ABSTRACT: This paper develops a spatial general equilibrium model to explore the endogenous relations between urban sprawl, job decentralization, and traffic congestion, and then compares the efficiency and welfare impacts of anti-congestion policies. Differing from many existing non-moncentric models, the model in this paper fully endogenizes both production and congestion externalities, relaxes the assumption of fixed city/metropolitan boundary, and relies on values of travel and work time. Simulation results suggest that congestion spurs firms to decentralize and agglomerate away from the urban center, with households living more centrally. A congestion-toll policy brings slightly more compact urban form and job decentralization, and serves as an effective strategy for correcting congestion externalities, by maximally improving social welfare. Urban growth boundary (UGB) strategies tested here alleviate congestion externalities and lower travel times, vehicle-miles traveled, and travel costs; but the UGBs carry certain loss of social welfare owning to land rent escalation and UGBs’ limitations on job decentralization.

Key Words: urban economics, sprawl, congestion pricing, job decentralization, Urban Growth Boundaries (UGBs).

INTRODUCTION

Urban sprawl connotes an excessive and uncoordinated urban expansion, with low-density development, auto-dominated designs, and decentralization of population, firms and infrastructure to the edge of cities. Such settings are regularly believed to be at the root of many
urban and suburban woes, such as auto-dependent lifestyles, residential segregation, loss of open
space amenities, and insufficient public infrastructure, facilitating urban decay (Gottlieb, 1999;
Brueckner, 2000; Nechyba and Walsh, 2004; Knaap, 2007). Many of these issues link to traffic
congestion, of which urban sprawl can be both cause and effect. For example, workers living in
sprawling suburbs may commute to the urban core by automobile, resulting in heavier traffic on
the roads, air pollution, accidents, and rising reliance on fossil fuels, especially in monocentric
regions. On the other hand, sprawl can be an effective solution for those seeking to escape high
land prices and congestion in the core, due to over-centralization.

The relationship between urban growth and traffic congestion in a polycentric region, where
sprawl is associated with both job and housing decentralization, is even more complex. Many
suggest that population of most US urban cores is falling and employment is decentralizing
(Glaeser and Kahn, 2001; Kim, 2007; Kneebone, 2009). Job decentralization changes the nature
of urban sprawl, by re-agglomerating households and firms in city edges or sub-centers
(McMillen and Smith, 2003; Gilli, 2009). Strategies for coping with congestion-related issues in
non-monocentric regions can be quite different from those of monocentric settings (see, e.g.,
Giuliano and Small, 1991; Crane and Chatman, 2004), but empirical findings remain
inconclusive regarding policy effects. Rigorous investigation is needed.

This paper explores the connection between urban sprawl, job decentralization, and traffic
congestion in a relatively flexible setting via application of a spatial general equilibrium
framework. It integrates production externalities that agglomerate firms in some locations and
congestion externalities that tend to decentralize firms while attracting people to their workplaces.
Using this theoretical framework, we examine the efficiency and welfare effects of congestion
tolls and UGB regulations. The paper is organized as follows: Section 2 reviews existing urban
equilibrium models and their findings; Section 3 describes this new model’s assumptions and
equilibrium conditions; Section 4 compares simulation results for land use and congestion and
evaluates different policy scenarios; Section 5 concludes the paper.

LITERATURE REVIEW

Many theoretical models of city land use have been developed within a traditional monocentric
framework to reflect traffic and its externalities (e.g., Pines and Sadka, 1985; Wheaton, 1998) as
well as examine the efficiency of second-best land use policies, like UGBs and building size
regulations (e.g., Brueckner, 2007; Kono et al., 2012). Some conclude that a properly chosen
UGB may be an effective second-best substitute for first-best tolling, since the shadow price of
land is less than its market value at the region’s edge, in a congested (and monocentric) setting
(Arnott, 1979; Pines and Sadka, 1985). Others have argued that UGBs may achieve far lower
welfare levels than first-best tolling strategies provide, and a UGB policy alone is a poor
substitute for first-best tolling (Brueckner, 2007; Kono et al., 2012).

Of course, a monocentric assumption conflicts with the polycentric context of most US cities.
Decreasing transportation costs, rising incomes, and better suburban amenities propel
decentralization of both population and jobs (Crane and Chatman, 2004; Kim, 2007; Kneebone,
2009). This mismatch between theory and reality makes planners and practitioners less interested
in using policy instruments developed by economic theories (Gottlieb, 1999). Fortunately, there
are some sophisticated polycentric and multi-city models to better reflect the real world.
Anas and Kim (1996) presented a comprehensive CGE model integrating the decisions of consumers and firms, alongside congestion and agglomeration externalities. Simulation findings from a linear city with discrete zones suggest that congestion externalities bring a dispersive urban form, with more shopping centers, while shopping agglomeration tendencies bring a more compact form, with fewer and bigger centers. Anas and Xu (1999) examined the effectiveness of congestion pricing and the relationship between congestion and urban form, using the Anas-Kim model but without considering shopping agglomeration. Their simulations suggest that levying congestion tolls generated job decentralization as well as residential centralization. However, these papers neglect positive agglomeration (or production) externalities that regularly exist among firms.

In reality, agglomeration economies for firms have been important in shaping regions. Firms benefit from locating close to each another through access to intermediate inputs and labor, and knowledge spillovers (Fujita and Thisse, 2002; Glaeser, 2008). Firm agglomeration also changes the location choices of workers, who wish to moderate their commutes. Such agglomeration effects may be not necessary for reinforcing existing urban centers but rather shaping some new suburban centers, thanks to lower commute costs and land rents outside the urban core. ‘Suitable’ sprawl or decentralization may be the welfare-maximizing choice of residents and firms, and serves as a solution for various urban issues (Anas, 2012a).

Several studies have explicitly recognized the importance of production externalities and polycentric structures in their economic assessments of land use policies and/or fiscal policies (e.g., Fujita and Ogawa, 1982; Anas and Kim, 1996; Lucas and Rossi-Hansberg, 2002; Berliant et al., 2002; Wheaton, 2004; Arnott, 2007). Two papers closely related to our study are those by Lucas and Rossi-Hansberg (LRH, 2002) and Wheaton (2004). LRH’s model established an elegant spatial general equilibrium for firms and worker location choice within a circular region that fully endogenizes production externalities, and allows for job decentralization in a non-monocentric urban structure. They found that Mills’s monocentric form exists when commute costs are low enough. When these travel costs rise, a polycentric equilibrium may exist, and then everything becoming a mixed land use patterns when commuting costs are high enough. Wheaton’s (2004) paper combined a congestion externality and center-agglomeration forces. His numerical analysis compared market outcomes and socially optimal outcomes on the basis of land use mixing. He made some strong assumptions such as inward-only radial commuting, exogenous land consumption levels of households and firms, roads provision without any of land, and production externalities determined by distances to the CBD. His simulation suggest that longer commuting distances and worse congestion are associated with more centralized firm agglomeration, while employment decentralization brings shorter commuting distance and low congestion levels.

Our paper differs from the LRH and Wheaton’s papers in several ways. First, we build a CGE model that fully endogenizes both production and congestion externalities. Congestion externalities can be simply introduced as a negative component of production, as suggested by Rossi-Hansberg (2004); but we believe that congestion externalities should be fully considered, as an influence on people’s daily travel. Second, there is a latent assumption in all the above non-monocentric models; the city/metropolitan boundary is fixed. We relax this strong
assumption and replace it with fixed agricultural land rents at the region edge. It appears that for
any fixed boundary there is a corresponding edge rents that yields the same equilibrium. But a
fixed-boundary assumption is not equivalent to an assumption of fixed edge rent, since the
former also constrains land availability for firms and housing. Third, our approach relaxes
several assumptions used in Wheaton’s and LRH’s models, by acknowledging the difference
between the value of commute time and wage, and land use share for transportation
infrastructures. Finally, this new spatial general equilibrium model can be used to evaluate the
welfare and land-use influence of a list of anti-congestion policies.

ANALYTICAL FRAMEWORK

City Endowments
The model applied here assumes a continuous symmetric circular region with a radius, $\bar{x}$. The
assumption of symmetry essentially implies that people need travel only towards or away from
the center along radial street networks. Two agents, households and firms, exist and can reside at
the same location inside the region. For any location $x$, $\theta_f(x)$, $\theta_h(x)$ and $\theta_t$ represent the
fractions of land area used by firms, households, and transportation infrastructure.

Household Choices
Each household chooses its home location $x$ to maximize its Cobb-Douglas utility function
involving goods $c(x)$ and residential lot size $q(x)$. Households are assumed to be identical and
their maximization problem is
\[
\max_{(c,q)} u(c(x),q(x)) = c(x)^\alpha q(x)^{1-\alpha}, \quad 0 < \alpha < 1
\]
subject to the budget constraint:
\[
c(x) + r_h(x)q(x) = y(x) = w(x) + \bar{y}\text{rent}
\]
where $r_h(x)$ is land rent at location $x$, $y(x)$ is the total money budget of a household living at
$x$, $w(x)$ is wage income for households living in location $x$, and $\bar{y}\text{rent}$ reflects a potential
lump-sum redistribution of overall land rents that exceed the edge (agricultural use) rent. It
implies that land is owned collectively by the consumers or that landlords are taxed away all
their extra rents for non-agricultural use (and those tax revenues are then equally redistricted to
residents).

If $\bar{u}$ is the maximized utility level of each household in the region, constant over locations (for
equilibrium), solving the relevant first-order conditions of utility maximization for $r_h(x)$ and
$q(x)$ yields their optimal solutions:
\[
r_h^*(x) = (1 - \alpha)\alpha^{\alpha/(1-\alpha)}(\frac{y(x)}{\bar{u}})^{(1/(1-\alpha))}
\]
\[
q^*(x) = \alpha^{-\alpha/(1-\alpha)}y(x)^{-\alpha/(1-\alpha)}(1/\bar{u})^{1/(1-\alpha)}
\]

Characterizing Firms and Production Externalities
Each firm is a price taker in the output and input markets, and decides how much labor and land
to use for production, at each location $x$. The first part of a firm’s two-part production function is
an ordinary, constant-returns production technology that relates land and labor. If $f(x)$ is
production per unit of land and $n(x)$ is employment density, then constant-returns production
appears as follows (LRH, 2002):
\[
f(x) = \delta n(x)^\kappa \quad (\delta > 0, 0 < \kappa < 1)
\]
The second part of the production function is a positive technological externality from firm agglomeration. Such external effects rise with the density of economic activities and proximity to other firms (Fujita and Ogwa, 1982; Lucas and Rossi-Hansberg, 2002). Here, production externalities are defined proportional to the local employment density (at x) and the integral of exponentially distance-weighted job counts within a pre-existing cluster around the region’s center point, up to an (exogenously set) boundary distance of \( \bar{r} \). This implies that a firm’s productivity is affected by the presence of firms within the pre-existing urban core, \([0, \bar{r}]\), and any external effect of firms outside the urban core is negligible. This assumption is typically used in the monocentric model or the core-periphery model (e.g., Glaeser and Kahn, 2001; Wheaton, 2004; Anas, 2012b), in which only firms in an abstract center point exhibit agglomeration effects. Following LRH (2002), the production externality at each location \( x \) is set as

\[
F(x) = \zeta \int_0^\bar{r} \int_0^{2\pi} r \theta_f(r)n(r) e^{-\zeta l(x,r,\psi)} d\psi dr
\]

where \( \zeta \) is the production externality scale parameter, and exogenously determined. \( \psi \) is the polar angle around the center (ranging from 0 to \( 2\pi \)), and \( l(x,r,\psi) \) is the straight-line distance between a firm at location \( x \) and any firm lying within \( \bar{r} \) miles of the center (at a counter-clockwise angle of \( \psi \) from the first firm). Thus,

\[
l(x,r,\psi) = \sqrt{x^2 + r^2 - 2xrcos(\psi)}
\]

Total production per unit of land \( P(x) \) at location \( x \) can be calculated as follows (LRH, 2002):

\[
P(x) = f(n(x))F(x)^{\gamma} = \delta n^k(x)F(x)^{\gamma}
\]

The firms then maximize the profit function with respect to each of the two input quantities (density of workers and location: \( n, x \)), while the price of firm output is set as the numeraire without loss of generality:

\[
\text{Max } \Pi(n, x) = f(n(x))F(x)^{\gamma} - w(x)n(x) - r_f(x) = \delta n(x)^kF(x)^{\gamma} - w(x)n(x) - r_f(x)
\]

From the first-order condition of profit maximization with respect to \( n \), one can obtain an optimal employment density at location \( x \) as follows:

\[
n^*(x) = \left( \frac{k^\delta F(x)^{\gamma}}{w(x)} \right)^{1/(1-\kappa)}
\]

Given perfectly competitive input and output markets, all firms make zero (excess) profit, with land rents rising to ensure this, as follows:

\[
r_f^*(x) = \delta n^*(x)^kF(x)^{\gamma} - w(x)n^*(x)
\]

Combining Eq. (6) with Eq. (5), land rent of a firm in location \( x \) will thus be:

\[
r_f^*(x) = (1 - \kappa)\delta^{1/(1-\kappa)}F(x)^{\gamma/(1-\kappa)} \left( \frac{k}{w(x)} \right)^{k/(1-\kappa)}
\]

**Recognizing Transport Technology and Congestion Externalities**

In a symmetric city, worker travel will take place in just the two, radial directions: inward (toward the city center) and outward. Here, \( t'(x) \) represents marginal travel time (instantaneous travel pace in hours per mile, for example) at location \( x \), with negative values representing inward travel and positive values representing outward travel. Since only one travel mode or transport technology (e.g., the private car) is included in this model, the magnitude of the
marginal travel time in an uncongestible network will equal a constant, $\varphi$ (in hours per mile), representing the inverse of free-flow travel speed by that mode. A lower $\varphi$ value represents more advanced transport technology, with higher (free-flow) speeds.

Since transportation systems are congestible, the true marginal travel time contains an additional component to reflect congestion. Here, this second component is assumed proportional to a power of the ratio of travel demand to supply or transport capacity at location $x$ (as used, for example, by Solow, 1972; Wheaton, 1998, 2004; and Brueckner, 2007). Here, $D(x)$ represents total travel demand passing location $x$. When $D(x) < 0$, travel flow is inward; when $D(x) > 0$, commute travel is outward; and, when $D(x) = 0$, no travel demand crosses location $x$. Under these three potential travel settings, the marginal travel time is as follows:

$$t'(x) = \begin{cases} 
-\varphi - \rho \left(\frac{-D(x)}{2\pi x \theta_t}\right)^{\sigma} & \text{if } D(x) < 0 \\
\varphi + \rho \left(\frac{D(x)}{2\pi x \theta_t}\right)^{\sigma} & \text{if } D(x) > 0 \\
\varphi \text{ or } -\varphi & \text{if } D(x) = 0 
\end{cases} \quad (8)$$

where $\rho$ and $\sigma$ ($\sigma \geq 1$) are positive parameters and reflect network congestibility.

Such behaviors imply that congestion externalities exist in the city, thanks to the added travel-time impacts of higher travel demand (versus a constant background capacity). Using workers’ value of travel time or VOTT (i.e., $\lambda w(x)$ with $\lambda$ representing the ratio of VOTT to wage) to quantify this congestion externality and simply multiplying marginal travel time (per traveler passing location $x$) by total demand at that location, one has the following cost of delay at each location for one-way travel in the region:

$$\tau(x) = \lambda w(x) \frac{\partial t'(D(x))}{\partial D(x)} D(x) = \begin{cases} 
-\sigma \rho \lambda w(x) \left(\frac{|D(x)|}{2\pi x \theta_t}\right)^{\sigma} & \text{if } D(x) < 0 \\
\sigma \rho \lambda w(x) \left(\frac{|D(x)|}{2\pi x \theta_t}\right)^{\sigma} & \text{if } D(x) \geq 0
\end{cases} \quad (9)$$

where $\tau(x)$ also represents the congestion toll (per mile) at location $x$ that charges commuters for the damage from the congestion externalities at $x$.

The Land Market’s Equilibrium Conditions

Since both firms and households can exist in the same location, a competitive market requires they bid for the land via their willingness to pay (or maximized rents). Given the optimal solutions $\{q^*(x), n^*(x), r^*_f(x), r^*_h(x)\}$ from the partial equilibrium of households and firms at each location $x$ (as shown in Eqs. (2), (3), (6) and (7)), the land market equilibrium requires that land rents satisfy the following equations:

1. $r(x) = \max\{r^*_h(x), r^*_f(x), R_A\}$.
2. $r(x) = r^*_h(x)$ if $\theta^*_h(x) > 0$.
3. $r(x) = r^*_f(x)$ if $\theta^*_f(x) > 0$.
4. $r(\bar{x}) = R_A$.

From these equilibrium conditions, one can derive the optimal shares of land use for firms and households, $\theta^*_f(x)$ and $\theta^*_h(x)$. If both $r^*_f(x)$ and $r^*_h(x)$ are less than $R_A$, both $\theta^*_f(x)$ and $\theta^*_h(x)$ will equal zero. If $r^*_f(x)$ equals $r^*_h(x)$, a mixed land use pattern will emerge at location $x$, and the number of firm workers will equal the number of households (or residing workers) at
that location in an equilibrium (LRH, 2002). In other words:

\[
\theta_f^*(x) n^*(x) = \left(1 - \theta_t - \theta_f^*(x)\right)/q^*(x) \quad \text{if} \ r_f^*(x) = r_h^*(x)
\]

Given that both \( r_f^*(x) \) and \( r_h^*(x) \) will exceed \( R_A \) (except at the developed region’s edge), the land use shares for firms and households at each location \( x \) are as follows:

\[
\theta_f^*(x) = \begin{cases} 
1 - \theta_t & \text{if } r_f^*(x) > r_h^*(x) \\
\frac{n^*(x) q^*(x)}{n^*(x) q^*(x) + q^*(x)} (1 - \theta_t) & \text{if } r_f^*(x) = r_h^*(x) \\
0 & \text{if } r_f^*(x) < r_h^*(x)
\end{cases}
\]

(10)

\[
\theta_h^*(x) = 1 - \theta_t - \theta_f^*(x)
\]

(11)

Moreover, thanks to households’ budget constraint, the lump-sum redistribution of land rent to each resident, \( \bar{y}_{\text{rent}} \), in a spatial equilibrium satisfies the following:

\[
\bar{y}_{\text{rent}} = \frac{1}{N} \int_0^\infty 2\pi x \left[ \theta_f^*(x) (r_f^*(x) - R_A) + \theta_h^*(x) (r_h^*(x) - R_A) \right] dx
\]

(12)

where \( N \) is the region’s equilibrium population.

The Labor Market’s Equilibrium Conditions

Wage Equilibrium under Congestion

In a spatial equilibrium, the locations chosen by each household and firm should be stable. Thus, households living at location \( x \) can freely chose alternative work and home locations, but they cannot improve their utility by doing so. Similarly, no worker can achieve a higher net wage (net of commute costs) by changing his or her job location, which is labeled a “wage arbitrage condition” in LRH’s (2002) model. Here, each worker is assumed to allocate one unit of time to work plus his/her (two-way) commute. For residents who live and work in the same location, commute time is zero, so the worker’s net wage income equals to the wage provided by firms at this location.

Consider first the wage gradients of a laissez-faire equilibrium setting, across locations, when traffic congestion is un-priced. At location \( x \), where commuting is outward \( (D(x) > 0 \) and \( t'(x) > 0) \), the number of workers within the annulus \( [0, x] \) exceeds the number of jobs there. Workers living at location \( x-dx \) thus have to commute outward and choose any firm within \( [x, \bar{x}] \) to work freely, but experience identical net income/utility no matter which workplace they choose. Suppose workers living at location \( x-dx \) commute a distance of \( dx \) to work at location \( x \); then, their wage condition will be as follows:

\[
w(x - dx) = w(x)(1 - 2t'(x)dx) - 2w(x) t'(x)dx (\lambda - \lambda_w)
\]

where \( \lambda \) is the ratio of VOTT to wage and \( \lambda_w \) is the ratio of value of working time (VOWT) to wage. The second component on the right-hand side of the equation, often overlooked in urban economic models (e.g., Wheaton, 1998; LRH, 2002; Brueckner, 2007), represents the cost of commuting and the benefit of not working during one’s commute. The VOWT typically equals the wage because optimizing workers will work until marginal benefits (wage earned) equal marginal cost (wages foregone), and employers are generally willing to pay for additional work at this established, marginal rate (Jara-Díaz and Guevara, 2003). So \( \lambda_w \) is generally assumed to equal 1. In this case, the above equation can be rewritten as:
Thus, a worker commuting from $x - dx$ outward to $x$ can earn a higher wage from firms in location $x$ than those that do not commute any distance, in order to compensate such workers for their efforts and thus sustain the spatial equilibrium among the region’s homogeneous workers. Similarly, in locations where $D(x) < 0$ and $t'(x) < 0$, workers at location $x + dx$ find jobs inward, in the annulus $[0, x]$, so wage at location $x$ satisfies the following:

$$w(x + dx) = w(x)[1 - 2\lambda t'(x)dx]$$

Combining the above equations, the wage gradient at location $x$ in the laissez-faire equilibrium is as follows:

$$w'(x) = 2\lambda w(x)t'(x)$$

Notably, when $D(x) = 0$, the marginal wage at location $x$ may be positive or negative, with two possible values, as $t'(x)$ having two values in Eq. (8). This is because since wages are falling on either side of such points, as worker households approach living in such no-commute locations.

Similarly, if a congestion toll is applied for all travel, workers commuting across location $x$ will pay a toll that equals to the marginal cost of delay on other road users, as $\tau(x)$ defined in Eq. (9). Thus, the wage gradient at location $x$ in an equilibrium under marginal-cost road pricing is

$$w'(x) = 2\lambda w(x)t'(x) + 2\tau(x)$$

**Clearing the Labor Market**

A spatial equilibrium requires that travel demand at the city edge, $D(\bar{x})$, and in the city centerpoint, $D(0)$, equals zero (since there are no jobs or workers beyond this boundary, to attract or generate such trips). In between these two locations, travel demand can and regularly does vary greatly. For $D(x) > 0$, $D'(x)dx$ represents the additional number of travelers passing the infinitesimal interval $dx$ from location $x$ outward, to location range $[x + dx, \bar{x}]$ and it involves two components: one is the net number of travelers generated in the interval $dx$, or number of workers residing in the interval minus number of workers needed by firms in the interval: $2\pi x \left( \frac{\theta_h(x)}{q(x)} - \frac{\theta_f(x)n(x)}{q(x)} \right) dx$; the other is the number of travelers hired in the interval $dx$ (and thus those who stop commuting across $dx$) to compensate for lost work hours when $D(x)$ workers pass the interval $dx$, i.e., $2\lambda t'(x)D(x)dx$. The change in travel demand (regardless of the sign of $D(x)$) is thus given by:

$$D'(x) = 2\pi x \left( \frac{\theta_h(x)}{q(x)} - \frac{\theta_f(x)n(x)}{q(x)} \right) - 2\lambda t'(x)D(x)$$

As noted above, the two boundary conditions for demand are:

$$D(0) = 0 \text{ and } D(\bar{x}) = 0$$

**Spatial General Equilibrium**

Given the transportation parameters described above, one can combine the households’ and firms’
partial equilibria with equilibrium conditions for labor and land markets, thereby creating a spatial general equilibrium model for the region. Three types of spatial equilibrium are discussed in this paper, including the laissez-faire city -- without road pricing, the congestion-toll equilibrium, and equilibrium under two restrictive UGBs.

Under, for example, the laissez-faire setting, competition drives households to determine optimal bid rents, \( r^*_h(x) \), and housing lot sizes, \( q^*(x) \), by minimizing expenditures given the target utility level, while driving firms to choose optimal rent bids, \( r^*_f(x) \), and employment densities, \( n^*(x) \), in order to maximize their profits. At the same time, available land or properties are assigned to agents offering the highest bid rents, while city edge rents equal the background (agricultural) land rent, jobs and housing are balanced, consistent with Eq. (15), and each worker’s net wage (after considering commute costs) is constant across locations, as shown in Eq. (13).

As shown in Appendix I, the sufficient and necessary conditions for the other two equilibrium policy scenarios are quite similar to the laissez-faire spatial equilibrium setup. For example, in the UGB case, the condition of a fixed land rent at the city edge is replaced by the assumption of a fixed metropolitan boundary:

\[
x^* = x_{u gb} = 0.9 \text{ or } 0.8 \times x_{l aisses f aire}
\] (17)

In the congestion-toll equilibrium, the money budget of each household change since a lump-sum congestion toll, \( t_{toll} \), is redistributed back to each household, and the wage difference between two locations for a worker should cover not only the difference of commuting costs but also the difference of congestion externalities, due to sustain the condition of wage equilibrium. In this case, the marginal wage distribution thus should satisfy Eq. (14), instead of Eq.(13), and the money budget, \( y_{ct}(x) \), and the congestion toll, \( t_{toll} \), are given by

\[
y_{ct}(x) = w(x) + y_{rent} + t_{toll}
\] (18)

\[
t_{toll} = \frac{1}{N} \int_0^{x^*} D(x) \tau(x) dx
\] (19)

Net surplus, including both consumer and producer surplus, is maximized when a city reaches any spatial general equilibrium defined in Appendix I. Given \( \theta^*_f(x) \), \( n^*(x) \), \( F(x) \), \( c^*(x) \), \( q^*(x) \), \( x^* \), total welfare can be computed as:

\[
TSW = \int_0^{x^*} 2\pi x \left\{ \theta^*_f(x)f\left(n^*(x)\right)F(x)\gamma - \frac{1-\theta_t-\theta^*_f(x)}{q^*(x)} c^*(x) \right\} dx
\] (20)

**NUMERICAL SIMULATIONS**

**Parameter Values and Algorithm**

Table 1 shows parameter values calibrated using data from the metropolitan areas of Houston and Austin, Texas, and values found in existing literature (e.g., LRH, 2002; Wheaton, 1998; Brueckner, 2007). Some parameters are held constant across scenarios. For example, the Cobb-Douglas utility function’s parameter \( \alpha \) reflects a household’s expenditure shares on goods and services, versus rents (relative to a household’s or worker’s net income). Here, we rely on LRH’s (2002) data-based value of 0.9, with \( 1- \alpha = 0.1 \) as the share of net income going to housing.
rent. In 2009, Houstonites’ annual expenditures on goods and services, after paying for housing
and transportation, were around $30,000 per person. The Austin region’s total residential parcel
area and population in 2008 were 84,000 acres and 750,000 persons, respectively; so the average
residential lot size is around 4800 square feet per person. With such numbers, the utility level
 provided by $\bar{u} = c^\alpha q^{1-\alpha}$ is thus set as 4000 utils. Since farmland at the edge of Austin sells for
about $50,000 per acre, amortization of such costs over 40 years at a discount rate of 5% results
in rural land rents over $4,000,000 per square mile per year (as used in Wheaton’s (1998) setting).
Thus, here agricultural land rent, RA, is set to $4,000,000 per square mile -- or 14.35 cents per
square foot per year in this work’s numerical simulations.

Key parameters for firm behaviors also refer to LRH’s paper, where $\kappa = 0.95$ and $\gamma = 0.04$.
The parameter of production externality, $\zeta$, will affect urban from in different values (LRH,
2002). This paper focuses more on the congestion effects, so $\zeta$ is fixed as 5. Total factor
productivity, $\delta$, is set at 30,000, by calibrating Eq. (5) assuming that Austinites’ per-capita money
income is $31,000 (as it was in 2011) and Austin’s downtown holds over 100 persons per acre on
average (as it did in 2010). Following Wheaton’s (1998) study, roadways’ or transportation’s
share of land is assumed to be 30%. The influence of doubling $\lambda$ (on modeling results) is
equivalent to doubling $\varphi$ and $\rho$ simultaneously, holding all other parameter values constant.
Since $\varphi$ and $\rho$ vary in different simulations, $\lambda$ is fixed at 0.5, indicating that commuting’s
VOTT is 50 percent of hourly wage here. The agglomeration-limit boundary, $\tau$, is set to 3 miles.

Table 1’s congestion-related parameters were calibrated using Austin area data, holding other
parameters fixed. When $\varphi = 0.005$ (representing the free-flow travel speed of 25 mile/hour),
$\rho = 1 \times 10^{-8}$, and $\sigma = 1.2$, the region’s limiting radius and employment total under a
laissez-faire equilibrium hit 11.64 mile (or 426 sq mi total) and 513,000 workers, respectively,
which approximate Austin’s values. In order to get a sense of transport and congestion impacts,
the congestion-related parameters are varied across scenarios. For example, the congestion
indicator $\rho$ changes from 0 to $1 \times 10^{-7}$, $5 \times 10^{-8}$, $1 \times 10^{-8}$ and $1 \times 10^{-9}$, with $\sigma$ fixed at 1.2. The
results of these variations are discussed in the next section.

The spatial equilibria were solved for using MATLAB, following LRH’s two-step fixed-point
algorithm (2002). The first step computes equilibrium of land use and labor distribution, given a
production externality function, $F^0(x)$, while the second step calculates a new $F^1(x)$ based on
Eq. (4). The simulation has converged when $F^*(x)$ reached a fixed point, after several

---

1 The regional data come from several sources: income data are from a 2011 report on “Income, Expenditures,
Poverty, and Wealth” by the United States Census Bureau (http://www.census.gov/prod/2011pubs/12statab/income.pdf, p. 448); lot-size data are from a 2009 draft report on
“Land Use Zoning” by City of Austin ftp://ftp.ci.austin.tx.us/GIS-Data/planning/compland/4-community_inventory_LandUseandZoning_v4.pdf, p.4-4); 2008 population data is from
http://www.austintexas.gov/sites/default/files/files/Planning/Demographics/population_history_pub.pdf; and
farmland rent is estimated using commercial real estate sales data from LoopNet (at
2 From U.S. Census data (see http://quickfacts.census.gov/qfd/states/48/4805000.html) and Capital Area
3 In 2010, Austin’s city area was 297 square miles with about 550,000 persons available for working (from 18 to 65
iterations\(^4\). Since our model differs from LRH’s model, by virtue of including congestion effects, allowing for a relaxed city boundary, and enabling redistribution of rents and toll revenues to residents, the algorithm in the first step differs from that in LRH’s work. For example, given an initial wage \(w_0(0)\) at the city center point \((x = 0)\), wages and land uses at other locations can be derived via a recursive process based on Eq. (13) (the laissez-faire case) or Eq. (14) (the congestion-toll case) and Eq. (15). The process of finding an equilibrium corresponds to seeking an equilibrium initial wage \(w_0^*(0)\) to clear all land and labor markets. This process involves two processes: The first uses a grid-search algorithm to find a \(w_0^*(0)\) given an initial amount of redistributed rent, \(y_{\text{rent}}^0\). The second calculates a new lump-sum redistributed rent based on Eq. (12) and goes back to the first procedure until reaching a fixed point for \(y_{\text{rent}}^*\) (i.e., \(y_{\text{rent}}^*\)). The run time for finding such spatial equilibria on a standard personal computer ranges from 10 minutes to 1 hour, depending on parameter assumptions used.

### Relating Congestion and Sprawl

The simulated equilibria suggest that higher levels of congestion result in more centralization of households and a less dense/less centralized agglomeration of firms, while less congestion results in a more monocentric urban form. For example, assuming speeds of 25 mile/hour \((\varphi = 0.005)\), as shown in Figure 2, the laissez-faire equilibria under light congestion \((\rho = 1 \times 10^{-9})\) or \(\rho = 1 \times 10^{-8}\) produce monocentric urban structures with larger city boundaries and population, while heavy-level congestion \((\rho = 5 \times 10^{-8} \text{ or } \rho = 1 \times 10^{-7})\) produces an annulus structure with smaller city areas and population. As congestion levels increase, workers will live closer to their workplace, and firms will move away from the urban core, in order to avoid excessive labor costs.

Network congestibility is an important determinant of equilibrium city size and land use patterns. Here, several findings are comparable to those found in monocentric, open-city settings. For example, in the Figure 1 scenario, higher congestion levels are estimated to make the city/region more compact (as noted in Kono and Joshi [2012]). The boundary of 15.52 mile defines the region’s limiting radius under the less congested case \((\rho = 1 \times 10^{-9})\), falling to 7.44 mile in the high congested case \((\rho = 1 \times 10^{-7})\). When the congestion levels decrease, residential densities at each location away from the employment cluster rise. However, some findings differ from, or not easily detected in, a monocentric model. Since our models allow for job decentralization, higher congestion levels tend to decentralize jobs but make jobs more agglomerated in a smaller area. The locations of peak jobs density move from 2.14 mile under the less congestion case \((\rho = 1 \times 10^{-9})\) to 2.46 miles under the high congestion case \((\rho = 1 \times 10^{-7})\), while jobs agglomerate in a smaller band of land, from \(x = [0, 3.62]\) to \([1.52, 3.27]\).

These findings suggest two potential and related market adjustments when facing congestion: one is a decline in land use densities, (in order to lower traffic intensities), and another is firm decentralization (to achieve somewhat higher transport capacity at less central workplaces, along with lowered commute distances). These findings underscore the challenges of land use policy for addressing congestion externalities. Many existing studies have shown how regulating residential density is equivalent to levying first-best congestion tolls when correcting congestion

\(^4\) The algorithm’s convergence is proven in LRH’s model when congestion effects are absent. Although the lemma that a convergence can be reached by the algorithm introduced in this paper are not rigorously proven to apply, the results presented in this paper are all convergent in practice.
externalities in monocentric settings (Pines and Sadka, 1985; Wheaton, 1998). But many regions are no longer monocentric, and our results suggest that regulating only residential density is not enough to achieve a first-best optimum. It appears that an optimal land use strategy should probably allow for both job decentralization and residential densification.

**Policy Scenarios**

In this section, two distinct policies’ efficiency and welfare effects vis-a-vis traffic congestion (and its associated negative externalities) are specifically examined. The policies are application of congestion tolls and imposition of two different UGB regulations (where the laissez-faire region’s radius is reduced 10% and then 20%). All three sets of results are compared to the laissez-faire equilibrium, where congestion externalities are un-priced. In these policy scenarios, the transport technology indicator is fixed at $\rho = 0.005$, while the congestion indicator changes from $\tau = 1 \times 10^{-9}$ to $1 \times 10^{-8}$, $5 \times 10^{-8}$ and $1 \times 10^{-7}$, as part of a sensitivity analysis.

Table 2 provides various aggregated travel attributes of different congestion levels. These attributes are average commuting time, distance and costs. One common benefit of all three policy scenarios is that they reduce (average) travel times, distance and costs as compared to the laissez-faire case – even though tolls are applied and/or traffic densities rise. The UGB regulations reduce average travel distance more than the congestion-toll policy, largely because the UGB regulations bring more compact urban form (smaller region size and higher residential densities) than the congestion-toll policies. In the high congested case ($\tau = 5 \times 10^{-8}$), the average commute distance of round trips in a congestion-toll case is 5.99 miles, smaller than 6.84 miles in the laissez-faire case, but larger than 5.82 miles in the 10% UGB regulation and 4.76 miles in the 20% UGB regulation. As shown in Figure 2, both equilibrium boundaries of the congestion-toll case (8.35 mile) and the 20% UGB case (6.82 mile) are smaller than the laissez-faire case (8.53 mile), and the overall/average residential density of the 20% UGB equilibrium (2904 workers/sq mi) is 44% higher than that of the congestion-toll equilibrium (2013 workers/sq mi), and 55% larger than that of the laissez-faire equilibrium (1869 workers/sq mi). Meanwhile, the peak of job density is 2.69 mile in the congestion-toll equilibrium, 2.56 mile in the laissez-faire case, and 2.54 in the 20% UGB equilibrium. If reducing travel distances and thus vehicle-miles traveled (VMT) is a key community objective, an appropriate UGB policy may be effective.

In addition, the congestion-toll policies may bring significant reduction in travel costs when network congestibility is high enough. (For example, such tolls result in 17% lower travel costs than the laissez-faire equilibrium when $\rho = 5 \times 10^{-8}$, and 30% lower when $\rho = 1 \times 10^{-7}$.) The 10% UGB case is estimated to bring a 10% to 14% reduction in travel costs, while the 20% UGB case is estimated to reduce per capita travel costs by more than 20%. In the cases of low congestion, the UGB’s travel cost benefits tend to be larger than those under congestion-toll policies.

Although better travel outcomes may be gained by UGB regulations, these policies clearly lower the region’s per-capita social welfare levels. From Table 2, the more severe a region’s/network’s congestibility, the more effective a toll-related policy will be, in terms of welfare improvements. For the most congested network modeled here ($\rho = 1 \times 10^{-7}$), per-household welfare rises almost 19 percent following the levying an optimally designed congestion toll. For the low congested case ($\rho = 1 \times 10^{-9}$), only a 6 % increase in social welfare per household or worker is gained by the
congestion-toll strategy. In contrast, the UGB policies produce up to 20% and 40% declines in welfare per household (for the 10% and 20% area-reduction cases), vs. the laissez faire case. For example, for $\rho = 5 \times 10^{-8}$, the less restrictive UGB policy (10%) brings a 22% loss in per-household welfare, while the more restrictive UGB (20%) delivers a 35% loss in per-household welfare.

Several factors may explain such losses. First, the UGBs may limit the market’s ability to decentralize jobs when facing congestion. Levying a congestion toll is associated with some jobs decentralization (with the employment peaks shifting slightly outward, for example, from a radius of 2.5 mile to 2.69 mile, as shown in Figure 2a), while the peak shifts slightly inward for the 20% UGB case (from a radius of 2.5 mile to 2.48 mile). Second, the UGBs cause edge rents to escalate, versus the background agricultural-use rent. While such policy saves land for other uses, and is estimated to lower commute costs here, less land overall means more competition for land (even with population endogenous here), resulting in higher rents and smaller parcels per household and worker, and thus lowered household utilities and lowered economies of production. In a real setting, lower-income households and lower-paying jobs may be unable to remain in the region, creating other issues (in equity and industrial balance, for a fully functioning economy, for example). As shown in Table 2, the increases in households’ bid-rents under the UGB regulations are much higher than those under congestion-toll policies. With relatively high network congestibility ($\rho = 1 \times 10^{-7}$), average bid-rents per household rise significantly (by 69% in the 20% UGB equilibrium), versus the congestion-toll equilibrium (just 12%). For the low congestibility case ($\rho = 1 \times 10^{-9}$), the corresponding increases in household rents are 45% (under the 20% UGB policy) and as low as 0.6% (under the congestion-toll policy).

For further understanding, UGB scenarios with the same boundary (final radius) as found in the congestion-toll equilibrium was also examined, along with 5% UGB and 15% UGB cases. As described above, all the UGB regulations raise the residential densities and land rents for households, while slightly centralizing jobs locations, and making the regions more compact, but they do not deliver social welfare improvements.

Welfare implications were also evaluated when the transport technology indicator $\varphi$ was set to 0.01 and 0.002. The larger the $\varphi$, the more effective the congestion-toll policies tend to be, and the more social-welfare losses incurred under UGB regulations. These sensitivity analyses reconfirm Table 2’s relationships, suggesting a robust conclusion: UGB strategies tend to alleviate congestion externalities and lower VMT and travel costs, but are not an effective substitute for the appropriately designed congestion tolls, especially in non-monocentric settings, due to escalating land rents and limitations on job decentralization.

CONCLUSION AND DISCUSSION

This paper develops and then applies a new spatial general equilibrium model in order to explore the impacts of tolling and growth-boundary policies on region size and population, land use patterns and travel costs, land rents and traffic congestion. Results of many parameter and policy scenarios allow one to evaluate the welfare and commuting effects of such anti-sprawl policies. This new model differs from many existing studies (e.g., Fujita and Ogwa, 1982; Anas and Kim, 1996; Lucas and Rossi-Hansberg, 2002; Wheaton, 2004) by recognizing both congestion and production externalities, while working households’ and firms’ land-use decisions are
endogenous across continuous space, reflecting both the value of travel time and work time.

Equilibrium solutions across a wide range of parameter assumptions and policies suggest that improvements in network congestibility tend to lower travel costs (in time and money), allow firms to cluster in the region center (and benefit from positive production externalities), and enable households to locate less densely (while enjoying lower rent per acre and larger lot sizes). In contrast, when congestion dominates the region, via relatively high travel costs, the model predicts a decentralized annulus for firms or a mixed-use urban structure, with relative compact boundaries, due in large part to escalating residential land rents and increasing residential densities. These findings are generally consistent with those of Fujita and Ogawa (1982), Berliant et al. (2002), and Lucas and Rossi-Hansberg (2002), although those other models do not allow for congestion. Such connections support the notion that job decentralization and polycentric urban forms are at least in part driven by worsening congestion levels in existing, evolving regions, and in turn help relieve traffic congestion, as suggested by commute times and costs in Giuliano and Small’s (1991) and Crane and Chatman’s (2004) empirical work.

Among the various policies examined, congestion-based tolling appears better for correcting its associated market failure. It delivers greater improvements in regional and per-worker social welfare, relative to laissez-faire settings, along with a slightly more compact urban form, density increases, and some jobs decentralization. The toll policy’s effectiveness increases as congestion levels become more severe (ranging from 6% to 25% of total welfare gains in this paper’s simulations).

The efficiency and welfare effects of the UGB policies are mixed. The two UGB scenarios (reducing land area by 10 to 20 percent, vs. laissez-faire conditions) are predicted to reduce travel costs and distances, and city size, without changing equilibrium job levels much. However, their rent-escalation effects (rising 20% to 30% under a 10% UGB and 45% to 70% under a 20% UGB) and anti-job-decentralization effects mean lowered social surplus levels. Such UGB effects have been anticipated in some prior studies, like those of Anas and Rhee (2007) and Anas and Pines (2008). And they appear present in regions like Portland, Oregon and Knoxville, Tennesse, where housing rents/prices inside the UGBs rise faster than outside the UGBs (Staley and Mildner, 1999; Cho et al., 2008). Within the confines of a boundary, higher-density development at pace with population growth and immigration is important, but can be challenging. Speculation is also problematic in various settings. London, England and Auckland, New Zealand, for example, have reportedly experienced major rent escalations due to relatively low housing supply from release of land release for new development (Cox, 2010; Heath, 2013). Home affordability is thus a key topic for debate under growth management discussions (Downs, 2004). Moreover, development activities in 95 relatively “contained” U.S. metro areas (as contained by city limits, greenbelts, and/or UGBs) are more agglomerated near their central cities than those in uncontained areas (Nelson et al., 2004).

Multiple opportunities also exist to make these models more realistic. For example, there is only one household/worker type and one firm type, only one worker per household and a fixed time budget for travel plus work. Home and work locations (which then determine travel times and costs) and residential lot size are the only decision variables available to workers here. The associated utility function is quite simplistic, and often criticized by the planners and
practitioners (Knaap, 2007). In reality, community welfare is affected by much more than home size and work and commute durations. For example, other benefits of higher density living may include better health from more active (less motorized) travel, lower energy demands and infrastructure costs, less climate change, more habitat for animals and plants outside the city boundary, a closer and more cohesive social setting. But denser settings may also be associated with more exposure to crime, noise, and emissions. Every context is distinct, and net benefits may go either way, depending on the local economy and how the community addresses design and planning.

A congestion-toll policy also affects community welfare in ways not modeled here, for example by shifting travel modes and trip timing. Moreover, a model that enables a gradual, dynamic city evolution is important to explore. The one-shot, static equilibrium typical of papers in urban economics is never achieved in practice. In reality, cities already exist, and populations regularly expand, in the midst of great uncertainty and imperfect information, along with speculation and other complex -- but very realistic -- human behaviors. Several recent studies have explored in this topic (Boucekkine et al., 2009; Desmet and Rossi-Hansberg, 2010). Finally, allowing for more diverse and realistic policies, like flat-rate tolls only on freeways, and cordon area congestion pricing, would be meaningful, since first-best congestion tolls and UGBs are not common in practice. Nevertheless, the tool developed here extends urban economic modeling while illuminating multiple impacts of a several important policies and a wide range of behavioral assumptions, relating to human settlement in the past, present and future.

ACKNOWLEDGMENTS
The authors thank Alex Anas, Jan Brueckner, and Esteban Rossi-Hansberg for their inspired comments and questions.

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13, 20–45.


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Heath, A. 2013. Rent controls are madness, we need to build more homes. *The Telegraph*, June 11.


Table 1 Parameter value assumptions

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# Table 2 Simulation Results of Travel Attributes and Welfare Effects under Different Policy Scenarios and Different Network Congestibility ($\rho = 0.005, \sigma = 1.2$)

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Notes: Travel time and distance are round-trip-based. Travel time is calculated based on 1 unit of time equaling 8 hours. Percentage changes (%’s, in bold) are relative to the Laissez-Faire equilibrium.
Figure 1 Effects of network congestibility on urban form: equilibrium densities when the congestion indicator $\rho$ varies from $1 \times 10^{-9}$ to $1 \times 10^{-7}$ (and $\varphi = 0.005$)
Figure 2 Equilibrium rents and land use patterns under three policy settings (with $\varphi = 0.005$ & $\rho = 5 \times 10^{-8}$)