Analyzing Anti-Sprawl Policies in a Location Model with Congestion, Agglomeration Economies and Open Space*

Chen Feng Ng

Abstract

This paper develops a model with heterogeneous households and firms who can locate anywhere in the city. The main features of the model are traffic congestion and household preferences for open space, both of which are closely associated with urban sprawl. The model also includes agglomeration economies, providing a more complete picture of how households and firms choose locations. Numerical results show equilibrium location patterns, rents, and wages under different model specifications. This paper then compares the impacts of two popular anti-sprawl policies: urban growth boundaries (UGBs) and congestion pricing. Congestion pricing may not be optimal when unsubsidized agglomeration economies are very high, and a UGB may or may not be welfare-improving, depending on the strength of household preferences for open space.

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1 Introduction

The trend toward suburbanization and decentralization has led to rising popular concern about urban sprawl. Although there are many different definitions of sprawl, it is generally associated with low-density, scattered development that causes urban boundaries to expand spatially. Sprawl has been blamed for a host of problems, such as traffic congestion and air pollution as a result of long commutes, loss of open space, encroachment on wildlife sanctuaries, expensive infrastructure, low aesthetic value, income segregation, reduced social interaction, and even obesity.

Numerous policies have been proposed to combat sprawl or specific problems associated with it. These policies include urban growth boundaries (UGBs), open space preservation, congestion pricing, zoning laws, development taxes, infill development, and regional land-use planning.

To analyze the impacts of different anti-sprawl policies, this paper develops a model in which travel is subject to traffic congestion, households have preferences for open space and there are agglomeration economies, where a firm's output depends positively on its proximity to other firms. It is reasonable to think that households place some amenity value on open spaces such as forests, parks, mountains, etc. Meanwhile, aside from Arnott (2007), there has been very little research on the impacts of anti-sprawl policies in the presence of agglomeration economies. Including agglomeration economies in the model helps provide a more complete picture of how firms choose locations. This is especially important since agglomeration economies and traffic congestion can have opposing effects, with the former leading firms to cluster together and the latter encouraging the dispersion of firms.

The basic setup of the model is that the city is linear, with a greenbelt at either end. Households and firms have heterogeneous preferences and can locate anywhere within the city, leading to dispersed employment. Each household has one worker, who can travel in either direction to his/her workplace, and each firm employs one worker.

To see how the different features of the model come into play, it is useful to examine the equilibrium location patterns, rents, and wages that emerge under different model specifications, e.g., with or without agglomeration economies. We then compare the impacts of two popular anti-sprawl policies: a UGB which increases the amount of open space but reduces the amount of land available for residences and firms; and a tolling policy based on the marginal external cost of congestion.

From numerical results we can see that congestion pricing may not be optimal when agglomeration economies (which are unsubsidized) are very high because the policy causes households and firms to distribute more evenly across the city. Meanwhile, a UGB may or may not be welfare-improving, depending on the strength of household preferences for open space.

It is hoped that this paper adds to the literature on urban location models and sprawl by highlighting the interplay between congestion, agglomeration economies and open space preferences. This can help us gain a deeper understanding of how different policies affect households' and firms' location decisions in real life.

This paper first discusses the relevant literature on urban sprawl and anti-sprawl policies. Section 3 sets up the model, while the next section discusses how the model is solved. Section 5 compares the results of different model specifications and Section 6 examines the impacts of UGBs and congestion pricing. Section 7 concludes.

2 Urban sprawl and anti-sprawl policies

Bruegmann (2005) provides a historical overview of urban sprawl, its causes and remedies. He defines sprawl as "low-density, scattered, urban development without systematic large-scale or regional public land-use planning" (p. 18). He shows that many American cities, especially the older ones, have declined sharply in density since 1950, but this decline has either slowed or stopped since the late 1970s. He also points out that Los Angeles, often held up as the quintessential example of sprawl, is the densest urban area in the United States. In that case, defining sprawl as low-density development may seem at odds with popular opinion.

Two measures of urban sprawl have been developed by Ewing et al (2002) and Burchfield et al (2006). The former attempt to measure sprawl based on mix of jobs and housing, street network, residential density and centers of activity. Meanwhile, Burchfield et al's sprawl index is based on the percentage of undeveloped land surrounding an average residential development. Although there are some differences in their rankings of cities, both Ewing et al and Burchfield et al rank Greensboro and Atlanta among the most sprawled metropolitan areas while New York City is near the opposite end of the scale. Both indices rank the Los Angeles metropolitan area somewhere in the middle. In Section 6 I develop an index based on the Gini coefficient in order to compare the effects of UGBs and congestion pricing on urban structure in my model.

In terms of theoretical papers, Nechyba and Walsh (2004) argue, based on the standard monocentric city model, that declining transportation costs and rising incomes have enabled households to live further from their workplaces and occupy larger lots of land. Meanwhile, Brueckner (2001) distinguishes between sprawl due to fundamental forces and "excessive" spatial growth. The latter arises because of three main market failures: the failure of developers to take into account the value of open space, unpriced road congestion, and underpriced infrastructure for developers.

Numerous papers have examined the impacts of various anti-sprawl policies. These papers differ widely in terms of their modeling assumptions. Using a model where jobs are all located at a single point in the city center, Brueckner (2005) finds that UGBs are second-best to congestion tolls, although the utility gain from the former is very small. On the other hand, Anas and Rhee (2006) find that UGBs are not second-best policies in a model incorporating dispersed employment, discretionary trips, individual heterogeneity and a greenbelt at the city periphery.

Bento et al (2006) use a model with a greenbelt but with no traffic congestion to evaluate how policies aimed at preserving open space affect landowners at different locations. One of the few models which has open space both within and outside the city is formulated by Walsh (2007) using a zonal approach calibrated with data from North Carolina. Meanwhile, Turner (2005) has developed a model where preferences for open space may lead to scattered development.

Since the effects of various anti-sprawl policies may depend critically on modeling assumptions, careful attention should be paid to these assumptions. I try to provide a more realistic and complete picture of how firms and households choose their locations with this model, especially in terms of open space preferences and agglomeration economies.

2.1 The importance of open space and agglomeration economies

It is reasonable to think that households place some amenity value on open space both within and outside the city.[1] However, it is difficult to pin down the value of open space, partly because it is associated with a use value as well as an existence value, and also because most studies have looked at specific parcels of open space or housing markets. Some studies have used contingent valuation methods based on stated preference surveys, e.g., Breffle et al (1998), Earnhart (2006) and McGonagle and Swallow (2005). Other studies have used hedonic regressions to look at the capitalization of environmental amenities in house prices. For instance, Anderson and West (2006), Doss and Taff

[1] Open space is used as a generic term to indicate land (or water) that is not used for residential, commercial or industrial development. It can be either natural (forests, mountains, marshes, etc) or man-made (neighborhood parks, golf courses, etc).

(1996) and Shultz and King (2001) find that proximity to certain types of open space positively influence housing values.

The safest conclusion is that willingness-to-pay for open space varies widely depending on the type of open space in question and household characteristics. The alternative uses of a particular tract of open space as a result of possible development probably also affect how individuals value its preservation. It is evident, though, that households do place some value on their proximity to and the size of many types of open space.

Meanwhile, agglomeration economies have yet to be explicitly incorporated in a model analyzing sprawl policies, aside from Arnott's (2007) paper examining congestion tolling in the presence of agglomeration economies. It is probable that agglomeration economies are not viewed as an issue that is closely associated with sprawl. However, agglomeration economies have a tendency to draw firms to locate closer together and thus create more compact cities, but not all of its advantages are internalized by firms. Thus, it is important to take agglomeration economies into account to get more accurate comparisons of various anti-sprawl policies' welfare effects.

Agglomeration economies for urban firms can be classified either as localization economies (firms from the same industry benefit from locating close to each other) or urbanization economies (firms benefit from the scale and diversity of firms in other industries). These proximity effects arise because of various factors: access to a large – possibly specialized – labor pool or common inputs, knowledge spillovers, large demand markets, and common infrastructure (see Fujita and Thisse [2002] for an overview).

Numerous studies have provided empirical evidence for agglomeration economies in general, e.g., Ellison and Glaeser (1997) and Rosenthal and Strange (2003). One of the most important findings of the latter paper is that agglomeration economies attenuate rapidly with distance, at least initially. Meanwhile, Glaeser et al (1992) find evidence of urbanization economies but not localization economies, while Henderson (2003) finds that localization economies had stronger productivity effects in high-tech industries than urbanization economies.

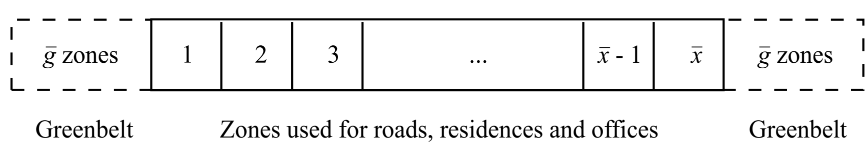
Although there may be disagreement as to whether localization or urbanization economies are prevalent in different industries, it is clear that firms do tend to cluster together and not just because of geographic features or natural resources. Therefore, it is important that an urban model in which firms choose their locations take agglomeration economies into account.

Another reason for including agglomeration economies is that agglomeration also causes congestion, which mitigates the benefits of clustering together. Since traffic congestion is one of main problems associated with sprawl, the inclusion of agglomeration economies gives a more complete picture of how firms and households trade off various factors in their location decisions.

3 Mathematical setup of the model

The city is linear, and land is divided into zones which can be either used for residences, offices and roads, or kept undeveloped as greenbelts at the city periphery (see Figure 1). The size of the greenbelt at either end of the city is $\bar{g}$ zones, where $\bar{g}$ is chosen exogenously. The habitable zones are indexed $x = 1, 2, ..., \bar{x}$ from left to right, with $\bar{x}$ also chosen exogenously. Each zone can be thought to have $\sqrt{Z}$ length and width, and so the amount of land available in each zone is Z.

Figure 1: Layout of the city



It is assumed that land goes to the household or firm willing to pay the highest rent, i.e., the highest bidder for land. Some exogenous fraction of land in each zone, ρ, is devoted to roads. Both leftward and rightward travel is allowed in the city, and may be subject to traffic congestion.

Following Anas (1990), it is assumed that households and firms have heterogeneous preferences, based on random utility theory. Households can locate in any zone and the number of households in the city is fixed at N (thus the city is closed). Each household has one worker. Firms, which can also locate anywhere in the city, employ one worker each, and so the number of firms is equal to N as well. It is assumed that land rents, firm profits and toll revenues (if congestion tolls are imposed) are distributed equally to households. The following subsections discuss the decision-making process of households and firms in detail.

3.1 Households

The household chooses consumption of the numeraire good, c, residential lot size, q_h, residential location, x_h, and workplace location, x_w. It pays rent $r(x_h)$ and receives wage $w(x_w)$. The household can travel either leftward or rightward to its job location, so its one-way commute is $|x_h - x_w|$.

The household's utility function depends on its consumption of the numeraire good, lot size, open space (s), and idiosyncratic taste for its residential and workplace locations (ε_h):

$$U(c, q_h, x_h, x_w) = \mu_1 \ln c + \mu_2 \ln q_h + \eta \ln s(x_h) + \varepsilon_h(x_h, x_w) \tag{1}$$

where it is assumed that $\mu_1 + \mu_2 = 1$ and $\mu_1, \mu_2, \eta \geq 0$.

The consumption of open space, $s(x_h)$, depends on the household's proximity to the greenbelts at either end of the city:

$$
\begin{aligned}
s(x_h) &= 1 + \alpha_1 \Big\{ \int_{1-\bar{g}}^{1} \exp\big[-\alpha_2(x_h - x)\big]\, dx + \int_{\bar{x}}^{\bar{x}+\bar{g}} \exp\big[-\alpha_2(x - x_h)\big]\, dx \Big\} \\
&= 1 + \frac{\alpha_1}{\alpha_2}\Big\{1 - \exp(-\alpha_2 \bar{g})\Big\}\Big\{ \exp\big[\alpha_2(1 - x_h)\big] + \exp\big[\alpha_2(x_h - \bar{x})\big]\Big\}
\end{aligned}
\tag{2}
$$

where $\alpha_1 \geq 0$ is the factor for the strength of open space values, while $\alpha_2 > 0$ determines the household's weight on proximity to the greenbelt. The first integral on the RHS is the value of open space from the greenbelt on the left side of the city, while the second integral is for the greenbelt on the right side. The functional form is chosen so that the value of open space declines with distance from the greenbelts, and when there is no open space outside the city, η has no effect on utility. The model can also be specified without preferences for open space, in which case η is set to be 0.

Heterogeneity among households is modeled along the lines of Anas (1990). ε_h is defined as an idiosyncratic constant measuring a household's preference for a joint residence-workplace combination, (x_h, x_w).[2] It is assumed that the $\bar{x}^2$ random variable $\{\varepsilon_h(x_h, x_w),\ x_h = 1, 2, ..., \bar{x},\ x_w = 1, 2, ..., \bar{x}\}$ is i.i.d. Gumbel with mean zero and variance $\sigma_h^2 = \frac{\pi^2}{6\lambda_h^2}$ where λ_h is the taste heterogeneity parameter. With this, the household's choice probabilities with respect to residence and workplace locations are multinomial logit; as $\lambda_h \to \infty$, taste idiosyncracies vanish (i.e., individuals are homogeneous) and as $\lambda_h \to 0$, random tastes dominate all other locational determinants (thus individuals choose randomly).[3]

[2] In this paper, we take the view of random utility as deterministic interhousehold variation, i.e., households which are otherwise similar have deterministic idiosyncratic tastes for locations. The idiosyncratic tastes of each household are unknown to the observer, but when the distribution of these idiosyncracies is known (and if the population of households is large relative to the number of location choices) we can predict the population's distribution of decisions. The same interpretation applies to firms in this model. Other views of random utility are stochastic instability (intrahousehold variation because of random changes in the utility function) or ex ante perception (households are not perfectly informed and make decisions based on ex ante perceived utility, which may differ from ex post utility). Anas (1982, pp. 49-79) provides an in-depth discussion on this topic.

[3] In the text, we refer to the household's choice of a residence-workplace combination as being proba-

It is assumed that all firm profits, rental income and toll revenues (if a congestion toll policy is imposed) are returned to households in the form of nonwork income. Let y denote the amount of nonwork income per household, which is equal across all households:

$$y = \frac{\left\{N\Omega\right\} + \left\{(1-\rho)Z\sum_{i=1}^{\bar{x}} r(i)\right\} + \left\{\sum_{i=1}^{\bar{x}}\left[n_L(i)\tau_L(i) + n_R(i)\tau_R(i)\right]\right\}}{N} \tag{3}$$

The first term in the numerator on the right hand side of the equation is total expected profits, with Ω denoting the firm's expected maximized profit level (to be determined). The second term is total rental income from land used for residential and office locations, where Z is the total area of each zone and ρ is the fraction of land used for roads. The last term is total toll revenues, which is set to 0 if there is no congestion toll policy. As detailed below, $n_L(i)$ and $n_R(i)$ are the number of households who are traveling leftward and rightward respectively in zone i, while $\tau_L(i)$ and $\tau_R(i)$ are the leftward and rightward tolls in that zone.

If there is no traffic congestion, the cost of traversing each zone is $\bar{t}$. In that case, total travel cost between x_h and x_w is $T(x_h, x_w) = \bar{t}|x_h - x_w|$. The household's budget constraint is thus:

$$y + w(x_w) - T(x_h, x_w) = c + r(x_h)q_h \tag{4}$$

Solving for c and substituting it in the utility function, we get (using simplified notation):

$$U = \mu_1 \ln\left[y + w - T - rq\right] + \mu_2 \ln q_h + \eta \ln s + \varepsilon_h \tag{5}$$

At any given household choice of (x_h, x_w), we can find the residential lot size, q_h, that

bilistic (see equation [8]) to retain the familiarity of the typical logit model, but this probability is more precisely the proportion of households who choose a specific residence-workplace combination.

maximizes utility by setting the differential of the above equation w.r.t. q_h equal to zero:

$$q_h = \left(\frac{\mu_2}{\mu_1 + \mu_2}\right)\left(\frac{y + w - T}{r}\right) \tag{6}$$

Since $\mu_1 + \mu_2 = 1$, replacing the above in equation (5) and subtracting ε_h results in the nonstochastic indirect utility function, V, conditional on residential and job location:

$$V(x_h, x_w) = \mu_1 \ln\big[\mu_1 \left(y + w - T\right)\big] + \mu_2 \ln\big[\left(\mu_2/r\right)\left(y + w - T\right)\big] + \eta \ln s \tag{7}$$

where $w = w(x_w), T = T(x_h, x_w)$, $r = r(x_h)$ and $s = s(x_h)$.

The number of possible joint location choices of (x_h, x_w) is $\bar{x}^2$, and the household's probability of choosing a particular residence-workplace combination i, j is:

$$P_h(i,j) = \frac{\exp\big[\lambda_h V(i,j)\big]}{\sum_{k=1}^{\bar{x}} \sum_{l=1}^{\bar{x}} \exp\big[\lambda_h V(k,l)\big]} \tag{8}$$

As in Anas (1990), the expected value of the maximized utility level (which is obtained using the Gumbel distributional assumptions) is used to measure the household's welfare, denoted by ψ:

$$\begin{aligned} \psi &\equiv E\Big\{\underset{i=1,\ldots,\bar{x};\ j=1,\ldots,\bar{x}}{\text{maximum}}\big[V(i,j) + \varepsilon_h(i,j)\big]\Big\} \\ &= \frac{1}{\lambda_h} \ln\left\{\sum_{i=1}^{\bar{x}} \sum_{j=1}^{\bar{x}} \exp\big[\lambda_h V(i,j)\big]\right\} \end{aligned} \tag{9}$$

If there is traffic congestion, travel cost at zone x is modeled along the lines of Brueckner (2005) and Anas and Rhee (2007). It is assumed that households going in one direction do not cause congestion to households going in the other direction, and total land used for roads (ρZ) is divided equally between rightward and leftward roads. For rightward travel, the cost of travel is:

$$t_R(x) = \delta + \gamma_1 \left[\frac{n_R(x)}{0.5\rho Z\nu}\right]^{\gamma_2} \tag{10a}$$

where the term in square brackets is the volume-to-capacity ratio. δ is the fixed cost of travel per zone, $n_R(x)$ is the number of households traveling rightward through that location, and γ_1, γ_2 and ν are parameters for congestion. Similarly, for leftward travel:

$$t_L(x) = \delta + \gamma_1 \left[\frac{n_L(x)}{0.5\rho Z\nu}\right]^{\gamma_2} \tag{10b}$$

It is assumed that households are on the road (and therefore cause congestion) in all the zones that they travel through during their commute including their origin (residence) zone but excluding their destination (work) zone. For rightward travel, $n_R(x)$ is the number of households who live in x and locations to the left of x and who work in locations to the right of x:

$$n_R(x) = N \sum_{i=1}^{x} \sum_{j=x+1}^{\bar{x}} P_h(i,j) \tag{11a}$$

For leftward travel, $n_L(x)$ is the number of households who live in x and locations to the right of x, and who work in zones to the left of x:

$$n_L(x) = N \sum_{i=x}^{\bar{x}} \sum_{j=1}^{x-1} P_h(i,j) \tag{11b}$$

For example, in a city with 4 habitable zones, the number of households who cause congestion in zone 3 are $n_R(3) = N[P_h(1,4)+P_h(2,4)+P_h(3,4)]$ and $n_L(3) = N[P_h(3,1)+P_h(3,2)+P_h(4,1)+P_h(4,2)]$ for rightward and leftward travel respectively.

Total travel cost is calculated for all the zones that the household travels through, including the residence zone but excluding the workplace zone. (With this, if the congestion parameter γ_1 is 0 and $\delta = \bar{t}$, total travel cost in this case is equal to that of the no-congestion case: $\bar{t}|x_h - x_w|$.) Travel cost is 0 for households who live and work in the same zone. Otherwise, for a household who lives in x_h and works in x_w, total rightward and leftward travel cost are, respectively:

$$T_R(x_h, x_w) = \sum_{i=x_h}^{x_w-1} t_R(i) \quad \text{if } x_h < x_w \tag{12a}$$

$$T_L(x_h, x_w) = \sum_{i=x_w+1}^{x_h} t_L(i) \quad \text{if } x_h > x_w \tag{12b}$$

If congestion tolls are imposed in the city, the toll in each zone is set equal to the marginal external cost of travel, i.e., the difference between marginal social travel cost and private travel cost in that zone, which is the Pigouvian tax. Note that if there are no other unpriced externalities in the city, then this would be the optimal toll. However, this may not be the case when there are unsubsidized agglomeration economies, since a tolling policy in this model causes firms to distribute more evenly across the city (as seen in Section 6). Arnott (2007) discusses this issue in depth with a variety of models. Including agglomeration economies subsidies (which is not a common anti-sprawl policy) in this model is a topic for future research.

For rightward travel, the toll in zone x would be:

$$\tau_R(x) = \frac{\partial \left[t_R(x) n_R(x)\right]}{\partial \left[n_R(x)\right]} - t_R(x) = \gamma_1 \gamma_2 \left[\frac{n_R(x)}{0.5\rho Z \nu}\right]^{\gamma_2} \tag{13a}$$

which is γ_2 times the part of t_R attributable to congestion. Similarly, for leftward travel:

$$\tau_L(x) = \gamma_1 \gamma_2 \left[\frac{n_L(x)}{0.5\rho Z \nu}\right]^{\gamma_2} \tag{13b}$$

When tolls are imposed, total rightward and leftward travel cost are:

$$T_R(x_h, x_w) = \sum_{i=x_h}^{x_w-1} \big[t_R(i) + \tau_R(i)\big] \quad \text{if } x_h < x_w \tag{14a}$$

$$T_L(x_h, x_w) = \sum_{i=x_w+1}^{x_h} \big[t_L(i) + \tau_L(i)\big] \quad \text{if } x_h > x_w \tag{14b}$$

Finally, the average commuting distance in the city can be computed as:

$$\text{Average commuting distance} = \sum_{i=1}^{\bar{x}} \sum_{j=1}^{\bar{x}} P_h(i, j)|i - j| \tag{15}$$

3.2 Firms

There are N firms that produce the numeraire good, each hiring one worker and renting q_f units of office space. The firm chooses its location x_f, and pays rent $r(x_f)$ and wage $w(x_f)$. It can be thought that firms take the price of the good as given, possibly because there is a world price for that good. Firms' output can be sold to households within the city or exported to other cities, and the city can import the good as well to meet local demand, all with zero transport and transaction costs.

Like that of Fujita and Ogawa (1982), this model assumes that there are agglomeration economies for firms: a firm's profit depends positively on its proximity to other firms with distance weighted by a negative exponential function. Since all firms produce the same good, this implies localization economies occur here. Let $F(x_f)$ denote the function for agglomeration economies:

$$F(x_f) = 1 + \beta_1 \sum_{i=1}^{\bar{x}} \big[\exp(-\beta_2|x_f - i|)NP_f(i)\big] \tag{16}$$

where $P_f(i)$ is the probability of a firm locating in zone i, so $NP_f(i)$ is the number of firms in that zone. $\beta_1 \geq 0$ determines the strength of the agglomeration economies and $\beta_2 > 0$ is the weight on distance. The model can also be specified without agglomeration economies, in which case $F(x_f) = 1$.

With this, let the firm's profit function be:

$$\Pi(q_f, x_f) = \theta q_f^\kappa F(x_f) - r(x_f)q_f - w(x_f) + \varepsilon_f(x_f) \tag{17}$$

where θq_f^κ is the firm's production function, with $\theta > 0$ as the scale parameter and $0 < \kappa < 1$. Similar to households, firms have idiosyncratic profits ε_f corresponding to different office locations. ε_f is i.i.d. Gumbel with mean zero and variance $\sigma_f^2 = \frac{\pi^2}{6\lambda_f^2}$. λ_f is some positive number where firms are more homogeneous the larger the value of λ_f. Note that since the number of firms is fixed, i.e., there is no free entry and exit of firms, there is no zero profit condition.

The firm first decides on the optimal amount of q_f conditional on office location x_f by maximizing equation (17), yielding:

$$q_f = \left(\frac{\kappa\theta F}{r}\right)^{\frac{1}{1-\kappa}} \tag{18}$$

Substituting (18) into (17) and subtracting the idiosyncratic constant ε_f yields a "systematic" profit function conditional on x_f, conceptually similar to the "systematic" indirect utility function, V, that was seen in the previous section:

$$\hat{\Pi}(x_f) = \left(\frac{\kappa\theta F}{r^\kappa}\right)^{\frac{1}{1-\kappa}} \left(\frac{1}{\kappa} - 1\right) - w \tag{19}$$

where $r = r(x_f), F = F(x_f)$ and $w = w(x_f)$.

Let $K = \left(\kappa\theta\right)^{\frac{1}{1-\kappa}}\left(\frac{1}{\kappa} - 1\right)$, which is a constant, resulting in:

$$\hat{\Pi}(x_f) = K\left(\frac{F}{r^{\kappa}}\right)^{\frac{1}{1-\kappa}} - w \tag{20}$$

With this, the firm's probability of choosing a particular office location i from $\bar{x}$ possible locations is:

$$P_f(i) = \frac{\exp\left[\lambda_f \hat{\Pi}(i)\right]}{\sum_{j=1}^{\bar{x}} \exp\left[\lambda_f \hat{\Pi}(j)\right]} \tag{21}$$

The expected value of the firm's maximized profit level (which is used in equation [3] to calculate nonwork income) is denoted by Ω and is similar to the household's expected maximized utility level:

$$\begin{aligned} \Omega &\equiv E\Big\{\underset{i=1,\ldots,\bar{x}}{\text{maximum}}\left[\Pi(\hat{i}) + \varepsilon_f(i)\right]\Big\} \\ &= \frac{1}{\lambda_f} \ln\left\{\sum_{i=1}^{\bar{x}} \exp\left[\lambda_f \hat{\Pi}(i)\right]\right\} \end{aligned} \tag{22}$$

3.3 Equilibrium conditions

Solving the model requires finding the rent and wage profiles that satisfy the following conditions:

- Land market equilibrium: The available supply of land for residences and workplaces in a zone is equal to the demand for land from all firms and households. The amount of land occupied by all firms in zone i is $Q_f(i) \equiv N P_f(i) q_f(i)$. Meanwhile, the sum of all households' residential land consumption in zone i is $Q_h(i) \equiv N \sum_{j=1}^{\bar{x}} P_h(i,j) q_h(i,j)$, where i indexes residential location and j indexes workplace location. Since ρ is the fraction of land used for roads and Z is total area in each zone, the land market equilibrium condition is:

$$Q_f(i) + Q_h(i) = (1 - \rho)Z \quad \text{for all } i \tag{23}$$

- Labor market equilibrium: Each household is associated with a workplace. That is, for each zone, the household's marginal probability of choosing that zone as its workplace multiplied by the number of households is equal to the firm's probability of choosing the same location multiplied by the number of firms.

$$N \sum_{i=1}^{\bar{x}} P_h(i, j) = NP_f(j) \quad \text{for all } j \tag{24}$$

With this, there are $2\bar{x}$ variables to be solved for (i.e., rents and wages in each zone) and a corresponding number of equations from the land and labor market equilibria conditions. The model can thus be solved as a system of equations.

4 Solving the model

4.1 Parameter values

Numerical results are obtained for the model using the parameter values listed below, which are based on previous literature where available. Sensitivity analyses with respect to the parameter values were performed, and are highlighted in the results section. Note that all monetary parameters and variables are in tens of thousands of dollars.

It is assumed that the number of households in the city, N, is 500,000. Each zone is assumed to be 3 miles in length and in width, and total area of each zone is 9 square miles (5760 acres). There are 15 habitable zones ($\bar{x} = 15$) and the size of each greenbelt, $\bar{g}$, is initially 1. With this, the entire city, including greenbelts, covers an area of 153 square miles (97,920 acres). Following Brueckner's (2006) example, the fraction of land used for roads in each zone, ρ, is assumed to be 0.2.

The household's weights on the numeraire good and on lot size (μ_1 and μ_2) are set at 0.8 and 0.2, respectively. The weight on open space in the utility function, η, is set at 0.1, while α_1 and α_2 in the open space function are set at 1 and 0.25 respectively. With these parameter values, having 1 zone of open space at each end of the city adds about 5% to the household's welfare, and the value of open space declines moderately with distance. As in Anas and Rhee (2007), the taste heterogeneity parameter for households, λ_h, is set at 10.

When there is no congestion, travel cost is approximated from Small and Verhoef's (2007, Table 3.3) calculation that operating and vehicle capital cost per vehicle-mile is \$0.31 in 2005 dollars. Rounding down to \$0.30 per mile, and assuming households travel to and from work 5 days a week, 50 weeks a year, the annual travel cost to traverse a zone is \$450, so $\bar{t} = 0.045$.

If there is congestion, the fixed cost of travel per zone, δ, is set equal to $\bar{t}$. As in Brueckner (2006), the exponent in the congestion function, γ_2, is set at 1.5. The other congestion parameters in equations (10a) and (10b), γ_1 and ν, are set at 0.008 and 75 respectively.

For firms, the scale factor in the production function, θ, is set at 4. The weight on lot size in the production function, κ, is set at 0.15, to generate results where households occupy 60-70% of total land in each zone. As in the case of households, the taste heterogeneity parameter for firms, λ_f, is set at 10. The multiplicative factor in the agglomeration economies function, β_1, is set at 0.0000006 to reflect Ciccone and Hall's (1996) finding that the elasticity of average labor productivity with respect to employment density is 0.06. Meanwhile, in line with Rosenthal and Strange's (2003) paper showing that agglomeration economies attenuate rapidly with distance, β_2 is set at 0.5.

4.2 Rent and wage levels

The model is solved as a system of equations for rents and wages in each zone using GAMS (General Algebraic Modeling System). In each model specification there is a unique solution for the rent profile.[4] It should be noted that many different initial values (including non-symmetric ones) are used to see if the GAMS algorithm always converges to the same values.

However, there is a continuum of wage levels that satisfy the equilibrium conditions, although the pattern of the wage profile is the same across solutions. This is because firms' profits depend linearly on wages, and so an increase in the household's wage corresponds to a decrease in its nonwork income from firms' profits. Due to the nature of the model, wage profiles that differ only by a constant all produce the same result in terms of household and firm behavior, e.g., $P_h(i, j)$ is the same in all solutions for a particular model specification. Although profit levels differ in magnitude depending on the wage level, firms' location decisions depend not on the magnitude of profits, but the relative differences in profits across zones. Moreover, firm lot sizes are not affected by the wages paid (see equation [18]). Thus, the equilibrium location pattern, rents, probabilities, lot sizes and utility level in each model specification are always the same regardless of the wage level.

To make it easier to compare wage profiles across different model specifications, the wage level is normalized so that the lowest wage paid by a firm in the city is 2.3 (equivalent to $23,000).[5] For instance, if in solving the model we find that the center zone (zone

[4] Since city size is fixed in this model, there is no boundary rent condition. In most standard urban models where the size of the city is endogenous, this condition requires that the rent at the edge of the city is equal to agricultural rent, and rents everywhere else within the city are greater than or equal to agricultural rent.

[5] This number was chosen so that the firm's "systematic" profit in each zone was around 0 in equilibrium. Profit levels which are large positive numbers are avoided for the sake of computational accuracy because they enter into the exponential function in equation (17). Note also that although this may seem like a low wage, total household income comprises wage and nonwork income (which is derived from firm profits, rental income and toll revenues, if applicable).

8) has the lowest wage, that zone's wage is set to 2.3 and wages in all other zones are adjusted correspondingly. With this normalization, the value of the lowest wage can be thought of as the household's reservation wage.

5 Results from different model specifications

The model can be specified with various combinations of the main features (preferences for open space, agglomeration economies and traffic congestion), to see how the presence of each feature affects location patterns, rents and wages. This section presents the results of four model specifications:

- "Bare" (no open space preferences, no agglomeration, no congestion);
- "S" (open space preferences);
- "SA" (open space preferences and agglomeration); and
- "SAC" (open space preferences, agglomeration and congestion).

We will then look at location patterns (including polycentric firm locations) that emerge under different parameter values. The next section uses the complete model with all three features to compare the impacts of congestion tolls and urban growth boundaries (UGBs).

Even though the model does not have any explicit symmetry constraints, the location patterns, rents, and wages that emerge for all model specifications are symmetric. This is not unexpected, since households can travel in either direction and zones are not differentiated prior to solving the model, except in terms of location and proximity to the greenbelts (which flank the city on both sides).

Aside from equilibrium location patterns (i.e., the probabilities of household and firm locations), rents and wages, other variables of interest are resulting lot sizes, average commuting distance, and of course, welfare. Lot size for a household, $q_h(i, j)$, depends on the household's residence and workplace locations. The (weighted) average household lot size in zone i is calculated as $\left[\sum_{j=1}^{\bar{x}} P_h(i, j) q_h(i, j)\right] / \left[\sum_{j=1}^{\bar{x}} P_h(i, j)\right]$.[6]

5.1 The "Bare" specification

Figures 2-4 show the results for the "Bare" specification and the other specifications using the parameter values listed in the previous section. In the "Bare" model with no open space preferences and no externalities, the equilibrium rent profile has an inverted U-shape, as seen in Figure 2a. Rents are higher in the center zones because households prefer to live there for greater accessibility to jobs everywhere in the city. This can be seen from the household's marginal probability of residential location in each zone (Figure 3a). However, the supply of land in each zone is limited, and so higher rents in the center work to dampen residential demand while the lower rents in the outer zones attract households to reside there.

The rent profile has a similar effect on firms' demand for office locations. However, the labor market equilibrium condition also comes into play here - demand for jobs is highest in the center zones due to their accessibility, and so in order for the supply of jobs to meet demand, there is a higher concentration of firms in the center zones as seen in Figure 3b. Higher rents in the center are offset by the U-shaped wage profile (Figure 2b) where firms in the outer zones have to pay higher wages in order to compensate

[6] It should be noted that the discussion of the results is related to the household's average lot size in each zone. However, lot sizes vary within zones because q_h depends on travel costs as seen in equation (6). Households who live and work in the same zones have bigger lots than households who work several zones away. In general, there are relatively more large lots than small lots within each zone because the probability of a household working in zones near its residential zone (who thus has a larger lot size) is higher than the probability of a household working in a zone far away.

Figure 2: Rents and wages under different model specifications

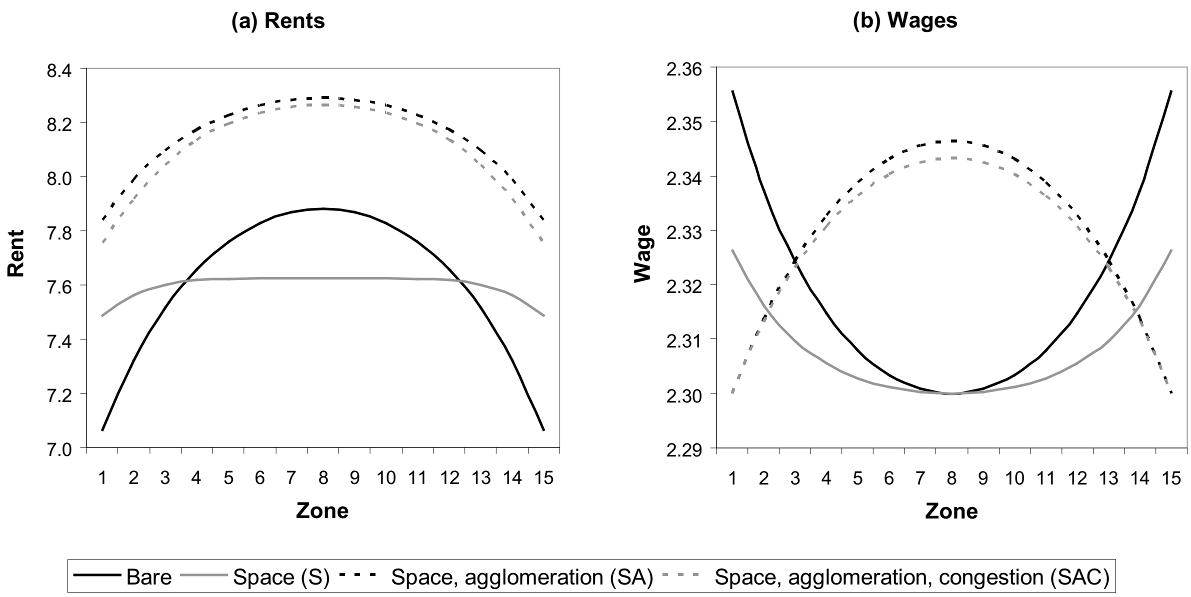


Figure 3: Location probabilities under different model specifications

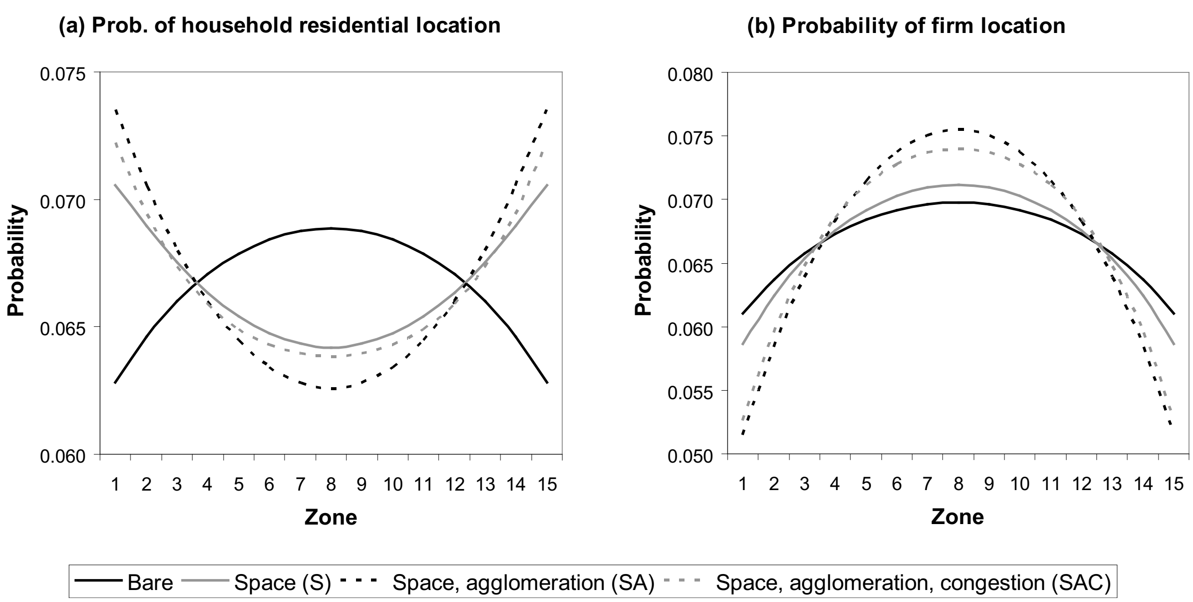
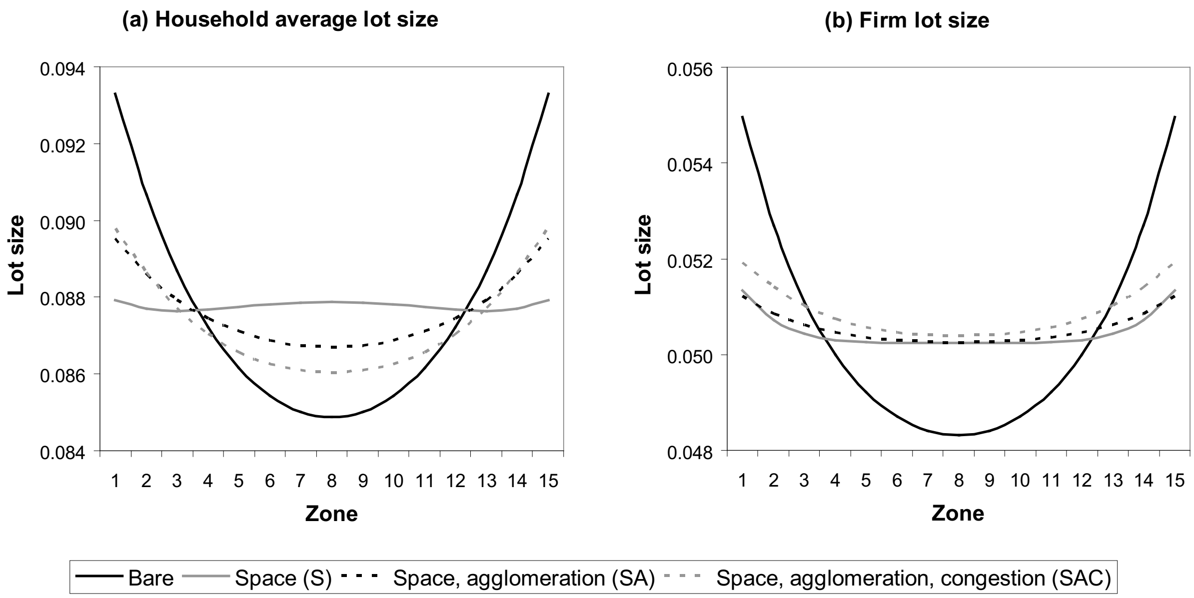


Figure 4: Lot sizes under different model specifications



workers for longer average commutes.

Both residential and office lots are smaller, on average, in the center zones (see Figure 4) since rents are higher there compared to the outer zones. Firms occupy smaller lots than households, although this depends on the values of various parameters, e.g., the weight on lot size in the firm's production function, κ.

5.2 Adding the main features of the model

We can now try to analyze the effects of gradually adding open space preferences, agglomeration economies and traffic congestion to the model. In the "S" specification, we can see that adding open space preferences to the model flattens the rent profile (Figure 2a). Households now want to live closer to the greenbelts, although residential locations in the center zones are still fairly desirable due to commuting cost considerations, as shown in the marginal probability for residential location (Figure 3a). Thus, rents at the city periphery are only slightly lower than rents in the center zones. This causes the concentration of firms - who are indifferent to open space - to increase in the center zones compared to the "Bare" case (see Figure 3b).

The wage profile, seen in Figure 2b, is also flatter compared to the "Bare" specification. With more households residing in the outer zones once open space preferences are included, demand for jobs in those zones has also increased. Therefore, it is easier than in the "Bare" case for firms in those zones to attract workers and so even though they still pay the highest wages, the zonal differences are less pronounced. Lastly, as seen in Figure 4, there is now less variation in average residential lot sizes and firm lot sizes throughout the city due to the flatter rent profile.

The "SA" specification includes agglomeration economies in addition to open space preferences. With agglomeration economies, a firm's productivity depends positively on its proximity to other firms both in its own zone and in neighboring zones. As expected, firms in the "SA" model are now more concentrated in the center zones than in the previous specifications (see Figure 3b).

Agglomeration economies do not directly affect households' residential decisions. However, since there is increased demand for land by firms in the center zones, this raises rents there, which in turn reduces households' choice probabilities for residences in those zones. Moreover, a firm's choice of lot size depends positively on agglomeration economies (and negatively on rents, of course) as seen in equation (18). With firms wanting larger lots in every zone, rents everywhere have to increase in order to satisfy the land market equilibrium condition, as seen in Figure 2a. Since the supply of land is very limited, the overall increase in rents compared to the previous case (without agglomeration) is significant while the change in lot sizes is less noticeable (Figure 4).

The wage profile in the "SA" specification is an interesting contrast to the wage profiles in the previous cases, as seen in Figure 2b. With agglomeration economies, wages are highest in the city center and lower in the outer zones. This is because there is now a higher concentration of firms (i.e., supply of jobs has increased) and at the same time a comparatively lower concentration of residents in the center zones (which leads to a slight decrease in demand for jobs there). Thus, wages in the center zones have be higher in order to equate supply to demand.

Finally, when we add congestion to the model using the "SAC" specification (which also includes open space preferences and agglomeration economies), commuting is now more expensive in general for households. This increases the desirability of the center zones once again, but it also leads to a decrease in lot sizes for households in those zones, as seen in Figure 4a, since they now have less money to spend on land consumption (as well as the numeraire good). With the decreased demand in land from households, rents have to be lower than in the "SA" specification without congestion in order for the land market to clear (see Figure 2a).

It can be seen that congestion mitigates the effect of agglomeration economies to some degree, since higher demand for land in the center zones from households decreases the firm's probability of locating in those zones (Figure 3b). It can also be seen from Figure 4b that due to the overall decrease in rents, firms can now afford larger lot sizes compared to the previous specification.

Finally, we can compare household welfare and average commuting distance in these three specifications (Table 1). Adding agglomeration economies to the model increases the household's welfare compared to the "S" specification, due to higher nonwork income from firms' profits. However, the average commuting distance is also higher because firms are more centralized when there are agglomeration economies. Traffic congestion decreases welfare, but since higher travel costs cause households to prefer jobs which are closer to their residential locations, the average commuting distance in the "SAC" specification is significantly lower than in the other cases.

Table 1: Comparison of welfare and average commute under different specifications

	S	SA	SAC
Welfare	0.870	0.925	0.910
Average commute (zones)	3.574	3.652	3.241

5.3 Other location patterns

Not unexpectedly, using different parameter values can cause differences in location patterns, rents and wages. For instance, if there are extremely strong preferences for open space (higher η or α_1), the rent profile may become U-shaped, with lower rents in the city center. This is because households' demand for land near the greenbelts increases significantly. With this, household lot sizes may also be higher in the city center than in the outer zones since supply of land is limited.

In general, the insights gained from the discussion above in terms of the effects of open space preferences, agglomeration economies and congestion still apply with different parameter values. One interesting point to note is that when there are open space preferences, polycentric location patterns for firms may emerge if travel costs are very high. Using the full model with all three main features, figures 5 and 6 show the results when the congestion parameter γ_1 is increased from 0.008 to 0.08, and when the multiplicative factor α_1 in the open space function is increased from 1 to 5 (with all other parameter values as stated in Section 4.1).

As seen in Figure 6a, households want to live close to the greenbelts and they also want to work very close to their residential zones due to extremely high total travel costs. Because of this, labor supply is relatively low in the city center (this is also evident from the fact that wages are very high there in order to attract workers, as seen in Figure 5b). As a result, there are slightly more firms in the zones surrounding the city center, leading to the somewhat polycentric firm location pattern, even though agglomeration

Figure 5: Rents and wages with high γ_1 and α_1

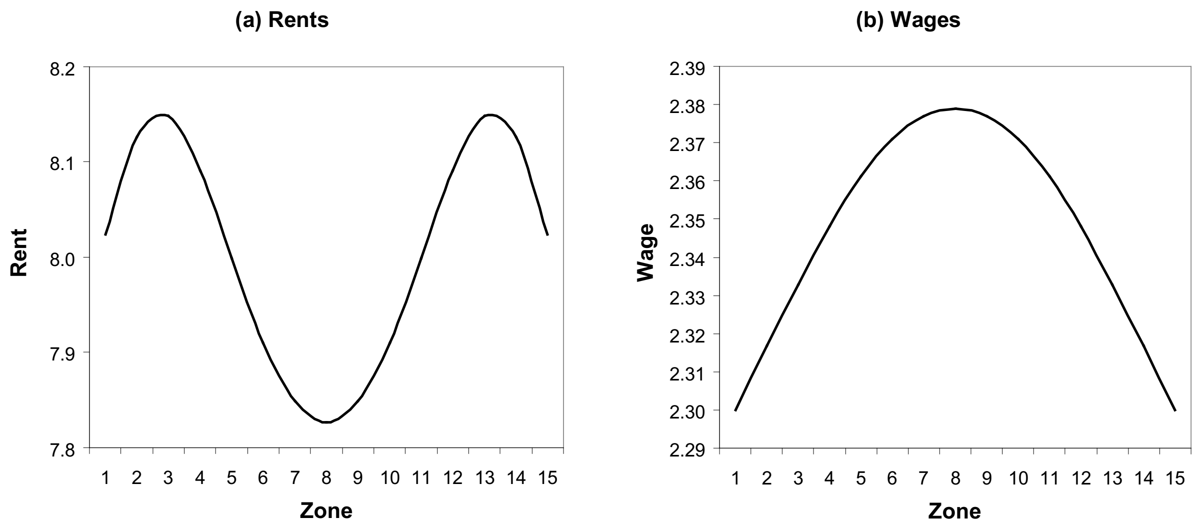
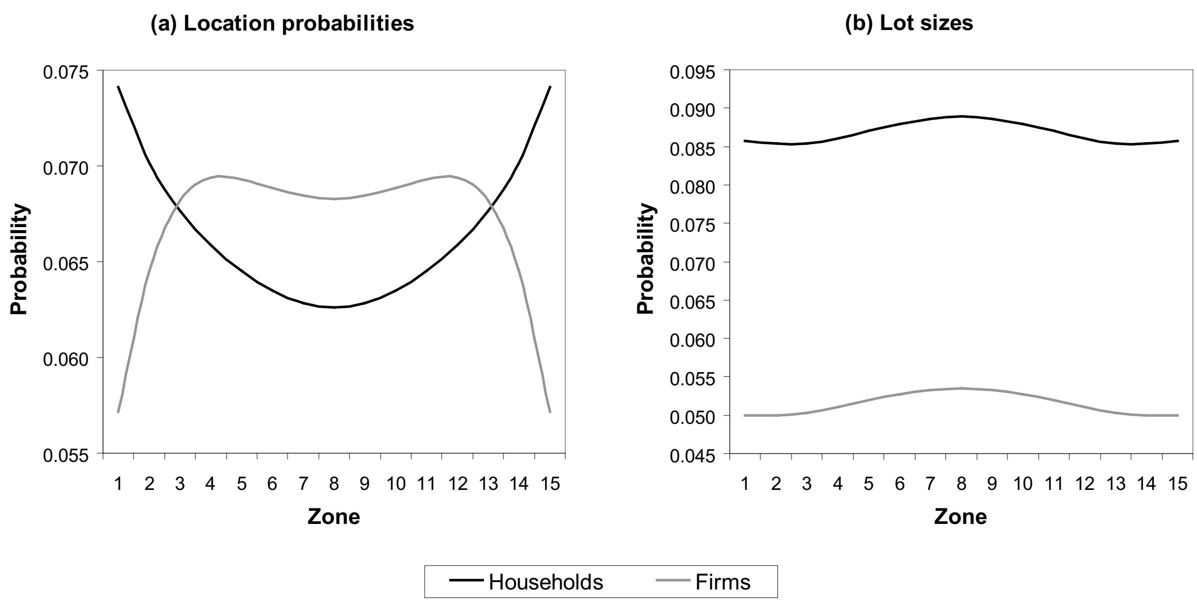


Figure 6: Location probabilities and lot sizes with high γ_1 and α_1



economies still draw firms to locate close to each other.

The rent function has an unusual shape (Figure 5a), but it makes sense: few households want to locate in the center zones, and low rents are needed to offset the high wages in order to for firms to locate in those zones. At the city periphery, there is high demand for land from households, but few firms want to locate there. Thus, it is in zones 3 and 13 that the joint demand for land from both households and firms is highest, leading rents to peak in those zones.

6 Comparison of policies

Using the complete model with open space preferences, agglomeration economies and traffic congestion (the "SAC" specification) with the parameter values listed in Section 4.1, we first examine how imposing congestion tolls and/or an urban growth boundary (UGB) affects rents, wages, and welfare. A measure of sprawl is then discussed so we can see the policy impacts on urban structure. Finally, the policies are compared using different parameter values.

As mentioned earlier, when congestion pricing is in place, the toll for each zone is the difference between marginal social travel cost and private travel cost in that zone. Toll revenues, like profits and rental income, are redistributed equally to households. Meanwhile, a UGB is implemented in this paper by not allowing one zone at each end of the city to be developed, in addition to the preexisting greenbelts. That is, the UGB reduces the number of habitable zones, $\bar{x}$, from 15 to 13, and $\bar{g}$ is now 2. Three different combinations of the two policies can be imposed: a congestion toll policy, a UGB policy, and both congestion pricing and a UGB policy.

Figures 7-9 show the effects of these policies on rents, wages and location patterns. Since a congestion pricing policy increases travel costs in general, the desirability of the inner zones as residential locations has increased because the household has easier access to jobs everywhere in the city in those zones. The higher cost of travel discourages commuting and households prefer to work even closer to their residential zones than before. This causes households and firms to be distributed slightly more evenly across

Figure 7: Rents and wages under different policy scenarios

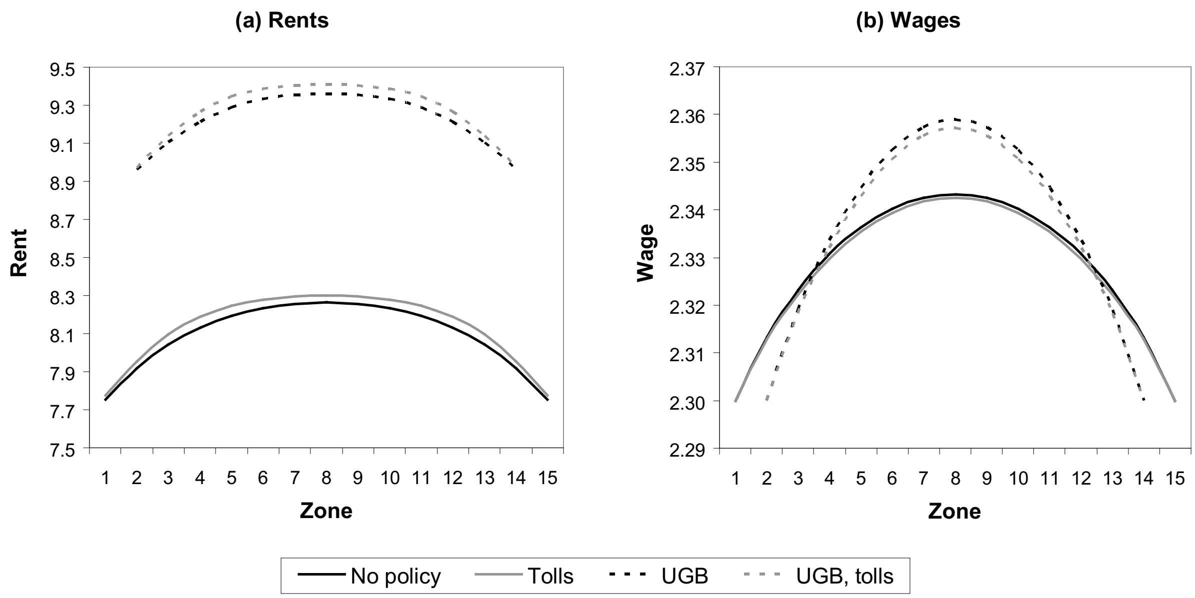


Figure 8: Location probabilities under different policy scenarios

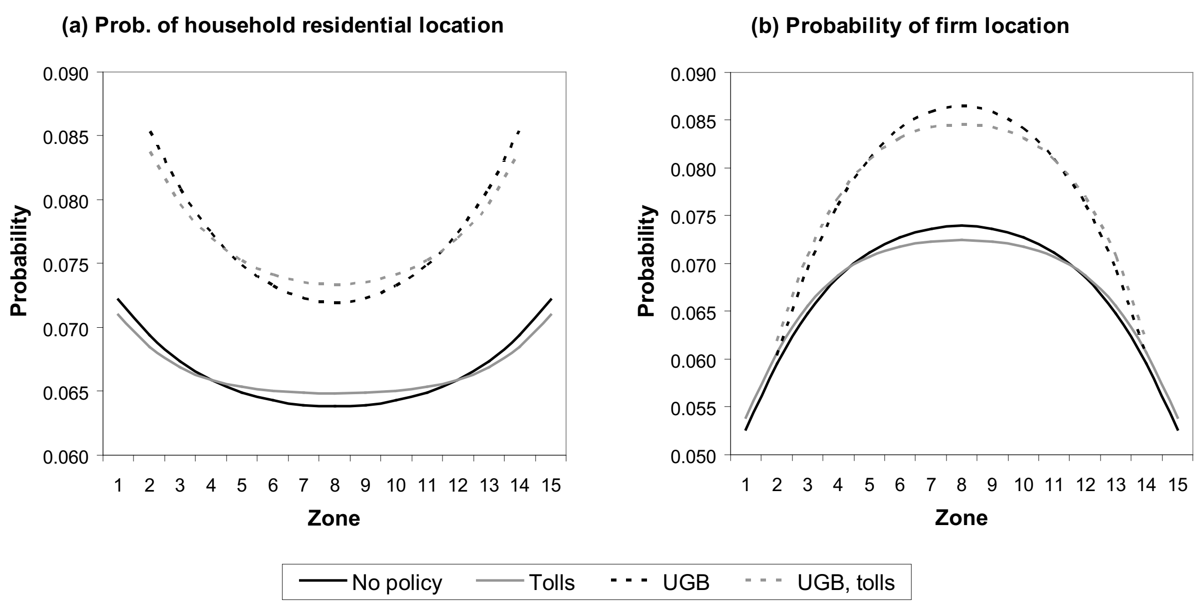
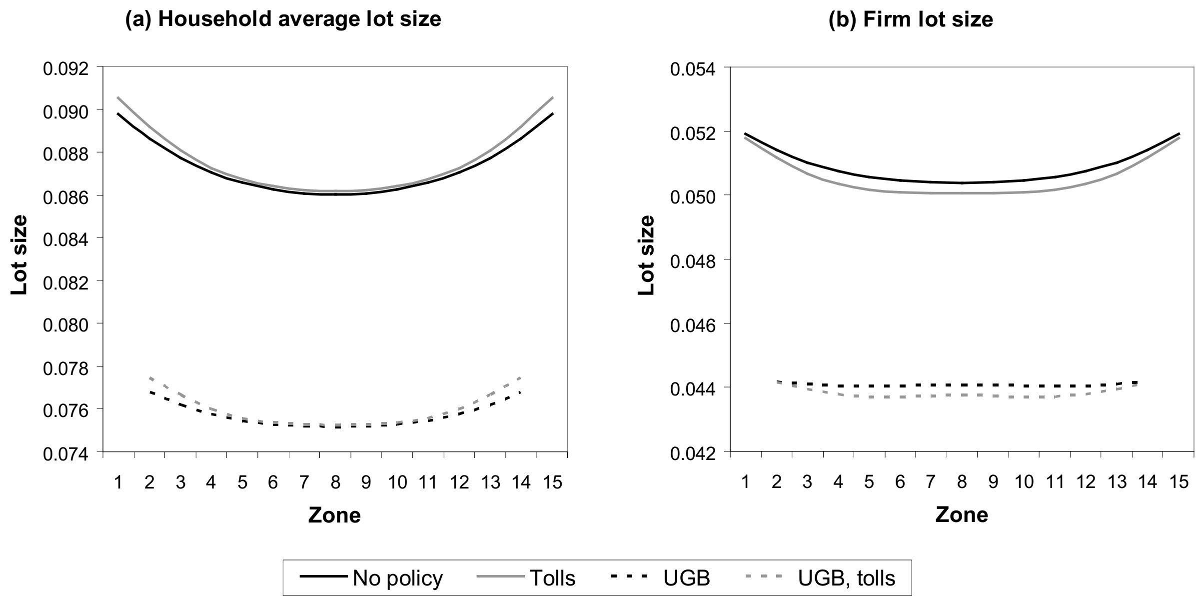


Figure 9: Lot sizes under different policy scenarios



the zones (Figure 8). The decentralization of firms seen here is similar in spirit to the polycentric firm location discussed in the previous section, and shows how a congestion pricing policy can mitigate the effects of agglomeration economies.

Higher travel costs also cause households to substitute away from commuting toward land consumption (as well as consumption of the numeraire good). As a result, average lot sizes for households increase slightly, leading to a small increase in rents and correspondingly, a decrease in firm lot sizes (see Figures 7a and 9).

When a UGB policy is imposed, the amount of land available for residences and offices is sharply curtailed, causing an overall increase in households' and firms' location probabilities in every available zone. This leads to a significant increase in the rent level (Figure 7a), and a decrease in lot sizes for households and firms (Figure 9). Since the amount of open space has increased and the value of open space declines with distance, relatively more households want to live in the outer zones and so wages in the city center are higher than in the "No policy" case in order to attract workers (Figure 7b).

When a congestion pricing policy is imposed in addition to the UGB, the most interesting point is that firms and households are, once again, distributed more evenly across the city, as seen in Figure 8.

Table 2 shows how the policies affect welfare and average commuting distance. Congestion pricing improves welfare by 0.04%, and the average commute falls significantly from 3.24 to 2.88. However, a UGB policy causes welfare to drop by 3.78%. Furthermore, even though the average commuting distance in the UGB case is lower than in the "No policy" case, it is slightly higher than in the case of congestion pricing. Finally, when tolls are imposed in addition to the UGB, welfare increases relative to the case with just the UGB and average commuting distance is at its lowest.

Table 2: The impacts of different policies using the base parameter values

	No policy	Tolls	UGB	UGB, Tolls
Welfare per household	0.9102	0.9106	0.8758	0.8762
Average commute (zones)	3.241	2.884	2.940	2.623

One point to note is that the UGB in this model is necessarily crude - it prevents two entire zones from being developed. Moreover, households no longer get any rental income from those two zones. An extension of this paper would be to allow some portion of the edge zones to be kept as greenbelts, while the remaining land can be used for development. This allows a finer scale of adjustment, but requires a rethinking of the open space function (equation [2]), which depends on zonal distances from the greenbelts. Anas and Rhee (2006) use a UGB of this type but open space preferences in their model do not depend on proximity to the greenbelts.

6.1 Policy effects on urban structure and sprawl

It is useful to have some measure of sprawl to compare the effects of UGBs and congestion pricing in this model. As discussed in Section 2, defining sprawl as low-density development does not seem to correspond to public opinion on which cities are sprawled. With this in mind and considering the fact that the sprawl indices developed by Ewing et al (2002) and Burchfield et al (2006) are not applicable here, this paper now develops a sprawl index that can be used to examine policy impacts on urban structure.

It is proposed that urban sprawl is associated with the variation of net residential density within the city. For example, residential densities may vary widely between different areas of New York City (which by most accounts is not sprawled), while Los Angeles may have a relatively flat density function throughout the city (Phoenix is another example, as pointed out by Bruegmann [2005]). It seems more appropriate to use net residential density than gross density since the latter does not differentiate between land used for residential purposes and land used for other purposes. For instance, a purely residential area and a mixed residential-commercial area may have the same population density but look very different physically.

An index similar to the Gini coefficient, called the Sprawl-Gini, is used to compare how "unequal" net residential density is within a city (see appendix for how this index is computed). The higher the Sprawl-Gini coefficient, the more variation there is in net residential density, and hence the city is less sprawled by this measure. Table 3 shows the Sprawl-Gini coefficient for New York City, Houston and Austin (the three major cities for which detailed land use data are available). We can see that the rankings correspond to those reported by Ewing et al (2002) and Burchfield et al (2006).[7]

In terms of the effects of UGBs and congestion pricing on urban structure in this paper, the Sprawl-Gini coefficient can be calculated for each of the four scenarios discussed earlier in this section. In the "No policy" case, the Sprawl-Gini coefficient is 0.028, indicating that there is relatively little variation in net residential density. A congestion

[7] Burchfield et al (2006) and Ewing et al (2002) use metropolitan statistical areas while the Sprawl-Gini coefficient is calculated based on the city's political jurisdiction due to data availability.

Table 3: Sprawl-Gini coefficient and sprawl rankings for different cities

City	Sprawl-Gini coefficient	Ranking (from most to least sprawled)		
		Sprawl-Gini	Burchfield et al	Ewing et al
Houston[1]	0.17	1	21	32
Austin[2]	0.26	2	n/a	59
New York City[3]	0.39	3	35	83

Notes:
1. Data from City of Houston (2003). The city is divided into 15 super neighborhoods. Land use and population data are for the year 2000.
2. Data from City of Austin (2005). The city is divided into 63 planning areas. Land use and population data are for the year 2005.
3. Data from New York City Department of City Planning (2007). The city is divided into 59 community districts. Land use and population data are for the years 2005 and 2000 respectively.

pricing policy increases the Sprawl-Gini coefficient to 0.032, i.e., the city becomes less sprawled. This is because tolls cause differences in household travel costs to become more pronounced, leading to more marked differences in land consumption as well.

The Sprawl-Gini coefficient in the UGB case is 0.025. A UGB causes residential areas to become more uniform in terms of lot sizes throughout the city (more sprawled) because there is less land available and so the differences between household lot sizes are now smaller. With a UGB-and-tolls policy, the Sprawl-Gini coefficient is 0.030.

6.2 Comparison of policies with different parameter values

It can be seen that a UGB policy is useful in terms of increasing the amount of open space in the city, but curtails the availability of land for residences and offices, causing an increase in the rent level and a decrease in lot sizes. Moreover, it causes the city to become more sprawled in terms of the Sprawl-Gini coefficient. With the reference parameter values, a congestion pricing policy performs better than a UGB only policy when it comes to improving welfare, decreasing average commuting distance, and increasing the variation in net residential density.

There are two main issues to take into account when comparing the effects of these policies. As discussed earlier, a tolling policy based on the marginal external cost of congestion may not optimal in the presence of unsubsidized agglomeration economies, since congestion pricing causes the decentralization of firms. Secondly, if households have very high preferences for open space, it is conceivable that a UGB may improve welfare.

Table 4 shows the impact of different policies when certain parameter values are changed while keeping all others at the values listed in Section 4.1. The following discussion will focus on the cases where we have stronger agglomeration economies, and stronger preferences for open space (the two issues mentioned above).

When agglomeration economies are very strong, congestion pricing may actually decrease welfare, as seen in part (a) of Table 4. This is because higher travel costs due to tolls encourage households to work closer to their homes in this model. This in turn leads to the decentralization of firms, thus reducing the productivity boost from agglomeration economies. This is a particularly interesting result because it shows that care should be taken with regard to congestion pricing when both congestion and agglomeration externalities exist in the economy.[8]

To see how the policies perform when there are stronger preferences for open space, the weight on open space in the utility function, η, is increased from 0.1 to 0.2, and the multiplicative factor α_1 in the open space function is increased from 1 to 5. As shown in part (b) of Table 4, a tolling policy increases welfare by 0.2% but a UGB increases welfare by about 4.2%.

Moreover, further increasing the amount of open space improves welfare, up to the point where $\bar{g} = 4$ (which means there are now 9 habitable zones compared to 15 in the original setting without a UGB). Beyond this, further increasing $\bar{g}$ causes welfare to

[8] Arnott (2007) argues with a different, simpler model that has both congestion and agglomeration economies (and the latter are uninternalized) that "the optimal toll might not only be substantially lower than the Pigouvian toll, but might even be negative, entailing a subsidy to urban travel" (p. 194).

Table 4: The impacts of different policies using different parameter values

	No policy	Tolls	UGB	UGB, Tolls
a) Higher agglomeration economies (β_1: 0.0000006 → 0.000002)				
Welfare	1.0320	1.0309	1.0124	1.0109
Average commute (zones)	3.428	3.057	3.111	2.788
Sprawl-Gini coefficient	0.040	0.042	0.037	0.039
b) Stronger open space preferences (η: 0.1 → 0.2, α_1: 1 → 5)				
Welfare	1.1229	1.1233	1.1698	1.1701
Average commute (zones)	3.324	2.936	3.007	2.667
Sprawl-Gini coefficient	0.057	0.057	0.052	0.052
c) Polycentric firm locations with more congestion and higher open space preferences as discussed in Section 5.2 (γ_1: 0.008 → 0.08, α_1: 1 → 5)				
Welfare	0.9488	0.9543	0.9399	0.9455
Average commute (zones)	2.104	1.489	1.914	1.474
Sprawl-Gini coefficient	0.037	0.040	0.035	0.039
d) Higher weight on land in firm production function (κ: 0.15 → 0.3)				
Welfare	0.5934	0.5937	0.5425	0.5428
Average commute (zones)	3.324	2.936	3.007	2.667
Sprawl-Gini coefficient	0.057	0.057	0.052	0.052

fall because the utility from the additional open space cannot offset the effects of the increase in rents and decrease in lot sizes. Thus, it can be seen that a UGB may increase or decrease welfare, depending on how strongly households like open space.

We can also see from the results that, as in the case with the reference parameter values, a UGB reduces the variation in net residential density within the city (hence the city becomes more sprawled by this measure) while congestion pricing has the opposite effect, although the effect is very small in some cases. Congestion pricing also tends to be more useful when it comes to reducing average commuting distance in the city.

7 Conclusion

This paper develops an urban location model to analyze the issue of urban sprawl and the impacts of different policies which have been proposed across the United States to combat sprawl. It is hoped that the modeling exercise presented in this paper helps provide a more complete picture and further our understanding of how households and firms choose locations. This is especially important because the impacts of congestion pricing and UGBs depend on the interplay between open space preferences, agglomeration economies and congestion. The results show that congestion pricing causes firms to decentralize, and so tolls may not be optimal when unsubsidized agglomeration economies are very high. Meanwhile, a UGB may or may not be welfare-improving, depending on the strength of household preferences for open space.

As seen in Section 4, the flexibility of this model allows us to include or exclude the three features mentioned above. Moreover, the degree to which these features matter can be adjusted by choosing different parameter values. Comparing different model specifications is not only of academic interest, but is also crucial because in reality, cities are not homogeneous. For example, preferences for open space may differ when there are swamps in the greenbelt instead of forests. The importance of agglomeration economies also differs depending on what industries are present in a city. A city which is considering the imposition of the above policies should aim to gather as much information as possible in terms of what its residents and firms view as important in order to better assess the effects of the policies.

In terms of future research, I am working on including subsidies for agglomeration economies as a policy. I would also like to incorporate open space within the city. Since this may lead to scattered development, we will then be able to examine the impact of an infill development policy.

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Appendix

The Sprawl-Gini coefficient is used to measure variation of net residential density within a city, and is conceptually similar to the Gini coefficient used to measure income inequality. Land use and population data on as fine a geographical scale as possible are required to rank households in a city by the amount of residential land they occupy.

Suppose that a city is divided into Q areas for which we have data. Let Pop_i denote the cumulative proportion of residential population, where $i = 0, 1, ..., Q$, $Pop_0 = 0$ and $Pop_Q = 1$. Similarly let $Area_i$ denote the cumulative proportion of residential land area, where $i = 0, 1, ..., Q$, $Area_0 = 0$ and $Area_Q = 1$. If a graph similar to the Lorenz curve is plotted with Pop_i on the horizontal axis and $Area_i$ on the vertical axis, the Sprawl-Gini coefficient is the area between the 45-degree line and this Sprawl-Lorenz curve. The Sprawl-Gini coefficient can be computed by approximating the abovementioned area using trapezoids: $1 - \sum_1^Q (Pop_i - Pop_{i-1})(Area_i + Area_{i-1})$.