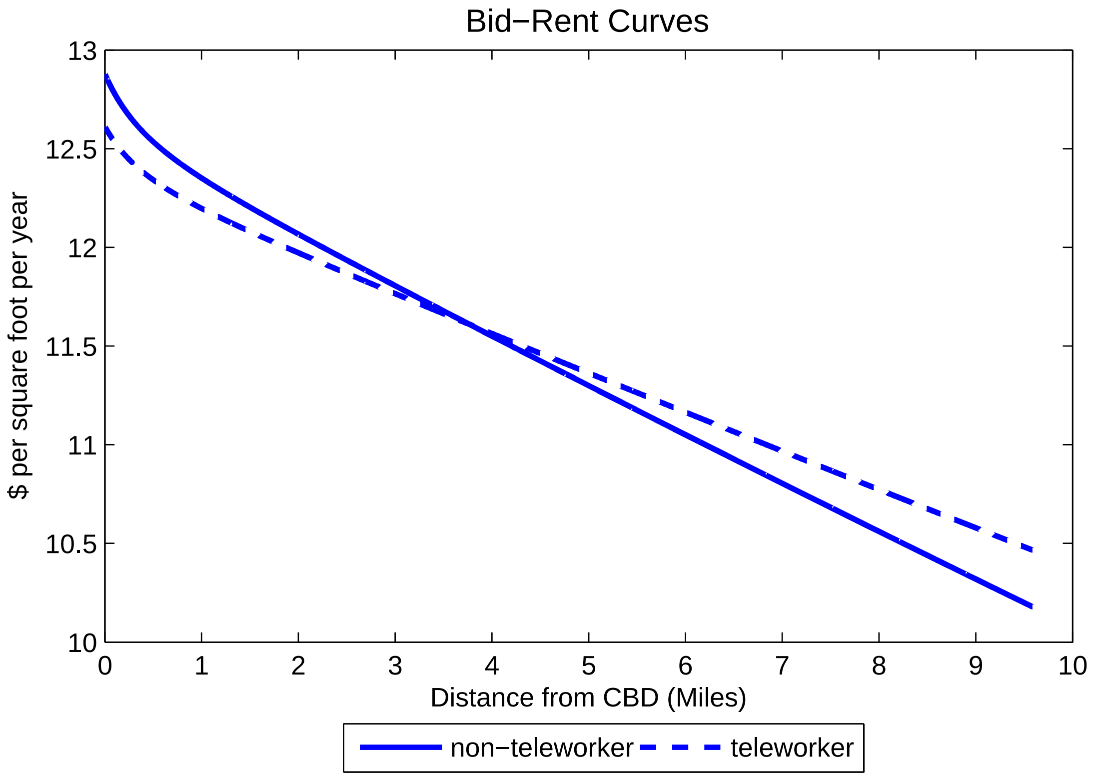
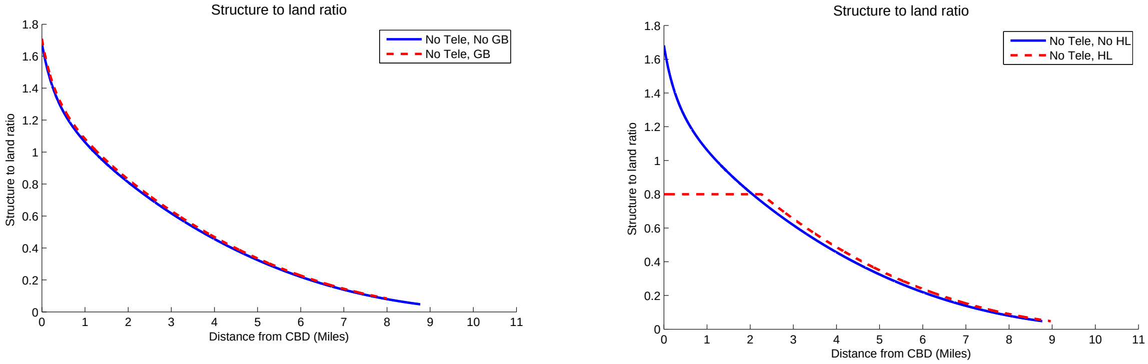


Figure 7: Telework with Urban Form Regulation (Wage Constant)

(a) Baseline, Greenbelt

(b) Baseline, Height Limit



(c) Telework, Greenbelt

(d) Telework, Height Limit

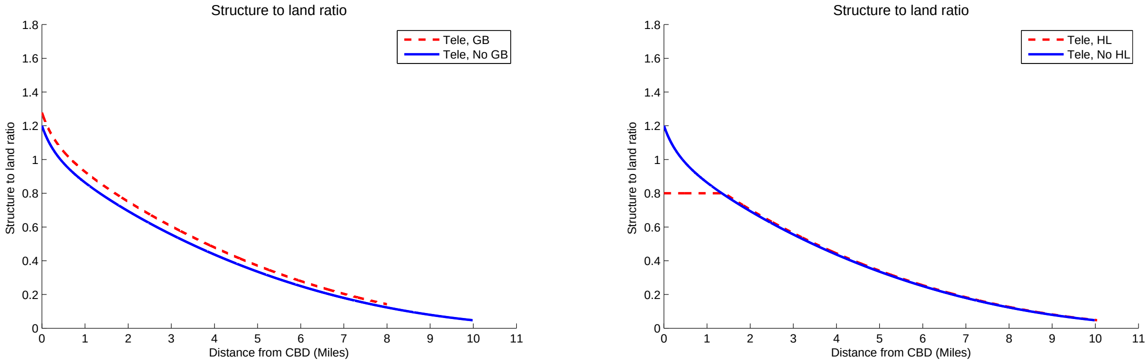


Table 1: Model Closing Conditions

Label	Wages	Population	Utility	Interpretation
Wage Constant	Fixed	Fixed	Free	Households bargain to keep wages as they were before telework.
Wage Discount	Free	Fixed	Fixed	Firms bargain to reduce wages so that households are no better off when teleworking.
Migration	Fixed	Free	Fixed	Households migrate to the city until residents are as well off as before telework.

Table 2: Simulation Calibration

City	Charlotte	Indianapolis	Kansas City	San Antonio	Average	Simulation
CBSA Code	16740	26900	28140	41700	Baseline	
Lot Size (acre) – Occupied Units[1]	0.36	0.31	0.25	0.20	0.28	0.16
Unit (square feet) – Occupied Units[1]	1,694	1,668	1,655	1,382	1,599	1,519
Area (sq. miles)[2]	444	409	515	505	468	300
Radius (assuming circle)[2]	11.9	11.4	12.8	12.7	12.2	9.8
Wharton Regulatory Index (WRLURI, 2008)	-0.53	-0.74	-0.79	-0.21	-0.57	-
Unavailable Land (Saiz, 2010)	5%	1%	6%	3%	4%	0%
Median Income[2]	$ 50,702	$ 46,970	$ 49,001	$ 43,586	$ 47,565	$ 49,868
Total Occupied Units[2]	412,445	410,594	360,109	547,627	432,694	450,000
Time to work[2]	25.1	23.8	22.3	24.6	23.9	20.3
Telework Share[2]	3.0%	2.0%	2.3%	2.4%	2.4%	0%
Fraction housed in 1 unit structures[2]	71%	71%	70%	54%	66%	55%
Fraction housed in 2-4 unit structures[2]	12%	12%	15%	14%	13%	17%
Fraction housed in 5+ unit structures[2]	16%	17%	15%	32%	20%	28%
Dwelling Energy (mmBTUs/hh)[3]	-	-	-	-	49.84	42.01

[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

Table 3: Simulation Parameters

Parameter	Baseline	Description	Source
$1/(1-\rho)$	0.75	Elast. of substitution in the housing prod. function	Altmann and DeSalvo (1981)
α_1	1	Structure share parameter in housing production function	Muth (1975); Altmann and DeSalvo (1981)
α_2	0.03	Land share parameter in housing production function	Muth (1975); Altmann and DeSalvo (1981)
A	0.105	Housing production technology parameter	Calibrated
$1/(1-\eta)$	0.75	Elasticity of substitution in the utility function	Altmann and DeSalvo (1981)
β_1	1	Numeraire share parameter in utility function	Numeraire
β_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)
θ	0.25	Fraction of land used for housing	Muth (1975)
θ_R	0.25	Fraction of land used for roads	Muth (1975)
k_{CBD}	1	City radius of the CBD	Calibrated
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)
τ	0.5	Time cost of commuting (fraction of wage)	Bertaud and Brueckner (2005)
p_g	3.5	Gasoline price per gallon	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)
$\bar{U}$	3200	Reservation utility	Calibrated
q_0	0.8	5+ unit building floor-area ratio cutoff	Calibrated
q_1	0.7	2-4 unit building floor-area ratio cutoff	Calibrated
q_2	0.6	sf. attached floor-area ratio cutoff	Calibrated

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

Table 4: Scenario 1 - Universal 20% Telework

Simulation Output	Baseline	Scenario					
		Wage Discount		*Wage Constant*		*Migration*	
		Δ	%Δ	Δ	%Δ	Δ	%Δ
Urban Form							
Total Occupied Units	450,000	-	0.0%	-	0.0%	201,591	44.8%
Lot Size (acre) – Detached Units	0.160	0.006	3.9%	0.012	7.4%	0.001	0.6%
Unit (square feet) – All Units	1,519	11	0.8%	61	4.0%	2	0.1%
City Area (sq. miles)	300	66	22.2%	79	26.3%	146	48.6%
City Radius (assuming circle)	9.8	1.0	10.5%	1.2	12.4%	2.1	21.9%
Residential Struct./Land ratio (CBD)	1.68	(0.48)	-28.6%	(0.48)	-28.6%	0.02	1.2%
Residential Density (hh per sq. mile)	1,516	(278)	-18.3%	(319)	-21.0%	(44)	-2.9%
Time to work	20.3	(3.7)	-18.1%	(3.6)	-17.5%	5.7	28.0%
Fraction housed in 1 unit structures	54.9%	14.6%	26.6%	14.8%	26.9%	2.0%	3.6%
Fraction housed in 2-4 unit structures	16.7%	0.4%	2.5%	0.4%	2.4%	0.1%	0.8%
Fraction housed in 5+ unit structures	28.4%	-15.0%	-53.0%	-15.2%	-53.4%	-2.1%	-7.4%
Income/Expenditure Accounting							
Base Income	$49,868	(1,467)	-2.9%	-	0.0%	-	0.0%
Numeraire Expenditure	$28,157	(1097)	-3.9%	(215)	-0.8%	43	0.2%
Time Cost of Commuting	$2,642	(962)	-36.4%	(899)	-34.0%	63	2.4%
Housing Services Expenditure	$17,844	(171)	-1.0%	399	2.2%	(24)	-0.1%
Energy Expenditure	$1,477	64	4.3%	79	5.3%	9	0.6%
Non-Energy Expenditure	$16,366	(235)	-1.4%	320	2.0%	(33)	-0.2%
Commuting Expenditure	$3,868	(198)	-5.1%	(183)	-4.7%	(19)	-0.5%
Gasoline Expenditure	$571	(137)	-24.0%	(131)	-23.0%	0	0.1%
Non-Gasoline Expenditure	$3,297	(62)	-1.9%	(52)	-1.6%	(20)	-0.6%
Energy Consumption per Household (million BTUs)							
Total	520.4	(10.3)	-2.0%	2.1	0.4%	0.8	0.2%
Numeraire	357.2	(10.4)	-2.9%	0.4	0.1%	(0.1)	0.0%
Commuting and Dwelling	163.2	0.1	0.1%	1.7	1.1%	0.9	0.5%
Commuting	24.6	(5.9)	-24.0%	(5.7)	-23.0%	0.0	0.1%
Dwelling	138.6	6.0	4.3%	7.4	5.3%	0.9	0.6%
Welfare Measures							
Households Attracted to City	450,000	-	0.0%	-	0.0%	201,591	44.8%
Firms' Wage Paid	$ 49,868	(1,467)	-2.9%	-	0.0%	-	0.0%
Utility per Household	5,200	-	0.0%	168	3.2%	-	0.0%
CO_2 Emissions per Household (tons)							
Total	27.63	(0.69)	-2.5%	(0.04)	-0.1%	0.04	0.2%
Electricity (Numeraire and Housing)	25.70	(0.23)	-0.9%	0.40	1.6%	0.04	0.2%
Gasoline (Commuting)	1.93	(0.46)	-24.0%	(0.44)	-23.0%	0.00	0.1%

Table 5: Comparison of Telework on the Intensive Margin

Fraction of households who telework Telework days per week	0% (Baseline)	100% 1 day	100% 2 days	100% 3 days	100% 4 days	100% 5 days
Wage Constant						
Urban Form						
City Radius (assuming circle)	9.77	10.98	12.54	14.78	18.58	28.09
Residential Struct./Land ratio (CBD)	1.68	1.20	0.83	0.52	0.26	0.05
Energy Consumption per Household (million BTUs)						
Total	520.4	522.5	525.3	524.5	522.5	518.4
Commuting	24.6	18.9	14.4	10.6	6.8	-
Dwelling	138.6	146.0	153.0	155.6	156.8	158.5
Numeraire	357.2	357.6	357.8	358.3	358.8	359.9
Welfare Measure						
Utility per Household	5200.0	5368.0	5507.7	5630.3	5755.6	5940.0
Wage Discount						
Urban Form						
City Radius (assuming circle)	9.77	10.80	12.17	14.18	17.63	26.29
Residential Struct./Land ratio (CBD)	1.68	1.20	0.83	0.52	0.26	0.05
Energy Consumption per Household (million BTUs)						
Total	520.4	510.0	502.9	493.9	483.9	468.8
Commuting	24.6	18.7	14.0	10.2	6.5	-
Dwelling	138.6	144.6	150.4	152.0	152.1	152.4
Numeraire	357.2	346.8	338.5	331.8	325.3	316.4
Welfare Measure						
Firms' Wage Paid	$ 49,868	$ 48,401	$ 47,243	$ 46,272	$ 45,320	$ 43,986
Migration						
Urban Form						
City Radius (assuming circle)	9.77	11.91	15.40	22.15	41.26	-
Residential Struct./Land ratio (CBD)	1.68	1.70	1.71	1.70	1.64	-
Energy Consumption per Household (million BTUs)						
Total	520.4	521.2	522.3	523.8	525.6	-
Commuting	24.6	24.6	24.5	24.3	23.2	-
Dwelling	138.6	139.5	140.7	142.5	145.5	-
Numeraire	357.2	357.1	357.1	356.9	356.9	-
Welfare Measure						
Total Number of Households	450,000	651,589	1,048,896	2,050,092	6,444,686	-

Table 6: Comparison of Telework on the Extensive Margin

Fraction of households who telework Telework days per week	0% (Baseline)	100% 1 day	50% 2 days	33% 3 days	25% 4 days	20% 5 days
Wage Constant						
Urban Form						
City Radius (assuming circle)	9.77	10.98	12.03	13.03	14.16	15.64
Residential Struct./Land ratio (CBD)	1.68	1.2	1.32	1.34	1.35	1.36
Energy Consumption per Household (million BTUs)						
Total	234,165	235,127	235,003	234,715	234,491	234,241
Commuting	11,049	8,504	8,154	7,945	7,747	7,522
Dwelling	62,371	65,699	65,873	65,754	65,686	65,618
Numeraire	160,744	160,924	160,976	161,017	161,059	161,102
Welfare Measure						
Utility per Household	5,200	5,368	5,397	5,412	5,423	5,434
non-Telework Household	5,200	-	5,313	5,311	5,309	5,307
Telework Household	-	5,368	5,481	5,615	5,766	5,940
Wage Discount						
Urban Form						
City Radius (assuming circle)	9.77	10.83	11.67	12.57	13.6	14.94
Residential Struct./Land ratio (CBD)	1.68	1.2	1.32	1.34	1.35	1.36
Energy Consumption per Household (million BTUs)						
Total	234,165	229,533	228,525	227,864	227,368	226,890
Commuting	11,049	8,408	8,053	7,857	7,675	7,467
Dwelling	62,371	65,069	65,121	64,952	64,845	64,744
Numeraire	160,744	156,056	155,351	155,055	154,848	154,678
Welfare Measure						
Firms' Wage Paid, Average	\$49,868	\$48,399	\$48,173	\$48,071	\$47,997	\$47,933
non-Telework Household	\$49,868	-	\$48,869	\$48,893	\$48,907	\$48,920
Telework Household	-	\$48,399	\$47,477	\$46,424	\$45,266	\$43,985

Table 7: Interaction of Telework with Urban Form Regulation

Scenario: Universal 20% Telework, Wage Constant Case

	(1) Baseline	(2) Baseline w/regulation	(3) %Δ (2) vs (1)	(4) Telework	(5) Telework w/regulation	(6) %Δ (4) vs (1)	(7) %Δ (5) vs (2)	(8) Δ (5) vs (4)
Height Limit								
Urban Form								
City Radius (assuming circle)	9.77	9.97	2.00%	10.98	11.04	12.40%	10.79%	0.53%
Residential Struct./Land ratio (CBD)	1.68	0.80	-52.47%	1.20	0.80	-28.62%	0.00%	-33.40%
Energy Consumption per Household (million BTUs)								
Total	520.4	529.1	1.68%	522.5	526.4	0.41%	-0.51%	0.75%
Commuting	24.6	25.6	4.46%	18.9	19.2	-23.04%	-25.24%	1.47%
Dwelling	138.6	147.1	6.14%	146.0	150.0	5.33%	1.96%	2.73%
Numeraire	357.2	356.3	-0.24%	357.6	357.2	0.11%	0.25%	-0.10%
Welfare Accounting								
Utility per Household	5200.0	5187.8	-0.24%	5368.0	5365.2	3.23%	3.42%	-0.05%
Greenbelt								
Urban Form								
City Radius (assuming circle)	9.77	9.00	-7.90%	10.98	9.00	12.40%	-0.01%	-18.07%
Residential Struct./Land ratio (CBD)	1.68	1.71	1.61%	1.20	1.28	-28.62%	-25.19%	6.50%
Energy Consumption per Household (million BTUs)								
Total	520.4	519.2	-0.23%	522.5	518.9	0.41%	-0.06%	-0.69%
Commuting	24.6	24.2	-1.62%	18.9	17.8	-23.04%	-26.52%	-6.07%
Dwelling	138.6	137.7	-0.66%	146.0	143.1	5.33%	3.95%	-1.97%
Numeraire	357.2	357.4	0.04%	357.6	358.0	0.11%	0.19%	0.12%
Welfare Accounting								
Utility per Household	5200.0	5196.2	-0.07%	5368.0	5354.3	3.23%	3.04%	-0.26%

Table 8: Telework and CO_2 Emissions

Scenario: Universal 20% Telework, Wage Constant Case

	Baseline Tons of CO_2 per HH per Year	%Δ
Electricity Mix, 2014 USA Average: Coal 39%, Natural Gas 27%, Green 34%		
Total Emissions	27.63	-0.14%
Electricity (Numeraire and Housing)	25.70	1.57%
Gasoline (Commuting)	1.93	-23.03%
Electricity Mix, Coal Region: Coal 100%		
Total Emissions	55.23	0.71%
Electricity (Numeraire and Housing)	53.30	1.57%
Gasoline (Commuting)	1.93	-23.03%
Electricity Mix, Natural Gas Region: Natural Gas 100%		
Total Emissions	30.94	0.03%
Electricity (Numeraire and Housing)	29.01	1.57%
Gasoline (Commuting)	1.93	-23.03%
Electricity Mix, Future Green Scenario: Coal 25%, Natural Gas 25%, Green 50%		
Total Emissions	22.51	-0.54%
Electricity (Numeraire and Housing)	20.58	1.57%
Gasoline (Commuting)	1.93	-23.03%

Note: "Green" includes any source that does not directly produce CO_2 emissions from non-renewable sources. This includes nuclear, wind, solar, hydroelectric, and biomass. In the case of biomass, emissions are considered CO_2-neutral due to the CO_2 capture during the creation of the biomass.