Optimal Energy Taxation in Cities

by

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Abstract

This paper presents the first investigation of the effects of optimal energy taxation in an urban spatial setting, where emissions are produced both by residences and commuting. We show that the optimum is generated by real estate taxes of a particular form along with a commuting tax, which yield the same tax liabilities as a carbon tax. We then analyze the effects of these taxes on urban spatial structure, showing that they reduce the extent of commuting and the level of housing consumption while increasing building heights, generating a more-compact city with a lower level of emissions per capita.

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1. Introduction

In step with growing concerns about the impact of global warning, urban research has increasingly focused on the energy consumption of cities. This research reflects the recognition that residential and commercial land-uses are important generators of greenhouse gas (GHG) and local emissions along with the transportation and industrial sectors. Their importance is seen in Table 1, which shows energy use by sector, with emissions from electricity generation "distributed" according to the final users of the electricity. As can be seen, when their electricity use is taken into account via the distribution method, the residential and commercial sectors each account for an appreciable 16.9% of total emissions, with their 33.8% total exceeding the shares of industry and transportation. Therefore, economic analysis of policies designed to control emissions should ideally include these two real-estate sectors in its focus along with other sources.

In advancing this goal, some researchers have studied the relationship between a building's energy use and its structural characteristics, with notable contributions by Costa and Kahn (2011), Chong (2012) (who also draws a link to climate), and Kahn, Kok and Quigley (2014). Using a hedonic approach, Eichholtz, Kok and Quigley (2010) ask whether the market values green buildings, finding that energy-efficient commercial structures indeed command higher rents. Glaeser and Kahn (2010) extend the focus beyond residential energy use to include emissions from driving and public transit, generating a ranking of US cities according to their overall carbon footprints. Zheng, Wang, Glaeser and Kahn (2011) extend this approach to Chinese cities.

In parallel with these empirical efforts, other researchers have imbedded energy usage into the familiar monocentric-city model of urban economics, with the ultimate goal of appraising the effect of urban policy interventions on emissions. These studies, which rely on numerical simulations of realistically calibrated urban models, include Larson, Liu and Yezer's (2012) study evaluating the energy-use impacts of higher gasoline taxes, better vehicle fuel efficiency, urban greenbelts, and housing density restrictions. Larson and Yezer (2015) ask how such policy impacts vary with city size, while Borck (2016) explores the effect of building-height limits on urban GHG emissions. Tscharaktschiew and Hirte (2010) study the impact of emission taxes and congestion on emissions from commuting.

Although this second group of studies has greatly increased our understanding of the links between urban spatial structure, energy use, and emissions, an important question remains unanswered. In particular, no study has analyzed *optimal* urban form when both housing and commute trips generate emissions. The present paper fills this crucial gap in the literature. We add energy use and both GHG and local emissions to the housing sector of the standard urban model, doing so in a novel and realistic fashion, while also recognizing the emissions from commuting. With both types of emissions assumed to reduce consumer utilities, the analysis then develops the conditions that characterize the optimal city, which embody a trade-off between the environmental gains from lower emissions and the losses from achieving them.

The form of these optimality conditions reveals that real estate taxes of a particular form along with a commuting (or gasoline) tax are needed to generate the optimum. The resulting tax liabilities are in fact the same ones that would be generated by a carbon tax on gasoline and on the fuels used to produce residential energy. Despite this equivalence, the analysis focuses on the real estate and gasoline taxes themselves rather than on the underlying carbon tax, partly because doing so facilitates second-best analysis, where one or more of these taxes is set at zero. For example, zero real estate taxes can be imposed, forcing the gasoline tax to address emissions from both residences and commuting, an exercise that is impossible under a carbon tax.[1] With this theoretical foundation, numerical simulation analysis then derives the changes in urban form that follow from imposition of the optimal taxes. The simulation results thus show how urban spatial structure responds to optimal energy taxation, in both first-best and second-best cases.[2]

More specifically, the model relies on principles from the engineering and architecture literatures by assuming that residential energy use from heating and cooling depends on a building's exposed surface area, reflecting heat transfer through exposed surfaces. According to Ching and Shapiro (2014), a building's energy use per square foot of floor space is proportional to its surface area per square foot of floor space, with surface area including the sides of the building along with the roof. Since the roof area stays constant as the height of the building increases, surface area increases less rapidly than floor space as height grows. The result is energy economies from building height, with energy use per square foot of floor space falling as height increases, a pattern seen in the empirical results of Larson et al. (2012).

If a building's total energy use (and hence its total emissions) just depended on its square footage of floor space, the appropriate residential energy tax would just be a tax per square foot of space. But with surface area mattering instead, the analysis shows that residential energy taxes should include a tax per square foot of floor space *along with a tax on the building's footprint*, which captures energy usage that depends on the roof area (equal to the footprint). When buildings completely cover the land, as in the standard urban model, the footprint tax is just a tax on the entire land input, hence a land tax. By raising the land cost to the developer, this land tax encourages the construction of energy-efficient tall buildings. Note that the land tax adds to the tax burden on land already inherent in the housing tax.[3]

In addition to these taxes on residential land-use, the model prescribes a commuting tax per mile to address GHG and local emissions per mile driven. This prescription emerges from a model without traffic congestion, in contrast to the work of Larson et al. (2012) and Larson and Yezer (2014), where congestion is realistically modeled.

While a carbon tax is equivalent to a commuting tax in conjunction with the two real estate taxes, as noted above, the political feasibility of these equivalent schemes may differ, as is clear from recent experience in the United States. Imposition of a national carbon tax has been blocked, mainly by Republican opposition, but greater policy flexibility exists at the state and local levels. Moreover, that fact that real estate and gasoline taxes are already levied at the subnational level may make the use of these taxes for environmental purposes more palatable than imposition of a state or local carbon tax. Furthermore, focus on the three taxes allows exploration of partial, second-best solutions, such as a state-level increase in the gasoline tax in pursuit of environmental goals with no change in real estate taxes.

In the numerical analysis, we calibrate the model in the most realistic possible fashion and then use it to predict the impact on urban spatial structure from imposing the optimal taxes on floor space, land, and commuting. The numerical results thus allow a comparison of the optimal city, where the emissions externalities are addressed, to the laissez-faire city, where no intervention is undertaken. With emissions generated by housing consumption and commuting, the expectation is that optimal energy taxation will reduce the levels of both activities, leading to a city that is more spatially compact than a city without such taxes. The simulations show whether this broad conjecture is confirmed while illustrating the details of the city's adjustment to taxation. In addition, by relying on three separate taxes rather than an equivalent carbon tax, we are able to explore second-best cases where some taxes are set at zero and provide numerical answers, as mentioned above.

As is well known, welfare analysis in urban economics is best carried out by focusing on a fully-closed city, where resources leakages are absent (see Pines and Sadka (1986)). The rental income from land in such a city accrues to the residents rather than leaking to absentee owners, and tax revenue is also redistributed to the residents in lump sum fashion, eliminating another potential leakage. The city simulated in the paper has both these features.

One of the paper's innovations is its modeling of energy economies from building height, and this feature's connection to previous work should be noted. The models of Larson et al. (2012) and Larson and Yezer (2014) include a similar feature, although in a discrete fashion. In particular, energy use per square foot is assumed to decrease discontinuously as building height passes through several discrete critical points, in contrast to the present continuous formulation. The model of Borck (2016), by contrast, includes no energy benefits from tall buildings. His exercise of imposing building-height limits therefore generates no sacrifice on this dimension, but the resulting supply restriction, by raising the price of floor space throughout the city, reduces residential emissions by shrinking individual dwelling sizes. The urban sprawl created by height limits, however, has an offsetting effect on emissions from commuting. The present paper borrows from Borck's (2016) approach while incorporating height economies.

The plan of the paper is as follows. Section 2 presents the theoretical analysis, which includes a demonstration of the equivalence between our taxes and a carbon tax. Section 3 explains the setup of the simulation model, and Section 4 presents the simulation results. Section 5 offers conclusions.

2. Model

2.1. The setup

The model is based on the standard model of a monocentric city, adapted to include energy use. In addition, the surface area of buildings, previously not an issue in urban modeling, plays a prominent role, as explained above. To incorporate surface area, suppose that buildings are square, occupying a land area of ℓ and completely covering that land, as in the standard urban model.[4] Structural density (capital per unit of land) is S and floor space per unit of land is given by $h(S)$. The h function is the intensive form of a constant-returns floor-space production function, and it satisfies $h' > 0$ and $h'' < 0$. Since floor space per unit of land is the most natural index of building height, $h(S)$ can also be viewed as the height of the building. Therefore, each of the four sides of the building has area $h(S)\sqrt{\ell}$ (height $\times$ width), and the area of the roof is ℓ. Surface area is then

$$4h(S)\sqrt{\ell} \ + \ \ell. \qquad (1)$$

Letting e denote energy use per unit of surface area, the building's energy use is e times (1). Energy use per unit of land is then given by

$$\frac{(4h(S)\sqrt{\ell} \ + \ \ell)e}{\ell} \ = \ \frac{4h(S)e}{\sqrt{\ell}} \ + \ e. \qquad (2)$$

The second term is energy use per unit of land due to heat transfer through the building's roof, while the first term captures heat transfer through the sides. It is clear from (2) that a building occupying more land has greater energy efficiency per unit of land, which would prompt the developer to increase ℓ, an incentive that is absent in the standard urban model (where ℓ is matter of indifference).[5] To abstract from this issue, we fix ℓ, and without loss of generality set the value at 16 so that energy use per unit of land becomes[6]

$$h(S)e \; + \; e. \tag{3}$$

Again, the last term captures energy use due to heat transfer through the roof (whose area matches the lot size), while the first term captures energy use from heat transfer through the building's sides, a transfer that is proportional to the floor space it contains. Note that the presence of the additive e term in (3) means that energy use increases less rapidly than floor space, implying energy economies from building height. Equivalently, dividing (3) by square footage ($h(S)$) shows that energy use per square foot is $e \, + \, e/h(S)$, an expression that is smaller in a taller building. Each unit of residential energy use generates ψ units of "composite" emissions (GHG plus local), so that (using (3)) residential emissions per unit of land are given by $\psi(h(S)e \; + \; e)$.

Let the cost per unit of energy be normalized to unity, and assume that the developer bears the building's energy cost. In addition, let p denote the price per square foot of housing, r denote rent per unit of land, and i denote the price per unit of capital. Then, using (3), the developer's profit per unit of land is

$$ph(S) \; - \; iS \; - \; r \; - \; \textit{energy cost per unit of land} \; = \; (p-e)h(S) \; - \; iS \; - \; e \; - \; r. \tag{4}$$

In the absence of taxes, the developer would choose S to satisfy

$$(p-e)h'(S) \; = \; i, \tag{5}$$

and land rent r would be determined by the zero-profit condition:

$$r \; = \; (p-e)h(S) \; - \; iS \; - \; e. \tag{6}$$

The form of both conditions is familiar from the standard urban model (see Brueckner (1987)).

Note that in a fully realistic model, e would be another choice variable of the developer, who could reduce energy use by improving the insulation of his building and taking other costly steps. This choice would in turn be influenced by residential energy taxes, a channel that is absent from the current model. Another point to note is that e will depend on climate, a possibility that is addressed in the sensitivity analysis of section 4.4. In addition, the model abstracts from the "urban heat island" effect, under which a concentration of tall buildings itself raises the ambient temperature, affecting e.

Energy is also used as workers commute to the CBD. Let the cost per mile of commuting (on a round-trip basis) be denoted t, so that commuting from a residence x miles from the CBD costs tx per period. The parameter t includes private energy costs, as reflected in the cost of fuel. Suppose that composite (GHG plus local) emissions per round-trip mile of commuting are given by γ, so that the energy used in commuting from a distance x generates γx worth of emissions.

Several other sources of residential energy use have been omitted from the model: kitchen appliances, such as refridgerators and stoves, and hot-water heaters. These sources can be viewed as generating a fixed amount of energy use that does not increase proportionally with the physical size of the dwelling.[7] This fixed usage presumably accounts for empirical findings showing that residential energy use per square foot of floor space falls as dwelling size rises (see, for example, Larson, Liu and Yezer (2012)). Since a city's total energy use from household appliances will thus be roughly proportional to the number of dwellings but unaffected by urban form, we omit it from the analysis. Energy used in producing the nonhousing good consumed by households (the commodity c introduced below) is also omitted from the model (Larson and Yezer (2014) include it).

2.2. Emissions and energy taxes

As explained in more detail below, GHG and local emissions are aggregated in a fashion that allows them to be treated as a single composite quantity. Let μ denote the social damage from each unit of composite emissions, which is endogenous in the model. Then, the taxes needed to support the social optimum can be derived from the model. These taxes are as follows:

- A tax of $\tau_q = \mu\psi e$ per square foot of floor space, addressing emissions from energy use due to heat transfer through the sides of a building
- A tax of $\tau_\ell = \mu\psi e = \tau_q$ per unit of land, addressing emissions from energy use due to heat transfer through a building's roof
- A tax of $\tau_t = \mu\gamma$ per mile of commuting, addressing emissions due to energy use in commuting

To demonstrate the need for these taxes analytically, let utility be given by $v(c, q, G)$, where c is consumption of a nonhousing good, q is consumption of housing floor space, and G gives the level of composite (GHG plus local) emissions affecting the city's residents. Two equivalent approaches to the social planner's problem used in deriving the optimal taxes are possible, following the past literature. Under the first approach, the planner minimizes the city's resource consumption, subject to several constraints: achievement of a fixed utility level u for its residents, the requirement that the city fits its population, and a condition giving the city's overall emissions G.[8] Under the second approach, which is dual to the first, the planner maximizes the common utility level of urban residents subject to a resource constraint, the population constraint, and the G condition. Since the first approach is somewhat simpler, the present analysis follows it.

To start, observe that the fixed-utility constraint, which can be written $v(c, q, G) = u$ for some constant u, implies $c = c(q, G)$, with the derivatives of this function equaling minus the marginal rates of substitution: $c_q = -v_q/v_c < 0$ and $c_G = -v_G/v_c > 0$ given $v_G < 0$ (subscripts denote partial derivatives). Using the $c(q, G)$ function and letting $\overline{x}$ denote the distance to the city's edge and r_a denote the opportunity cost of land (agricultural rent), the city's resource consumption is given by

$$\int_0^{\overline{x}} 2\pi x \left[iS \ + \ \frac{h(S)}{q}(c(q, G) + tx) \ + \ h(S)e \ + \ e \ + \ r_a \right] dx. \tag{7}$$

In (7), the choice variables S and q are implicitly functions of x. The first term in the integrand captures capital usage, the second term equals c consumption plus commuting cost per person at distance x multiplied by the population at x. That population equals the area $2\pi x dx$ of the ring at x times h/q, where h/q gives population density (housing square footage per unit of land divided by square feet per dwelling). The remaining terms capture building energy use and the opportunity cost of land.

Letting L denote the city's fixed population, the population constraint is written

$$\int_0^{\overline{x}} 2\pi x \frac{h(S)}{q} dx \quad = \quad L, \tag{8}$$

and the multiplier associated with this constraint is λ. Total emissions G satisfy

$$\int_0^{\overline{x}} 2\pi x \left(\psi[h(S)e + e] \ + \ \gamma \frac{h(S)}{q} x \right) dx \quad = \quad G, \tag{9}$$

where $2\pi x(xh(S)/q)dx$ gives total commute miles for consumers living in the ring at x. The multiplier associated with this constraint is $\mu > 0$, the social damage from an extra unit of emissions.

The planner chooses values of G and $\overline{x}$ and values of S and q at each distance to minimize (7) subject to (8) and (9). After forming a Lagrangean expression using (7)–(9), the optimality conditions for S and q are generated by differentiating inside the integrals, while the condition for $\overline{x}$ comes from differentiating with respect to the limits of integration. After a modest amount of manipulation (see the Appendix), these conditions reduce to equations that identify the taxes required to support the optimum. The first equation is

$$c(q, G) \ + \ q\frac{v_q}{v_c} \ + \ (t + \mu\gamma)x \quad = \quad -\lambda, \tag{10}$$

Recognizing that the consumer will set v_q/v_c equal to the price p per square foot of housing, the first two terms correspond to total consumption expenditure in a decentralized equilibrium. The tx term is the money cost of commuting, but (10) shows that this cost must be supplemented by a tax of $\mu\gamma \equiv \tau_t$ per mile traveled, as in the third bullet point above. The term $-\lambda$ is constant over x and corresponds to the common income of consumers in a decentralized equilibrium. Note that, ignoring differences in automobile fuel efficiency, the commuting tax has the same form as a gasoline tax.

The next condition is

$$\left(\frac{v_q}{v_c} - e - \mu\psi e\right) h'(S) \quad = \quad i. \tag{11}$$

Comparing to the profit-maximization condition (5) and recognizing $v_q/v_c = p$, (11) implies that the net price received by the developer per unit of floor space should be reduced below $p - e$ by the amount $\mu\psi e \equiv \tau_q$, an emissions tax per square foot of floor space (as in the first bullet point above).

The laissez-faire equilibrium condition determining the distance $\overline{x}$ to the edge of the city would set r evaluated at $\overline{x}$ equal to r_a, and using (6), this condition is written

$$(\overline{p} - e)h(\overline{S}) \ - \ i\overline{S} \ - \ e \quad = \quad r_a, \tag{12}$$

where $\overline{p}$ and $\overline{S}$ are the p and S values at $\overline{x}$. By constrast, the optimality condition for $\overline{x}$ reduces to

$$\left(\frac{\overline{v_q}}{\overline{v_c}} - e - \mu\psi e\right) h(\overline{S}) \ - \ i\overline{S} \ - \ e \ - \ \mu\psi e \quad = \quad r_a, \tag{13}$$

where v_q/v_c is also evaluated at $\overline{x}$. Comparing (12) and (13) indicates that, in addition to the tax of $\tau_q = \mu\psi e$ per square foot of housing floor space, a tax per unit of land equal to $\mu\psi e \equiv \tau_\ell = \tau_q$ is also needed, which reduces land rent by that amount (as in the second bullet point above). With these two taxes subtracted in the equilibrium condition, it then corresponds to the optimality condition.

Note that the housing tax corresponds to a standard property tax (levied, however, as an excise tax instead of an ad-valorem tax), while the land tax matches taxes of this type levied in some cities (in excise not ad-valorem form, however). Observe also that the property tax, if levied in ad-valorem fashion, is equivalent to separate ad-valorem taxes levied at a common rate on land and housing capital (see Brueckner and Kim (2003)). An additional ad-valorem land tax on land would add to the tax burden, with the combined taxes equivalent to a split-rate tax structure that taxes land and capital at different rates (see Oates and Schwab (1997)). While the excise form of the current housing and land taxes disrupts this simplicity, it remains true that the land tax adds to the tax burden on land already present in the housing tax.

Recall that the multiplier μ appearing in the tax terms equals the marginal social damage from emissions. From the first-order condition for G, the multiplier equals

$$\mu \quad = \quad -\int_0^{\overline{x}} 2\pi x \frac{h(S)}{q} \frac{v_G}{v_c} dx \quad > \quad 0. \tag{14}$$

The integral weights the MRS between G and c by population and sums across distance to yield the social damage from an extra unit of G.[9]

It is important to note that, because the planning problem portrays a city where the cost of land is the agricultural opportunity cost and where taxes are absent from the objective function, the corresponding decentralized city must have several features. First, the rental income generated in the city must accrue to its residents. In particular, the city must be "fully closed" in the sense of Pines and Sadka (1986), with differential land rent (the amount in excess of r_a) earned as income by the residents. The residents are thus viewed as owning a corporation that acquires the city's entire land area from its outside owners at a rental price r_a, with the land then rented to the residents themselves in a competitive market. The residents thus share the aggregate rental income net of r_a generated by the city, in effect paying rent to themselves. Second, since tax revenue is absent from the planning problem, the revenue from the energy taxes must be redistributed to the residents on an equal per capita basis. With these two requirements, the differential rent and tax revenue generated in the city stays within it, as envisioned in the planning problem. The ensuing numerical analysis imposes both requirements.

2.3. Equivalence to a carbon tax

The real estate and commuting taxes that have just been derived embody the tax liabilities that would be generated by a carbon tax, making the two approaches equivalent. To see this equivalence, note that under a carbon tax, the fuels producing energy for various uses would be taxed according to the carbon emissions they yield. The tax on gasoline would equal the social damage from emissions μ times the number of kilograms of carbon generated per gallon, denoted ξ_g. The resulting tax payment per mile of commuting would equal this expression times gallons/mile, denoted ω_g, yielding $\mu\xi_g\omega_g$. Since γ, emissions per mile, equals $\xi_g\omega_g$, this tax payment equals our commuting tax per mile, $\mu\gamma$.

Similarly, letting ξ_{hc} denote carbon emissions per unit of fuel used in residential heating and cooling, the tax per unit of fuel is $\mu\xi_{hc}$. The tax per kwh of residential energy use is then $\mu\xi_{hc}\omega_{hc}$, where ω_{hc} is units of fuel per kwh. Letting $\psi = \xi_{hc}\omega_{hc}$, the tax per kwh is then $\mu\psi$. Multiplying by kwh per unit of land $(h(S)e + e)$, the total tax liability per unit of land is then $\mu\psi[h(S)e + e]$, which includes a tax of $\mu\psi e$ per unit of land and a floor-space tax liability of $\mu\psi e$ times floor space $h(S)$ per unit of land.[10] Given the equivalence to a carbon tax, it is appropriate to view our commuting and real estate taxes as energy taxes, even though they are levied differently.

2.4. Predicting the impact of energy taxation

A main goal of the numerical analysis presented in section 3 is to illustrate the impact on the spatial structure of the city from levying optimal energy taxes. In principle, these effects might be predictable in advance through an appropriate comparative-static analysis, relying on Pines and Sadka's (1986) extension of Wheaton's (1974) comparative-static analysis to the present context of a fully closed city.

Unfortunately, however, the required comparative statics cannot be inferred from Pines and Sadka's results. Imposition of the land tax, for example, can be viewed as equivalent to an increase in the agricultural rent r_a, which Pines and Sadka (1986) analyze. However, the present tax change corresponds to an increase in r_a combined with an increase in income equal to the rebated per capita land-tax revenue, whose impact cannot be inferred from the results they present. A similar point applies to the effects of the commuting tax. Moreover, as mentioned above, the tax on housing square footage is similar to a standard property tax, whose effects are analyzed by Brueckner and Kim (2003). While they show that the property tax causes the city to shrink spatially when the elasticity of substitution between housing and c does not exceed unity (as under the Cobb-Douglas preferences imposed below), Brueckner and Kim's model is not fully closed, nor does it incorporate redistribution of tax revenues.

The previous literature thus cannot be used directly to predict the separate effects of the three taxes in the current model, and the need to predict their *combined effects* makes the prediction task even more daunting. Hence, in the next section, we present results from numerical simulations.

3. Simulation Setup

3.1. Preliminaries

To evaluate the effect of imposing the optimal energy taxes, we numerically compare the urban equilibrium without any taxes to the equilibrium where the taxes are imposed, relying on the first-best optimal tax formulas. The approach thus shifts from the orientation of the planner, whose goal was to minimize the city's resource consumption, to analysis of equilibria, knowing that an equilibrium where taxes are imposed according to the optimal formulas is efficient.

We impose specific functional forms in order to simulate the model numerically. Parameters are taken partly from published sources and partly calibrated to replicate key features of American cities. The utility function is assumed to take the following form:

$$v(c, q, G) \equiv Ac^{1-\alpha}q^{\alpha} - \nu G, \tag{15}$$

where $0 < \alpha < 1$, $\nu > 0$ is the marginal damage from composite emissions, and $A = 10^6/[(1-\alpha)^{(1-\alpha)}\alpha^{\alpha}]$. While the first part of (15) corresponds to standard Cobb-Douglas preferences over c and q, total composite emissions G appears in the third linear term. Using data from US metropolitan areas (MSAs), Davis and Ortalo-Magné (2011) show that the expenditure share of housing is remarkably constant across MSAs and over time, which supports the Cobb-Douglas assumption. However, the unitary implied price elasticity does not match the inelastic form of housing demand recently estimated by Albouy, Ehrlich and Liu (2016). Nevertheless, we follow the implications of Davis and Ortalo-Magné (2011), setting α equal to their estimated average expenditure share of housing (0.24). The parameter ν is set to generate a realistic value for μ, the marginal social damage from emissions, as explained further below.

In the consumer budget constraint, income is set equal to the 2011 US value of median household income, equal to $51,324. Commuting costs per mile are made up of monetary and time costs of commuting and are set at $t = \$503.53$ per mile per year (see the Appendix for details). City population is set at $L = 750,000$ households.[11]

As in Bertaud and Brueckner (2005), housing production is assumed to be Cobb-Douglas, which yields the intensive production function $h(S) = \rho S^{\beta}$, where $\beta < 1$. Ahlfeldt and McMillen (2014) use data from several cities to estimate the elasticity of substitution between land and capital and find that it is close to one, which supports the Cobb-Douglas assumption. In the simulation, we set $\rho = 0.00005$ and $\beta = 0.745$. Agricultural land rent r_a is set at \$58,800 per square mile (see the Appendix).

The computation of e is unfamiliar and closely tied to the model, and it proceeds as follows. For a square k-story building with floor space of q, surface area is $A_k = 4kH\sqrt{q/k} + q/k$, where H is the height of one story (the first term is the area of the sides and the second the area of the roof, assumed flat). The Residential Energy Consumption Survey (RECS)[12] provides q values for detached single-family homes of 1, 2, and 3 stories, and assuming $H = 12$ feet, the previous formula can be used to compute $A_k,\ k = 1, 2, 3$. Using the survey data underlying the RECS tables (which show square footages for individual sampled houses), the surface-area value for each house can be computed and the median among them derived. This median surface-area value is $A = 8,458.82$. Next, we use the RECS data to get median energy use for space heating and air conditioning across all detached single-family houses (with different numbers of stories), which equals 42,721 thousand BTUs or 12,520.29 kwh. We associate this median value with the median single-family surface area A, which allows us to divide 12,520.29 kwh by $A = 8,458,82$ to get a value for energy use per square foot of surface area. This value equals $e = 1.4016$ kwh/square foot, and it can then be applied to buildings of all heights.[13]

As mentioned above, the value of ν in the utility function is chosen to generate a realistic value for μ and thus realistic tax rates. For GHG emissions, a consensus value of μ is \$40 per metric ton of CO_2, or \$0.04/kg.[14] By appropriate choice of the units of local emissions, this \$0.04/kg applies to those emissions as well. The GHG components of γ and ψ, the commuting and residential emissions parameters, can be derived from available data, as seen in the Appendix. By applying the \$0.04/kg μ value to these γ and ψ components, the components of the tax rates τ_t, τ_q and τ_ℓ that pertain to GHG emissions follow immediately.

To derive the local emissions components of γ and ψ, we use tax rates that should be applied to correct for local emissions from commuting and residences, which are available in our sources. Each tax rate implicitly combines a social damage parameter and a local emissions value (the local component of either γ or ψ). However, by choice of units for local emissions, the social damage can be set at the same \$0.04/kg value used for GHG emissions. Knowing this μ value and the required tax rates, the local emissions components of γ and ψ can then be inferred (the units of these emissions are thus chosen). Knowing both their GHG and local components, the overall γ or ψ values are then determined, and the commuting and residential taxes follow by applying $\mu = \$0.04$/kg (see the Appendix for details).

This procedure yields $\gamma = 554.375$ kg CO_2 equivalent/mile, and multiplying by $\mu = \$0.04$/kg yields a commuting tax of \$22.18/mile. The procedure also yields $\psi = 0.4283$ kg CO_2 equivalent/kwh, and multiplying by μ and e yields taxes of $\tau_q = \tau_\ell = \$0.04/\text{kg} \times 0.4283$ kg/kwh $\times$ 1.4016 kwh/sq ft= \$0.024/square foot. Finally, the value of ν, the utility function parameter, that generates a μ of \$0.04/kg is $\nu = 0.00176$.

While the commuting tax represents 4.4% (22.175/503.53) of commuting costs t, a comparison to the existing gasoline tax gives a better sense of its magnitude.[15] The τ_t rate \$22.175 mile has been scaled up by the 625 annualizing factor, and dividing by this value gives a tax of \$0.035 for each mile driven. Multiplying by 20 miles/gallon, an estimate of average fuel economy for light vehicles,[16] this value implies a tax of \$0.71 per gallon. By comparison, the average gasoline tax paid in the US is \$0.487/gallon, so that the optimal tax is about 46% larger.[17] Our tax is smaller than Parry and Small's (2005) optimal US gasoline tax, which equals \$1.01/ gallon (lying below European taxes, whose maximum rates are around \$4.00 gallon).[18] Parry and Small's larger tax, however, addresses other externalities (congestion, accidents) in addition to emissions.

Although the exposition of the model assumes for simplicity that all land is used for housing, we assume in the simulations that a fraction 0.75 of each annulus is available for residential use. It should also be noted that the model and its calibration do not reflect existing real estate taxes, which are in effect assumed to be zero. For the property tax, this assumption is appropriate given that the distortionary nature of tax means that it would not be present at the social optimum. In line with the absence of real estate taxes, the value of commuting cost per mile t from above reflects subtraction of the \$0.487/gallon gasoline tax from the monetary component of commuting costs, leading to a net-of-tax value.

Even though our our assumed emissions damage of \$40 per metric ton (\$0.04/kg) seems to be representative of current views,[19] some much larger values can be found in the literature. Moore and Diaz (2015), for example, derive a value of \$220/metric ton, or \$0.22/kg. To explore the effect of such a larger value, we also simulate the first-best outcome with $\mu = \$0.22$.

3.2. Solution procedure

In the standard urban model, consumer maximization determines the housing price p as a function of utility u and the other variables of the model, given by $p(x, y, t, u)$ (see Brueckner (1987)).[20] The function $q(x, y, t, u)$ gives the associated solution for housing consumption, and the developer's profit maximization problem yields analogous functions $S(x, y, t, u)$, $r(x, y, t, u)$, and $D(x, y, t, u)$, where $D = h(S)/q$ is population density.

The arguments of these functions are modified in the current framework. The utility argument is replaced by $u + \nu G$ (see (15)), and commuting cost per mile t is replaced by $t + \tau_t$ to capture the tax on commuting. In addition, letting R denote total differential land rent and T denote total tax revenue, the income y is replaced by $y + (R + T)/L$ to capture redistribution of equal per capita shares of total differential land rent and taxes.[21] Therefore, p is now written as $p(x,\ y + (R + T)/L,\ t + \tau_t,\ u + \nu G)$. In addition, the S, r and D functions now depend on this same new list of arguments along with e and τ_q.[22]

To solve the model, the first step is to set land rent at $\overline{x}$ equal to agricultural rent r_a plus the land tax τ_ℓ, with the condition written as

$$r(\overline{x},\ y + (R + T)/L,\ t + \tau_t,\ u + \nu G,\ e,\ \tau_q) \quad = \quad r_a + \tau_\ell. \tag{16}$$

This condition is used to solve for utility u as a function of the remaining variables (which include $\overline{x}$ and r_a). The u solution is then substituted back into the r, S, and D functions. When this substitution is made, G drops out as a determinant of r, S and D, but all three variables now depend on $\overline{x}$ and $r_a + \tau_\ell$, as captured in the new functions $\widehat{r}$, $\widehat{S}$ and $\widehat{D}$.

Using $\widehat{D}$, the condition analogous to (8) stating that the city fits its population is written

$$\int_0^{\overline{x}} 2\pi x\ \widehat{D}(x,\ y+(R+T)/L,\ t+\tau_t,\ e,\ \tau_q,\ \overline{x},\ r_a+\tau_\ell)dx \quad = \quad L. \tag{17}$$

An additional condition states that differential land rent integrates to R and another condition sets T equal to total tax revenue.[23] A condition defining μ, the social damage from emissions, comes from (14), and G is given by a modified version of (9).[24] The resulting set of five equilibrium conditions determines solutions for the five endogenous variables R, T, $\overline{x}$, μ, and G, with the μ solution then yielding the optimal taxes. Note that while μ is endogenous, the targeted value is \$0.04/kg, which is generated by appropriate choice of ν.[25]

To solve for the equilibrium, we use an iterative procedure. It starts with guesses for initial values of R, T and μ. Given these values, the population condition (17) is solved for $\overline{x}$. With the solution in hand, the integrals in the R, T and μ conditions are computed, using the initial guesses of R, T and μ in evaluating the integrands. The integrals then give updated values of the variables R, T and μ, which are substituted in (17), yielding a new solution for $\overline{x}$. The process continues until convergence is achieved, which occurs after relatively few iterations. The equilibrium value of G is then computed from the modified (9).

4. Simulation Results

4.1. No-tax equilibrium

We first solve for the no-tax equilibrium.[26] The procedure is to set $\tau_t = \tau_q = \tau_\ell = 0$ and then to solve (17) and (18) for $\overline{x}$ and R. Figures 1–5 show the spatial contours of $h(S)$, D, r, p, and q in the no-tax city, represented by the light-blue/gray curves, and Table 2 gives the central (CBD) values of these variables. The solution gives $\overline{x} = 30.33$, which implies an average commuting distance of 14.83 miles, slightly longer than the average commute for workers in MSAs of 1–3 million inhabitants (13.74 miles, from the National Household Travel Survey).[27] Population (dwelling) density falls from 4002.69 dwellings per square mile at the CBD to 24.76 at $\overline{x}$ (average density is 259.53), and building height $h(S)$ falls from 22.50 at the CBD to 0.40 at $\overline{x}$.[28] Land rent r falls from \$13.2 million per square mile to $\$58,880 = r_a$. Units of q are chosen such that the average dwelling size is 2,196.23 square feet, with q rising from 1,501.03 square feet at the CBD to 4,288.49 at the city border $\overline{x}$.[29] Based on the same normalization, the housing price p falls from \$8.65 per square foot at the CBD to \$2.17 at $\overline{x}$. Despite the presence of rent redistribution and the emissions externality, these spatial patterns are familiar from the standard urban model. Total composite emissions G in the city are 5.96×10^9 kg (5.96 million metric tons), and per-capita emissions equal 7946.07 kg. Residential energy use is responsible for 22% of total emissions, with commuting responsible for the balance of 78%.

4.2. The first-best equilibrium

We now turn to the model solution when emissions taxes are levied. As explained above, the optimal taxes are given by $\tau_q^* = \tau_\ell^* = \$0.024$/sq ft and $\tau_t = \$22.18$/mile. On average, the housing tax corresponds to an ad valorem tax of 0.45% on housing rent, the land tax amounts to an ad valorem tax of 0.57%, and the commuting tax to 4.4% of commuting costs, as mentioned above. Note that the average rates of the housing and land taxes are given by τ_q/p and τ_l/r averaged across the city's x values, while the rate of the commuting tax, which is just τ_t/t, is spatially invariant.

Table 2 gives the central values of D, $h(S)$, r, p and q in the taxed city, and Figures 1–5 show the spatial contours of these variables, which are represented by the dark-red/black curves. The figures show that, relative to the no-tax city, the D, $h(S)$, r, p contours rotate clockwise, while the q contour rotates counterclockwise. These figures actually pertain to the $\mu = \$0.22$ case considered below, where the rotation of the contours is more visible than in the $\mu = \$0.04$ case, in which the contours lie closer together but follow the same patterns.

In response to the optimal taxes, the city shrinks spatially, with the urban boundary lying at $\overline{x} = 28.98$. Compared to the no-tax case, the radius of the city thus shrinks by 4.5%, with its overall land area ($\pi\overline{x}^2$) falling by 9.2%. This finding confirms the expectation that energy taxation makes cities more compact by discouraging long commutes, reducing housing consumption, and increasing building heights. In the taxed city, population density at the CBD is 4334.88 dwellings per square mile, 8.3% higher than in the no-tax city, and density falls to 27.51 at $\overline{x}$ (average density is 284.27). Building height $h(S)$ at the CBD is 23.93, 6.3% higher than in the no-tax city, and height falls to 0.43 at $\overline{x}$. Land rent r at the CBD is \$14.4

million per square mile, 8.3% higher than in the no-tax city, and r falls to $r_a = 58,880$ at $\overline{x}$. The housing price p at the CBD is \$8.86 per square foot, 2.4% higher than in the no-tax city, and p falls to \$2.26 at $\overline{x}$. Dwelling size q at the CBD is 1474.11 square feet, 1.8% smaller than the CBD value in the no-tax city, and q rises to 4169.40 at the new $\overline{x}$. Average dwelling size is 2148.86 square feet, 2.2% lower than in the no-tax equilibrium.

Total emissions G in the taxed city are 5.71×10^9 kg and per-capita emissions equal 7624.12 kg, with both values naturally smaller than in the no-tax city. The emissions reduction, at 4.2%, is relatively modest, matching the sizes of the optimal taxes (particularly the commuting tax, which raises commuting cost by 4.4%). Residential energy use is responsible for 23% of total emissions, with commuting responsible for the balance of 77%.

The contour rotations in Figures 1–5 are similar to the effects of an increase in the commuting-cost parameter t in the closed-city version of the standard model. While a higher commuting cost per mile is a consequence of the present model's commuting tax, partly accounting for this similarity of effects, many additional forces are at work in generating them. These forces include responses to the land tax τ_ℓ, which tends to raise the cost of land and thus encourages developers to economize on land in production of housing, tending to raise S and building height $h(S)$. But since the housing tax τ_q (which is analogous to a property tax) is a tax on output of housing floor space, it tends to depress S and $h(S)$, offsetting the effect of the land tax. The housing tax also tends to reduce the dwelling size q as consumers substitute toward nonhousing consumption. The tax's effects on $h(S)$ and q, both being negative, have an ambiguous effect on population density (h/q), as discussed in detail by Brueckner and Kim (2003). These varied tax effects are mediated by the impacts of redistribution of differential land rent and tax revenue, adding to the complex interplay of forces affecting urban form in the taxed city. Interestingly, though, this interplay yields qualitative impacts similar to the effects of increase in commuting cost in the standard model.[30]

To get a sense of magnitudes, the optimal housing and land-tax rates, which are on the order of 0.5%, can be compared to actual US property-tax rates, expressed as a percentage of rent rather than value. Recall that a standard ad-valorem property tax is absent from the model, with the rate set to zero. Letting κ denote the property-tax rate on value and θ denote the discount rate, the property-tax rate expressed as a percentage of rent is given by $\kappa/(\kappa+\theta)$.[31] Assuming $\theta = 0.04$ and using a representative 1.5% property-tax rate,[32] so that $\kappa = 0.015$, this expression reduces to 0.27, indicating that the existing property tax claims about 25% of rent. The average housing and land-tax rates of about 0.5% represent only one-fiftieth of this value. Thus, the revenue raised by environmental real estate taxes would be tiny compared to existing property-tax revenue.

The effects of a much larger target value of μ, equal to \$0.22/kg, are shown in the third column of Table 2 (recall that Figures 1–5 actually illustrate this case). This μ value is generated by increasing ν, the utility function damage parameter, from 0.00176 to 0.00941. As can been from the table, the commuting tax τ_t is now \$121.96/mile (a rate of 24.2%), which corresponds to a large gasoline tax of \$3.90 per gallon. The real estate taxes rise to \$0.13 per square foot, with average ad valorem rates of 2.21% and 2.25% on housing and land, respectively (about one-tenth of existing property-tax rates). In response to these taxes, $\overline{x}$ shrinks to 24.26 miles, a 20% reduction relative to the no-tax case, with the city's overall land area falling by 36%. Emissions per capita fall by 19%. CBD building height rises by 36% relative to the no-tax case, with central population density rising by 49%. Land rent at the CBD rises by 51% and the housing price rises by 13%, while the central dwelling size falls by 9%. All these effects are much larger than those generated by the smaller value of μ, showing that the first-best optimal taxes yield dramatic changes in urban structure when the social damage from emissions lies at the upper end of the range of recognized values.

The benefit from imposing the optimal taxes can be gauged by computing the compensating variation (CV) associated with the change. It equals the reduction in income needed to restore the no-tax utility level when all the endogenous variables are held at the levels prevailing in the first-best city. For the larger μ value, the CV is equal to 0.35% of income or \$177.81, a modest number similar to that associated with other corrective policies in monocentric cities. Brueckner (2007), for example, found a gain of 0.7% of income from imposition of congestion pricing. The CV associated with the smaller μ value, however, is much lower, at 0.02% of income or \$10.48. Thus, the gain from corrective taxation is quite small when emissions damages are moderate in size.

4.3. Second-best optima

The equilibrium in a city with optimal emissions taxes can be found in a different, equivalent manner to the one use above. Under this alternate approach, the taxes are treated as parameters, with the equilibrium system solved for $\overline{x}$, R, T conditional on τ_t, τ_q and τ_ℓ. Then, the value of u conditional on the taxes is determined by (16). The optimal values of the taxes (the ones that maximize u) can then be determined by a search procedure. Note that this procedure makes no use of the first-best optimal tax formulas, and thus does not require computation of a value for μ, the marginal social damage from emissions.

This approach gives the same numerical answers as the original approach and thus need not be used in finding the first-best equilibrium. But use of the approach is necessary in investigating the properties of second-best optima, which are utility-maximizing equilibria with one or two of the three taxes constrained to equal zero.[33] With some taxes set at zero, the utility-maximizing value(s) of the remaining tax(es) can be found using a search procedure.[34] The value of the utility function parameter ν remains at the original value of 0.00176, which was consistent with a μ value of \$0.04/kg in the first-best case.

First, we constrain the commuting tax to be zero. The resulting second-best optimal housing and land taxes are notably higher than in the first-best case, while no longer being equal. The second-best optimal housing and land taxes are $\tau_q = 0.085$/sq ft and $\tau_\ell = 0.053$/sq ft, values that are about triple and double, respectively, the first-best values. The housing tax now amounts to 1.6% of housing rents and the land tax to 1.3% of land rents, on average, still well below existing property-tax rates. The second-best city's $\overline{x}$ value, equal to 28.91, is about 0.3% smaller than the first-best value of 28.98. When commuting is not taxed, setting the housing and land tax at their first-best levels would lead to a city that is too spread out, since commuting costs are below social costs. Hence, both the housing tax and land tax must be raised, making the city more compact, even more so than the first best city, although the difference is small. Interestingly, this second-best city has a density contour that lies between the relatively flat one of the no-tax city and the steep contour of the first-best city. The same observation applies to the building-height contour, while the p contour rotates counterclockwise relative to the first best contour, showing the reduced value of access to the CBD in the absence of the commuting tax (the q contour rotates clockwise). Table 2 gives the central values D, $h(S)$, q, p and r in the second-best city along with emissions per capita.

When the housing tax is set to zero, the second-best optimal land and commuting taxes are both somewhat higher than the first-best values, given by $\tau_\ell = 0.027$/sq ft and $\tau_t = 23.73$/mile (the average rates are 0.65% and 4.7%). These taxes lead to a spatial city structure similar to that of the first-best city. The boundary distance $\overline{x}$ is 28.97, only slightly smaller than the first-best value. The absence of a housing tax leads to larger dwellings (and a lower p) at all distances relative to the first-best city, tending to increase the city's spatial area, but this effect is partly countered by the higher taxes on land and commuting. The increased land tax in particular leads to taller buildings at all distances, so that the pattern of population density is very similar to that in the first-best city. Table 2 again provides central data for this second-best city.

Next, we set the land tax to zero. The optimal second-best housing and commuting taxes are higher than their first-best values, given by $\tau_q = 0.032$/sq ft and $\tau_t = 23.90$/mile, with average tax rates of 0.61% and 4.7%. In this case, the urban boundary is $\overline{x} = 29.30$, 1% above the first-best level. The absence of the land tax thus causes the city to expand beyond the efficient size. The increases in the housing and commuting taxes partially compensate for the absent land tax. But dwellings are larger at all distances than in the first-best city (p is lower), and buildings are shorter everywhere. As a result, population density is lower at all distances out to the first-best boundary, accounting for the larger $\overline{x}$. See Table 2 for further information.

Finally, we set both housing and land taxes at zero, so that the commuting tax is the only second-best tax. Its optimal value is then $\tau_t = 26.49$/mile or 5.3% of average commuting costs, with the tax increasing by $4.31/mile relative to the first best. The urban boundary is $\overline{x} = 29.39$, which is 1.4% above the first-best level. As in the previous exercise, the absence of taxes on housing and land causes dwellings to be too large and buildings to be too short. While the commuting tax increases to counteract this tendency, the city remaings larger than optimal and population density is inefficiently low in the center. See Table 2 for more information. As would be expected, the compensating variations associated with all of these second-best tax schemes are smaller than the first-best value (the values are well below 1% of income).

If policy makers were to consider use of existing urban taxes to counteract a city's emissions, it would be natural for them to focus on the gasoline tax, not heeding this paper's prescription for taxes on land and housing. Dividing τ_t from the last exercise by the annualizing factor of 625 yields a cost per mile driven of \$0.042, and multiplying by 20 miles/gallon yields a corresponding gasoline tax of \$0.84/gallon, \$0.13 higher than the first best tax of \$0.71/gallon. Therefore, as a result of opting not to levy housing and land taxes, policy makers would have to raise the gasoline tax 13 cents above the first-best level.

4.4. Sensitivity analysis

This subsection provides sensitivity analyses. One by one, we vary some of the more interesting parameters, increasing each of the parameters by 50% of the benchmark value. The results of these exercises are shown in Table 3. Note that since ν is held fixed at the original value, the given parameter changes will cause the emissions damage μ to diverge from its previous target value. For parameter changes that do not involve other elements of the optimal tax formulas, the tax changes (which allow occur in the same proportion) reflect the change in μ.

First, we increase income by 50% from the benchmark value of \$51,324, to \$76,986. This value corresponds to the household income in very rich metro areas such as San Francisco or Boston. In the standard urban model, such an increase leads to higher average housing consumption, longer commutes, and urban sprawl. Obviously, these effects increase emissions. In the first-best city, the income increase leads to a 41% increase in $\overline{x}$ and a 53% increase in emissions per capita relative to the benchmark first-best city. Interestingly, the optimal taxes each fall by about 2%, reflecting the same decrease in μ.

Next, we increase population from $L = 750,000$ to 1,125,000. Comparing first-best cities, the population increase leads to a 4% increase in $\overline{x}$. Emissions increase by 44% while emissions per capita decrease by 4%, matching a pattern observed by Larson and Yezer (2015).[35] Each of the taxes increases by 54%, reflecting a large increase in μ.

A further exercise is to increase annual commuting cost t from \$503.53 to \$755.30 per mile. Comparing first-best cities, the commuting-cost increase leads to a 26% decrease in $\overline{x}$ and a 29% decrease in emissions per capita, with both changes partly reflecting the higher private cost of commuting. Each tax increases by 5%.

Finally, we vary the energy efficiency of buildings, e, and the emissions intensity γ of commuting. Comparing first-best cities, an increase in e (which could also be caused by a change in the local climate) reduces $\overline{x}$ by 1% and raises emissions per capita by 11%. In response to the higher e, τ_q and τ_ℓ rise by 50%, while τ_t rises by far less than 1%, indicating a small change in μ.[36] Again comparing first-best cities, an increase in γ reduces $\overline{x}$ by 1% and increases emissions per capita by 36%. The commuting tax rises by 50%, while the housing and land taxes rise are almost unchanged.

5. Conclusion

This paper has presented the first investigation of the effects of optimal energy taxation in an urban spatial setting, using a model that incorporates emissions economies from tall buildings. The first-best optimal tax structure has taxes on housing, land and commuting, which match the tax liabilities that would be generated by a carbon tax. Since emissions come from housing consumption and commuting, optimal taxation reduces the levels of both activities, generating a more-compact city with a lower level of emissions per capita. In response to optimal taxation, the spatial area of the city shrinks by 9.2%, with its central population density rising by 8.3%. Emissions per capita fall by 4.1%, a relatively modest reduction that matches the sizes of the optimal taxes, particularly the commuting tax (which raises commuting costs by 4.4%). While these impacts are based on a representative value of the social damage from emissions, much more dramatic effects on urban structure emerge when the optimal taxes are based on a higher damage value lying at the upper end of the recognized range.

Use of three separate taxes rather than a carbon tax allows the paper to carry out second-best exercises, with the most instructive setting the housing and land taxes at zero, so that the commuting tax must do all the work in limiting emissions from both residences and commute trips. In this case, the second-best optimal commuting tax would correspond to a gasoline tax of \$0.84 per gallon, equal to 175% of the current US average tax and \$0.13/gallon above the first-best optimal tax of \$0.71/gallon.

Future research could add detail to the model, especially on the commuting side, following the lead of Larson et al. (2012). Their model includes traffic congestion that in turn affects travel speed, along with a realistic relationship between speed and emissions. Under this relationship, a simple tax per mile of commuting would no longer be optimal, introducing complications that would be compounded by the computational burden of handling congestion. Another extension would explore more general forms for consumer preferences, replacing the convenient Cobb-Douglas form with realistically calibrated CES preferences. Such a change, however, is unlikely to significantly alter the main lessons of the paper. Finally, following Larson and Yezer (2014), the emissions generated by nonhousing consumption could be added to the model.

Appendix

A1. Planning-problem derivations

The Lagrangean expression for the planning problem is generated by subtracting the RHS expressions in (8) and (9) from the left-hand sides, multiplying the resulting expressions by the multipliers λ and μ, and adding (7). The first-order conditions for S, q, G and $\overline{x}$ are

$$S: \quad i + \frac{h'(S)}{q}[c(q,G)+tx] + h'(S)e + \lambda\frac{h'(S)}{q} - \mu\psi h'(S)e - \mu\gamma\frac{h'(S)}{q}x = 0 \qquad (a1)$$

$$q: \quad -\frac{h(S)}{q^2}[c(q,G)+tx] - \frac{h(S)}{q}\frac{v_q}{v_c} - \lambda\frac{h(S)}{q^2} + \mu\gamma\frac{h(S)}{q^2}x = 0 \qquad (a2)$$

$$G: \quad -\int_0^{\overline{x}} 2\pi x\frac{h(S)}{q}\frac{v_G}{v_c}dx + \mu = 0 \qquad (a3)$$

$$\overline{x}: \quad i\overline{S} + \frac{h(\overline{S})}{\overline{q}}[c(\overline{q},G)+t\overline{x}] + h(\overline{S})e + e + r_a + \lambda\frac{h(\overline{S})}{\overline{q}} - \mu\psi[h(\overline{S})e+e] - \mu\gamma\frac{h(\overline{S})}{\overline{q}}\overline{x} = 0. \qquad (a4)$$

Rearranging $(a2)$ yields (10), and $(a3)$ is the same as (16). Solving $(a2)$ for λ and substituting in $(a1)$ yields (11) after rearrangement, and substituting in $(a4)$ yields (13) after rearrangement.

A2. Data sources and calibration calculations

Income y is set at the 2011 value of median household income in the US, which is \$51,324 (the source is American Community Survey of the US Census Bureau).[37] To compute commuting cost per mile, t, we follow Bertaud and Brueckner (2005). We use the median hourly wage of \$17.09 (from Bureau of Labor Statistics)[38] and value it at 50% (Small (2012)) to get an hourly time cost of commuting \$8.545. Assuming that rush hour traffic moves at 30 miles per hour, the implied time cost of commuting is \$0.28/mile. As for the money cost of commuting, the current Federal allowance is \$0.55/mile, which includes an average gasoline tax of \$0.025/mile (\$0.487/gallon divided by the average light-vehicle fuel economy of 20 miles per gallon). Subtracting this amount yields a net-of-tax money cost of \$0.525/mile and an overall commuting cost per mile of \$0.805. Multiplying by 1.25 workers/household, by 250 work days/year and again by 2 to convert to a round-trip basis, annual commuting cost per mile is \$503.125/year.

The computation of agricultural rent r_a again follows Bertaud and Brueckner (2005). We take the average value of farm real estate per acre in 2011, \$2300 (the source is United States Department of Agriculture (2015), Land Values: 2015 Summary, `http://www.usda.gov/nass/PUBS/TODAYRPT/land0815.pdf`). To convert this number to annual rent, we use a discount rate of 4% to get a rent per acre of $\$2,300/0.04 = \$92$, yielding a land rent per square mile of $r_a = \$58,880$.

To derive GHG and local emissions from commuting, we use data from the National Research Council (2010), along with a standard estimate of GHG damage equal to \$40/metric ton CO_2, or \$0.04 per kg CO_2. NRC (2010), Table 3-5 (p. 180), gives 0.552 kg CO_2/mile as GHG emissions from gasoline, and valuing these emissions at \$0.04/kg gives GHG damage per mile of \$0.02208. If GHG damage were the only damage, this number (converted to an annual basis) would correspond to τ_t. Local damage exists as well, however, and NRC estimates this damage as \$0.0134/mile. Local damage can be viewed as the product of local commuting emissions per mile, γ_l, and social damage per unit of local automobile emissions, μ_l^{com}, which must satisfy $\mu_l^{com}\gamma_l = \$0.0134$/mile. However, by choice of units of local pollution, we can set μ_l^{com} equal to \$0.040/kg, the same damage as per unit of GHG emissions, and then use the previous equation to determine γ_l, which equals $0.0134/0.04 = 0.335$ kg/mile. Therefore, composite emissions from commuting consist of 0.552 kg CO_2/mile of GHG emissions and 0.335 kg/mile of local emissions, for a total of 0.887 kg/mile, with both valued at \$0.04/kg. Converting the 0.887 value to an annualized per mile value by multiplying by 625 $(2 \times 500 \times 1.25)$ yields $\gamma = 554.375$/mile, and using $\mu = \$0.04$, the annual first-best commuting tax is $\tau_t = \$0.04 \times 554.375 = \$22.175$/mile.

Turning to residential emissions, we use the Residential Energy Consumption Survey to apportion total BTUs of household energy use for space heating and air conditioning (converted to kwh) across five sources: electricity, natural gas, propane/LPG, and fuel oil and diesel/kerosene.[39] Then, from Carbon Trust,[40] we get CO_2 generation per kwh of energy for the five sources: 0.5246 kg CO2e/kwh for electricity, 0.1836 for natural gas, 0.2147 for LPG, 0.2674 for fuel oil, 0.2517 for diesel/kerosene. Multiplying by kwh for each source and summing gives total residential CO_2 generation, and dividing by total residential kwh gives CO_2 generation per kwh of residential energy use. This quantity is 0.1997 kg CO_2/kwh, which equals the ψ value for GHG emissions. Again valuing these emissions at $\mu = \$0.04$/kg (\$40/metric ton), and multiplying by $e = 1.4016$ kwh/sq ft would give the floor space and land taxes for GHG emissions: $\tau_q = \tau_\ell = \mu\psi e = \$0.04/\text{kg} \times 0.1997\ \text{kg/kwh} \times 1.4016\ \text{kwh/sq ft} = \$0.011$/square foot.

However, the local emissions component of composite residential emissions remains to be considered. NRC (p. 235) gives \$0.016/kwh as the local emissions damage from electricity generation, while the spreadsheet from Parry et al. (2014)[41] gives local damage from the natural gas used in heating as \$0.322/GJ or \$0.00116/kwh. We weigh these values by the adjusted electricity and natural gas proportions in heating and cooling from the RECS (ignoring the other energy sources), which equal 53.79% and 46.21% respectively. The resulting local residential emissions damage is then \$0.00914/kwh. As in the case of commuting, this damage is the product of a local ψ, denoted ψ_l, and a social damage per unit of local residential emissions, μ_l^{res}, whose product must satisfy $\mu_l^{res}\psi_l = \$0.00914$. As before, we can choose the units of local residential emissions so that the social damage μ_l^{res} per unit is the same \$0.04/kg value as for GHG emissions. The implied value of ψ_l is then given by $\psi_l = 0.00914/0.04 = 0.2285$ kg/kwh. Adding this value to the ψ value of 0.1997 for GHG emissions gives an overall ψ equal $0.2285 + 0.1997 = 0.4283$ kg CO_2/kwh. The overall first-best residential taxes are then $\tau_q = \tau_\ell = \mu\psi e = \$0.04 \times 0.4283\ \text{kg/kwh} \times 1.4016\ \text{kwh/sq ft} = \$0.024$/sq ft.

Table 1: 2013 Emissions by Sector (millions of metric tons CO_2 equivalent)

Electricity-generation emissions are distributed to final user

implied sector	*volume*	*percentage*
Industry	1922.6	30.0%
Transportation	1810.3	27.1%
Residential	1129.1	16.9%
Commercial	1126.7	16.9%
Agriculture	646.4	9.7%
Total	6673.0	100%

Columns do not sum since emissions from US Territories are excluded. Source is Environmental Protection Agency (2015, Table ES-7)

Table 2: City Characteristics

	No-tax	*First best* $\mu = \$0.04$	*First best* $\mu = \$0.22$	*Second best* $\tau_t = 0$	*Second best* $\tau_q = 0$	*Second best* $\tau_\ell = 0$	*Second best* $\tau_\ell = \tau_q = 0$
city border $\overline{x}$	30.33	28.98	24.26	28.91	28.97	29.30	29.39
emissions per capita	7946.07	7624.12	6464.71	7758.22	7628.25	7623.52	7637.15
central bldg. height $h(S)$	22.50	23.93	30.63	22.57	23.95	23.87	24.06
central density D	4002.69	4334.88	5980.41	4046.43	4331.31	4321.78	4355.57
central land rent r	13.3 m	14.4 m	20.0 m	13.3 m	14.4 m	14.4 m	14.5 m
central housing price p	8.65	8.86	9.75	8.75	8.84	8.86	8.85
central dwelling size q	1501.03	1474.11	1368.02	1489.47	1476.87	1474.98	1475.38
commuting tax τ_t	0	22.18 (4.4%)	121.96 (24.2%)	0 (4.7%)	23.73 (4.7%)	23.90 (5.3%)	26.49
housing tax τ_q	0	0.024 (0.45%)	0.13 (2.21%)	0.085 (1.58%)	0	0.032 (0.61%)	0
land tax τ_ℓ	0	0.024 (0.57%)	0.13 (2.25%)	0.053 (1.30%)	0.027 (0.65%)	0	0

Table 3: Sensitivity Analysis

(*percentage change in first-best value relative to benchmark first-best value*)

	y rises to \$76,986	L rises to 1,250,000	t rises to \$782.65/mile	e rises by 50%	γ rises by 50%
city border $\overline{x}$	+41%	+4%	−26%	−1%	−1%
emissions per capita	+53%	−4%	−29%	+11%	+36%
commuting tax τ_t	−2%	+54%	+5%	0%	+50%
housing tax τ_q	−2%	+54%	+5%	+50%	0%
land tax τ_ℓ	−2%	+54%	+5%	+50%	0%

Figures

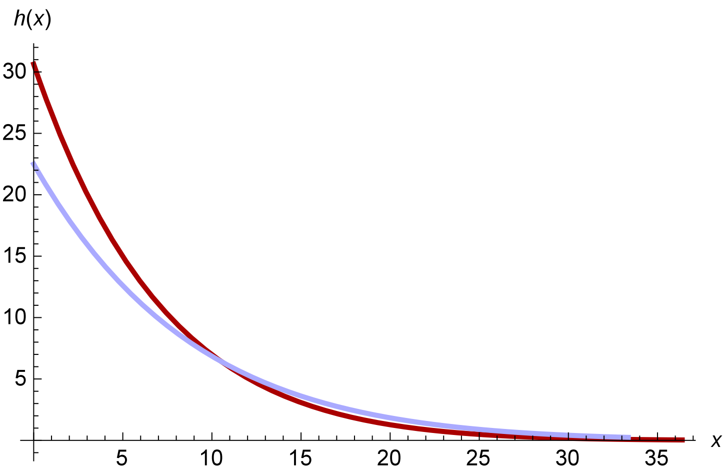

Figure 1: Building height in the first best (dark red/black) and no-tax city (light blue/gray)

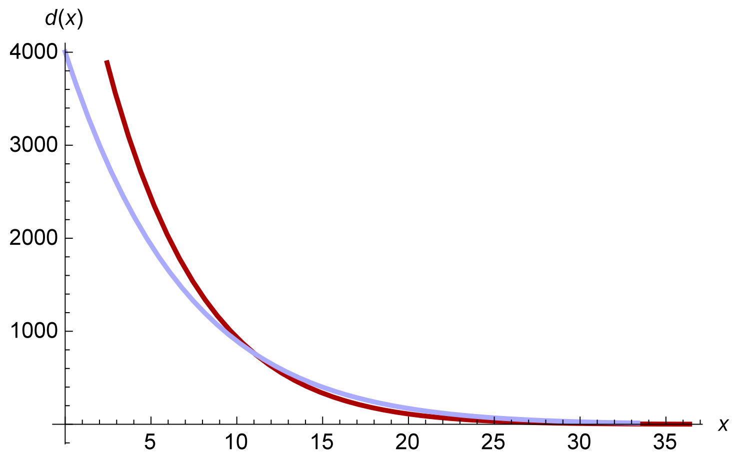

Figure 2: Population density in the first best (dark red/black) and no-tax city (light blue/gray)

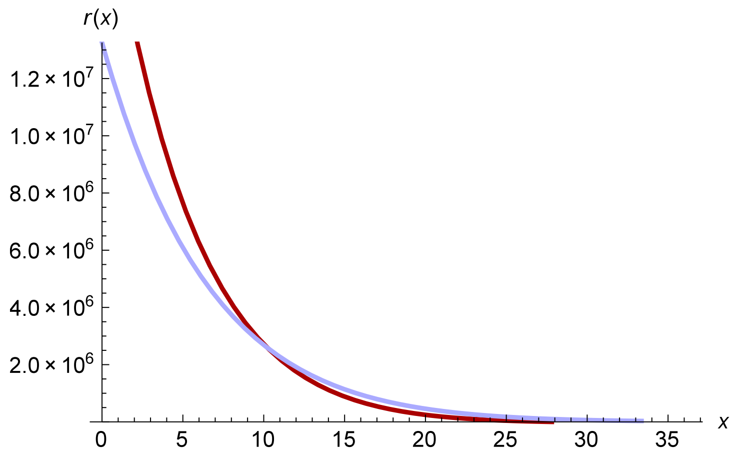

Figure 3: Land rent in the first best (dark red/black) and no-tax city (light blue/gray)

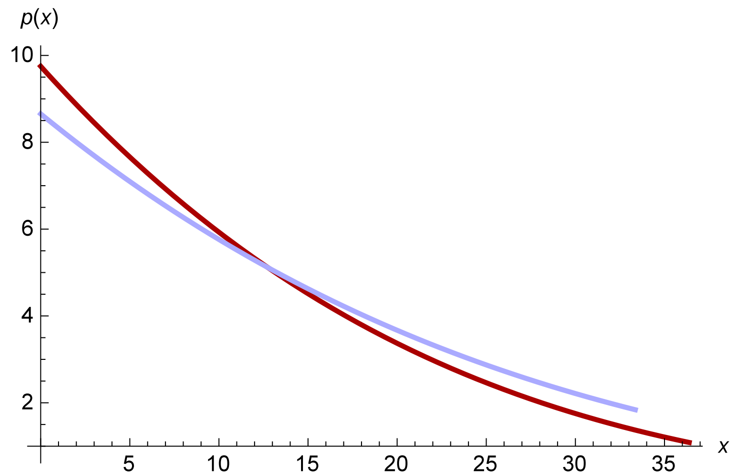

Figure 4: Housing price in the first best (dark red/black) and no-tax city (light blue/gray)

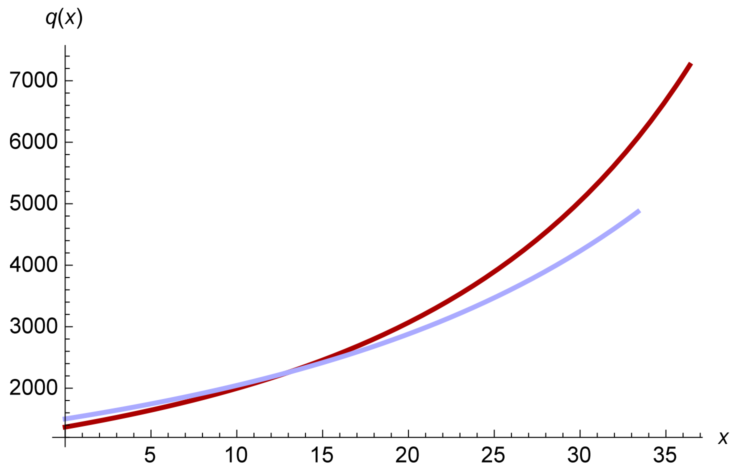

Figure 5: Dwelling size in the first best (dark red/black) and no-tax city (light blue/gray)

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Footnotes

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[1]In similar fashion, Fullerton and West (2002) show that, in treating automobile emissions, a carbon tax can be replaced by taxes with other features that acheive the same outcome (i.e., a gas tax that depends on fuel type, engine size, and installed pollution control equipment, or a vehicle tax that depends on mileage).

[2]See Borck and Pflüger (2015) for a multi-city analysis with global emissions, as well as Gaigné, Riou and Thisse (2012).

[3]For additional analysis where adjustment of building heights serves to amerliorate an externality, see Joshi and Kono (2009). With unpriced traffic congestion, population in a monocentric city is insufficiently concentrated, and this paper shows that a second-best remedy is building-height regulations that impose a minimum near the center and a maximum in the suburbs.

[4]Among buildings with a given footprint area, square buildings have the smallest surface area (see below).

[5]Taken literally, the model implies that developers should construct buildings with the biggest possible footprint, limited only by the city's street grid.

[6]The term $4/\sqrt{\ell}$ is absorbed by the multiplicative factor that is part of the chosen h function in the numerical model, so its value can be set arbitrarily. For the same reason, the capital price i (see below) is normalized to 1 without loss of generality.

[7]Energy use from appliances (and lighting) may, of course, show a modest increase with dwelling size (from larger refridgerators and hot-water heaters or additional televisions), but omission of this effect is acceptable as an approximation.

[8]See Fujita (1989) for another use of this approach.

[9]The dual version of the planning problem starts by deriving income-compensated demand functions for c and q conditional on G, denoted by $c(p, G, u)$ and $q(p, G, u)$. In (7)–(9), the first function is substituted in place of $c(q, G)$ and the second is substituted in place of q. Then, (7) is set equal to I, which gives the economy's total endowment of c. Finally, u is maximized subject to the three modified constraints, with p, G, and $\overline{x}$ treated as choice variables along with u. The optimality conditions in (10), (11) and (13) again emerge. See Pines and Sadka (1986) for another use of this approach.

[10]While a carbon tax would normally not cover local pollution damage, the taxes computed below do so. As result, equivalence of the two approaches would require broadening of the carbon tax to include damages from local pollutants.

[11]With an average household size of 2.6, the city would then have 1.95 million inhabitants.

[12]The survey can be found at `http://www.eia.gov/consumption/residential/`.

[13]By ignoring the possible irregular shapes of single-family houses, this calculation may lead to a biased value of e, but the result is acceptable as an approximation.

[14]See Interagency Working Group on Social Cost of Carbon, United States Government (2015) (`https://www.whitehouse.gov/sites/default/files/omb/inforeg/scc-tsd-final-july-2015.pdf`).

[15]Comparison of the residential taxes to existing property taxes is carried out below.

[16]US Department of Transportation data at the following link show miles per gallon for the US fleet of cars and light trucks of 23 and 17, respectively. With light trucks constituting about 40% of the overall light vehicle fleet (White (2004)), average miles per gallon is around 20. (`http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/national_transportation_statistics/html/table_04_23.html`)

[17]See the following webpage from the American Petroleum Institute: `http://www.api.org/oil-and-natural-gas-overview/industry-economics/fuel-taxes/gasoline-tax`.

[18]See the following webpage from US Department of Energy: `http://www.afdc.energy.gov/data/10327`.

[19]Nordhaus (2014), for example, reports estimates using different assumptions that range between \$21 and \$104 per metric ton.

[20]Under the Cobb-Douglas preferences in (15) (with $\nu = 0$), $p(x, y, t, u) \equiv B(y - tx)^{1/\alpha}u^{-1/\alpha}$, where B is a constant.

[21]In reality, tax revenues might be used to subsidize energy-efficient public transit or building modifications designed to reduce energy use. Analysis of these options would require a more detailed model.

[22]The dependencies of S can be seen in (11), where $\mu\psi e = \tau_q$ and the MRS expression is replaced by the modified p function. The S that satisfies the equation then depends on the arguments of p and on e and τ_q (D inherents these dependencies). The r dependencies can be seen from the LHS of (13). Land rent r is given by the LHS expression in (13) with p in place of the MRS and the bars removed, so that r depends on the arguments of p along with e and τ_q.

[23]The R condition is written as

$$R \;=\; \int_0^{\overline{x}} 2\pi x\; [\widehat{r}(\cdot) - r_a]dx,$$

where the arguments of $\widehat{r}$ are suppressed (note that R appears on both sides of this condition). The condition giving total tax revenue is

$$T \;=\; \tau_t \int_0^{\overline{x}} 2\pi x \widehat{D}(\cdot)x dx \;+\; \tau_q \int_0^{\overline{x}} 2\pi x h(\widehat{S}(\cdot))dx \;+\; \tau_\ell \int_0^{\overline{x}} 2\pi x dx,$$

where the arguments of $\widehat{S}$ and $\widehat{D}$ are suppressed. Note that, since T appears in these arguments, it is present on both sides of this condition.

[24]The μ condition is

$$\mu \;=\; -\int_0^{\overline{x}} 2\pi x \widehat{D}(\cdot)\widehat{MRS}(\cdot)dx,$$

where $\widehat{MRS}(\cdot)$ is the function corresponding to $v_G/v_c = -\nu/v_c$, which has the same list of arguments as $\widehat{D}$. In deriving the G condition, S in the first term of (9) is replaced by $\widehat{S}(\cdot)$ and h/q is replaced by $\widehat{D}(\cdot)$. Since G does not appear in the arguments of $\widehat{S}$ and $\widehat{D}$, the modified (9) thus gives G in terms of the other endogenous variables, whose values are determined by the previous conditions.

[25]It should be noted that endogeneity of the taxes would be eliminated if the $\widehat{MRS}$ expression in footnote 24 (and in the original equation (14)) were a constant. This case emerges, for example, if preferences over c and q in (15) take the Leontief form, making v_c a constant, denoted ϕ. With v_G equal to the constant ν, the MRS is then μ/ϕ and footnote 24 gives $\mu = L\nu/\phi$, yielding exogenous taxes via the tax formulas.

[26]It could be argued that ν should be chosen to yield the target value of μ in the no-tax equilibrium rather than in the first best, given that this equilibrium matches the current real-world one. However, under the chosen ν, the no-tax equilibrium generates a μ almost identical to the target value of \$0.04/kg, making this choice moot.

[27]See `http://nhts.ornl.gov/`.

[28]This population density is similar to that of Buffalo-Niagara Falls, NY, or Dallas-Fort Worth-Arlington, TX, according to the 2010 Census [`www.census.gov`]. In all MSAs with population between 1.5 and 2.5 million, the average population density is 540 people, or 208 households, per square mile.

[29]We solve the model, and then rescale the resulting q values by multiplying by a factor ξ that makes the average value in the city equal to 2,196 square feet. This average value is given by $1/N$ times the integral of q, weighted by population density, over x. Then, the p solution at each x is divided by ξ, as is the floor space tax. This procedure follows Bertaud and Brueckner (2005).

[30]It is interesting to ask whether non-tax interventions could guide the city toward a first-best outcome. One such intervention is suggested by Joshi and Kono's (2009) demonstration that a combination of minimum and maximum height restrictions for buildings can be used to address land-use distortions generated by traffic congestion. Following their logic and referring to Figure 4, imposing appropriate minimum height limits (which follow the dark first-best curve) in the central part of the city and imposing maximum height limits in the outer part of the city could generate the optimal building-height pattern. However, since dwelling sizes would remain uncontrolled, these limits would not generate a first-best outcome.

[31]To derive this expression, note that property value P is determined by the relationship $P = (p - \kappa P)/\theta$, with P equaling the discounted value of the flow of rent minus taxes. Solving yields $P = p/(\kappa + \theta)$, so that the tax liability as a percentage of rent is given by $[\kappa p/(\kappa + \theta)]/p = \kappa/(\kappa + \theta)$.

[32]See, for example, Song and Zenou (2006).

[33]For a similar exercise in the context of automobile pollution, see Fullerton and West (2010).

[34]In another second-best exercise, Borck (2016) studies building-height limits as a different tool for combating global warming. The intuition is that, by tightening housing supply, lower building heights may depress housing consumption, thus reducing emissions. However, the

population-density contour in a city with building-height limits is too flat, compared to a city with first-best taxation.

[35]Their result emerges when the population increase is caused by an exogenous increase in amenities in an open-city context.

[36]This analysis also applies to the effects of a change in ψ, emissions per unit of residential energy usage.

[37]The source is available at https://www.census.gov/prod/2013pubs/acsbr12-02.pdf.

[38]See http://www.bls.gov/oes/current/oes_nat.htm.

[39]While the raw data are used for this computation, the average figures are shown in line 1 of Table CE4.1.

[40]See Carbon Trust, Conversion factors: Energy and carbon conversions, 2011 update (http://www.carbontrust.com/media/18223/ctl153_conversion_factors.pdf).

[41]The spreadsheet can be found at http://www.imf.org/external/np/fad/environ/data/data.xlsx.