BROOKINGS-WHARTON

papers on URBAN AFFAIRS

2008

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BROOKINGS INSTITUTION PRESS
Washington, D.C.

THE BROOKINGS INSTITUTION
1775 Massachusetts Avenue, N.W., Washington, DC 20036

ISSN 1528-7084
ISBN 978-0-8157-1357-9

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Purpose The *Brookings-Wharton Papers on Urban Affairs* is an annual publication containing articles and formal discussant remarks from a conference held at the Brookings Institution and arranged by the editors. The annual forum and journal are the products of a collaboration between the Brookings Institution's Metropolitan Policy Program and the Zell Lurie Real Estate Center at the Wharton School of the University of Pennsylvania. All of the papers and discussant remarks represent the views of the authors and not necessarily the views of the staff members, officers, or trustees of the Brookings Institution or the Wharton School of the University of Pennsylvania.

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Toward a Comprehensive Assessment of Road Pricing Accounting for Land Use

CONGESTION ON U.S. HIGHWAYS is a well-known social and economic problem that becomes progressively worse every year.[1] Travel delays impose large costs, currently approaching some $40 billion annually, on motorists, truckers, and shippers.[2] Economists have repeatedly attributed the problem to policymakers' failure to implement marginal cost congestion tolls to charge road users efficiently for their contribution to delays.

By undercharging vehicles for using the nation's roadways, policymakers have also reduced the per-mile cost of commuting (including out-of-pocket and travel time costs) for most motorists and distorted the development of metropolitan areas by inducing households to live in more distant, lower-density locations, thereby contributing to urban sprawl. Precise definitions of sprawl and estimates of its costs are elusive, because it is difficult to characterize an optimal pattern of land use.[3] At the same time, it is likely that households' decisions regarding residential location—while maximizing households' utility—have resulted in socially inefficient outcomes because they reduce economies of agglomeration.

For instance, according to the U.S. census, between 1970 and 2000 the metropolitan population in the United States grew approximately 60 percent. We

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We are grateful to participants in the 2007 Brookings-Wharton Conference on Urban Affairs and to Jan Brueckner, Steven Morrison, Kenneth Small, Tara Watson, and especially Don Pickrell for helpful comments.

[1] We are reminded of this fact by media summaries of the Texas Transportation Institute's latest *Urban Mobility Report* (http://mobility.tamu.edu/ums/).

[2] Winston and Langer (2006).

[3] As a working definition, Nechyba and Walsh (2004) defines sprawl as a tendency toward lower city densities as city footprints expand. Optimal land use requires efficient pricing of rural land and city services. Determining efficient prices for both is difficult.

therefore would expect in a given city that a representative central city neighborhood that housed 10,000 residents in 1970 would house an additional 6,000 people in 2000. These people would live in new and converted housing, pay taxes, and consume city services. Neighborhood schools might add a new wing for more classrooms, police and fire departments might hire additional employees, and so forth. But, in fact, such expectations have not been realized. According to the U.S. census, central city *density* declined roughly 35 percent between 1970 and 2000—that is, 3,500 people moved *out* of the neighborhood. In effect, 9,500 people (6,000 plus 3,500), nearly the entire original population of the neighborhood, chose to live in newly constructed homes farther from the urban center on land that may not have been part of the metropolitan area in 1970.

Of course, those residents were able to buy more house per dollar in the suburbs, but they also incur the costs of longer commutes and other trips that sharply increase per capita vehicle miles traveled within the metropolitan area. In addition, they live in lower-density residential areas where each household requires more feet of utility lines, more miles of school bus routes, and longer police and fire department response times than are required in dense neighborhoods closer to the urban center. Meanwhile, the schools and fire and police departments in more centrally located neighborhoods might now have excess capacity because the population has decreased. If the communities close to and the communities far from the urban center are located in different municipalities, as is almost always the case in U.S. metropolitan areas, then extra resources are not likely to be reallocated.

In sum, although residents' location choices reflect their self-interest, the city's economy would be more efficient if current residents remained and new residents relocated to higher-density urban communities or subcenters instead of to lower-density suburbs. The divergence between residents' choices and land use efficiency can be explained by public investments in limited access highways *and* the undercharging of highway travel during congested periods.[4] In addition, zoning laws and other land use controls also may induce households to make choices that conflict with the public interest.

It is well-known that congestion pricing can reduce travel delays and smooth the flow of highway traffic throughout the day, but its effect on land use has received little empirical attention. This paper presents rough estimates of the costs and benefits of congestion pricing, accounting for its effects on land use that could help reduce inefficient urban sprawl. Quantifying the full effects of road pricing is important because policymakers are giving it unprecedented con-

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[4] Baum-Snow (2007).

sideration as a way to reduce congestion and provide stable, long-term financing for the nation's highways without unduly affecting households' welfare.[5]

Because we expected road pricing's effects on road users' travel time and out-of-pocket expenses to be capitalized in property values, we developed a hedonic model of housing prices that includes travel delays and unpriced congestion (that is, the benefits of not implementing road pricing) as influences. Housing prices also are influenced by elements of land use, such as citywide density and entropy (that is, the spatial variation in density), which also are treated as simultaneously determined by travel delays, unpriced congestion, and housing prices. Finally, travel delays and unpriced congestion are determined by characteristics of the metropolitan area.

Our model allows residents to increase their welfare by moving in response to the adoption of congestion pricing or by remaining in their present location and, in most cases, benefiting from improvements in land use, such as greater density. Either response will increase the social net benefits of road pricing and reduce its adverse distributional effects. Policymakers have generally opposed road pricing because it imposes direct losses on most travelers, but by accounting for changes in land use, we show that policymakers can substantially reduce the undesirable effects by returning some of the congestion toll revenues to households through lower local taxes and still have sufficient revenues to finance maintenance and expansion of the road system.

Analyzing a sample of the ninety-eight largest metropolitan statistical areas (MSAs) in the nation, we find that efficient road pricing would generate $120 billion in annual revenues (2000 dollars) while reducing the value of the annual flow of services from housing by $80 billion dollars, thus generating an annual net benefit of $40 billion. Our estimate of the benefits of congestion pricing is considerably greater than previous estimates that do not account for adjustments in land use, and it represents a first step toward accounting fully for road pricing's benefits. We conclude that policymakers should recognize that road

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[5] Congress established the National Surface Transportation Policy and Revenue Commission and the National Surface Transportation Infrastructure Financing Commission to consider policies to relieve traffic congestion and to meet short-term and long-term highway revenue shortfalls, among other challenges. The U.S. Department of Transportation has encouraged the nation's cities to submit plans for reducing congestion, which it would help fund. The department has indicated that it would help New York City mayor Michael Bloomberg finance his plan to reduce traffic in Manhattan by charging tolls to drivers entering the busiest parts of the borough. However, that plan has collapsed. It also indicated that it would help San Francisco pay for construction on Doyle Drive, which approaches the Golden Gate Bridge and handles some 90,000 vehicles a day, if local officials agreed to charge a congestion toll for use of the road. The economic effects of and political obstacles to road pricing are well documented in, for example, Small, Winston, and Evans (1989), Mohring (1999), Santos (2004), and Lindsey (2006).

pricing mitigates congestion and improves the quality of life in a metropolitan area by improving land use.

Conceptual Framework

The standard conceptual framework for assessing the economic effects of congestion tolls has been presented so often that it is referred to as the *conventional diagram*.[6] Our discussion proceeds without the diagram, which assumes that residents' locations are fixed, and accounts for road pricing's standard effects as well as its potential effects on land use.

When the volume of traffic on a road is low, every vehicle is able to travel at free flow speed and each driver incurs the private cost of a trip, which includes vehicle operating costs and the value of the driver's travel time. As traffic volume increases, drivers must reduce their speed and each driver's private cost diverges from the social cost of his or her trip because the social cost includes the driver's contribution to congestion, which is indicated by the cost of the delay incurred by other drivers. An efficient congestion toll applied to all drivers on a congested road bridges the gap between the average private cost of drivers' trips and the marginal social cost of their trips by making them pay for their contribution to the delays imposed on other drivers; hence, scarce road capacity is used efficiently by drivers whose marginal benefit of driving equals or exceeds the marginal social cost of their trips.

By affecting drivers' behavior, the toll reduces congestion on the road and increases travel speeds. In the short run, when road users' residences and workplaces are fixed, motorists may respond differently to congestion tolls because the values that they place on travel time differ. Behavioral responses include the choice by some motorists to use the next-best alternative to peak period travel on the road, which may be traveling on it at a time when it is less congested, using a less congested but undoubtedly slower route, using another mode of transportation, or not traveling at all. In any case, these drivers are clearly worse off from the toll. Other motorists will stay on the road because their next-best alternative is worse than continuing to use the road, but on balance they are worse off because the out-of-pocket costs of the toll exceed the value of their saving in travel time. Still other motorists will stay on the road and are better off, because their value of the time saved exceeds the out-of-pocket costs of the toll. In fact, other motorists whose value of time is high and who were deterred from using the road in congested conditions will now find that they

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[6] Lindsey (2006).

also are better off using the toll road. But, on average, travelers' welfare will be reduced by the toll because the initial full price of travel, including the cost of travel time, was below the marginal social cost of travel. On net, the toll results in a welfare gain, but only because the toll revenues to the government exceed the net loss to motorists.[7]

In the long run, in response to a toll, motorists can change where they live and work while continuing to live in the same metropolitan area or they can move to a new metropolitan area. In this paper, we confine our long-run analysis to motorists' residential moves within the same metropolitan area. We discuss the likely effects of the other long-run responses on our findings in the conclusion. We also discuss our findings in light of how policymakers' can allocate the revenues raised through congestion pricing to ameliorate distributional concerns.

From a theoretical perspective, changes in motorists' residential locations in response to road pricing and their effect on land use can be determined from the relationship between transportation costs and household location decisions analyzed by, for example, Alonso (1964), Mills (1967), and Muth (1969). We draw on the theoretical discussion presented by Pickrell (1999).

Households locate where the costs of commuting to work exactly balance the savings in housing costs that accrue from living in a more distant location. Formally, that result is derived under the assumption that a household chooses a combination of housing, h, and other goods, g, to maximize a utility function, $U(h,g)$, subject to a budget constraint given by $Y = p_g g + p_h(d)h + T(d,v)$, where Y is income; p_g denotes the composite price of the nonhousing good; $p_h(d)$ is the price per unit of housing, which is a function of distance d from the workplace; and $T(d,v)$ denotes transportation costs for commuting to and from work, which depend on commuting distance and the value of travel time, v, which itself is a function of income, Y.

Assuming for simplicity that households have identical preferences for identical units of housing, the relevant first-order condition for a constrained utility maximum is $-h(\partial p_h/\partial d) = \partial T/\partial d$ (see Pickrell for the complete derivation). The condition states that at the household's equilibrium location, the change in its housing costs from moving slightly closer to or farther from the workplace, exactly offsets the resulting change in commuting costs. We can rewrite the first-order condition to obtain the household's bid-rent function, $(\partial p_h/\partial d) = -(\partial T/\partial d)/h$, which indicates that the price that the household is willing to

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[7] Lindsey (2006) discusses in detail the simplifying assumptions of the standard framework for analyzing congestion pricing and its findings.

pay for housing declines with the distance from its workplace in proportion to the rate of increase in transportation costs.

If the assumptions of identical housing preferences and housing units are relaxed, households will consume different quantities of housing; in particular, they will respond to the decline in housing prices with distance from the city center by demanding more housing services (nicer or larger homes) at more distant locations. Thus larger households and others with preferences for more residential space will tend to seek more distant locations because they can realize significant savings in housing costs. Home builders will respond to declining land prices at increasing distances from the city center by substituting progressively more land for capital—that is, by constructing lower-density housing. The result is that the density of residential development will decline as the distance from the city's central business district increases and households that live in lower-density developments will incur longer commutes.

Given this framework, we can assess how households will adjust their locations in response to the adoption of road pricing and determine the resulting impact on land use. Congestion tolls will increase household members' out-of-pocket expenses and reduce their travel time. But as noted, households on average will face higher per-mile transportation costs, and the rate at which their commuting costs rise with increasing distance from their workplaces will be higher. Because households seek to locate where the savings in land and housing costs in distant locations offset the increase in commuting costs, the increase in per-mile commuting costs will induce some households to seek closer and higher-density residential locations. The households that make this adjustment increase their utility by reducing the out-of-pocket cost of their toll and travel time costs—savings in transport costs that presumably exceed the increase in land and housing costs. In the process of moving closer to their workplaces, such households also reduce the cost of social services by increasing citywide density.

Wheaton (1998) shows that congestion tolls in a monocentric city should increase density, with the largest increase at the city center and increases in other parts of the city decreasing with distance from the central business district. Lee (1992) assesses congestion pricing in a polycentric city and argues that it should increase density in the central city as well as in suburban subcenters. Lee also suggests that density should increase more in the part of the suburban subcenter that is closest to the central city than it should in other locations, thereby decreasing the variation in density because residents would take into account both their distance from the central city and the subcenter to reduce total transportation costs.

Figure 1. Urban Density Functions with and without Congestion Pricing

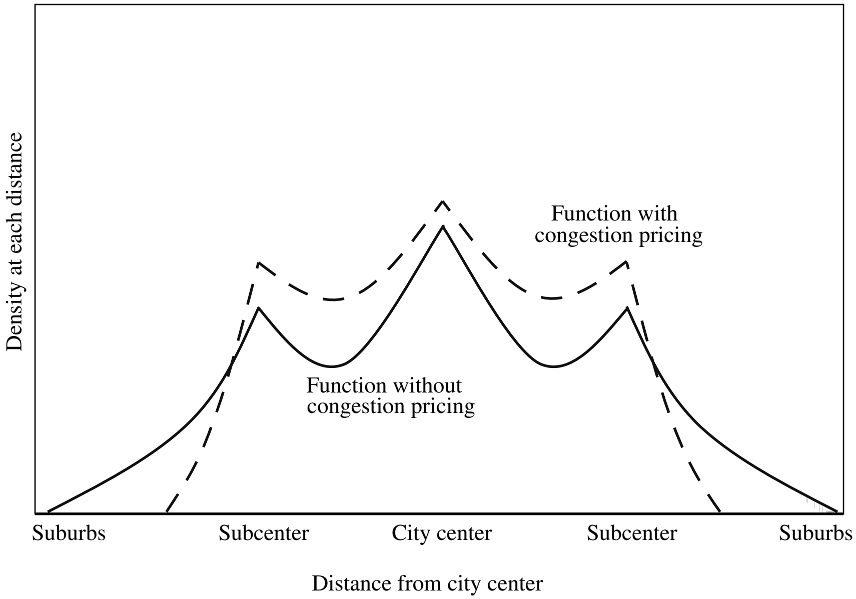

Figure 1 illustrates these ideas with a two-dimensional cut of a stylized city that consists of a central business district, two subcenters, and suburbs. The figure shows that congestion pricing causes the urban density function to have higher peaks and fewer neighborhoods in low-density areas, indicating greater densities near the city center and subcenters as well as less variation in density.

Econometric Approach

How can one estimate the economic effects of road pricing while accounting for its impact on land use? A disaggregate approach for a metropolitan area would model the determinants of a commuter's choice of mode of transportation, departure time, destination, route, and residential location and simulate how those choices change in response to an efficient congestion toll. Given the aggregate change in land use measures implied by changes in residential location, it would be possible, in principle, to estimate how households' responses affect the cost of city services and other costs related to sprawl. The change in social welfare from road pricing would be obtained by summing the costs and benefits to residents and the government from the changes in peak period travel conditions (namely, the toll and travel time) and the resulting changes in land use.

Unfortunately, the data and modeling requirements of a disaggregate approach—especially in determining a commuter's residential location alternatives and their attributes—are formidable.[8] In addition, as noted, little quantitative evidence exists on the costs of sprawl, so it would be difficult to estimate directly how changes in land use would affect those costs. Finally, even if one could estimate and simulate a disaggregate model for one metropolitan area, its findings would not necessarily generalize to other areas.

As an alternative and more tractable approach, we draw on the idea—long recognized by economists—that housing prices reflect many factors, including access to workplaces and recreational activities. Accordingly, we estimate a basic hedonic model of housing prices across U.S. metropolitan areas including, among other influences, highway congestion variables. We then simulate how annualized housing values would change if efficient prices were set to internalize congestion costs. An advantage of our approach is that we can extend the specification to include measures of land use as endogenous determinants of housing prices and allow highway congestion variables to affect land use. Thus, road pricing is modeled as having a direct effect on housing prices and an indirect effect through its impact on land use. A disadvantage of our approach, besides its use of aggregate data, is that the current state of economic theory enables us to identify the model only through exclusion restrictions.

Extending a Hedonic Model of Housing Prices

We wish to extend a basic hedonic model of housing prices—Song and Knaap (2003) is a recent example—which typically is specified as a function of attributes of the housing stock and characteristics of the metropolitan area, to capture salient features of highway congestion and land use. A useful starting point is the monocentric city model, which suggests that commuting costs should affect home prices. In our case, the time costs of travel delays caused by congestion should decrease home prices for two reasons. First, residents incur costs from longer commutes, whether by auto or surface transit, especially during peak

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[8] Discrete choice models with random parameters are specified to capture unobserved preference heterogeneity. In practice, researchers have often found it necessary to include more than one observation for each individual in the sample to obtain precise estimates of unobserved deviations from mean tastes. In the case of a disaggregate model of the choice of residential location, that could be done by estimating a household's *ranking* of alternative residential locations. But such data are not publicly available, so it is likely that a researcher would have to conduct a new and expensive survey of residential location choices to obtain satisfactory estimates of preference heterogeneity.

periods, and from longer nonwork trips, some of which may be taken in congested conditions. Second, residents incur costs because they have to wait longer for services such as package delivery, appliance repair, and emergency services. Those costs could become quite large if police, fire, or medical services are delayed.

The cost of delays must be balanced against the benefit realized by residents because they and the people who provide them with services do not face out-of-pocket costs, besides vehicle operating costs, for driving whenever and wherever they choose, regardless of the social costs.[9] We capture the effect with a metropolitan area–wide measure of unpriced congestion—that is, the difference between the average private cost and the marginal social cost of driving—which should increase home prices because residents can spend more money on housing if their auto transportation and services are subsidized. On balance, we expect that the net effect of delays and unpriced congestion is to increase home prices because the average resident benefits more from driving than he or she is hurt by delays. We treat delays and unpriced congestion as endogenous because both capture the economic vitality of a metropolitan area and could be correlated with unobserved metropolitan area characteristics that affect housing prices.

Land use may affect home prices as consumers balance the benefits from greater proximity to social, cultural, and economic opportunities with the cost of crowding, noise, and a higher likelihood of crime. The basic variable for characterizing urban residential land use is citywide density, or population per unit of land area. Given that individuals choose a combination of distance from employment and lot size (land per person) to maximize utility, density is simply the citywide aggregation of individual households' lot size decisions. We expect density to have a positive effect on home prices because the economies of agglomeration are likely to outweigh the diseconomies of crime and noise. Of course, density must be treated as endogenous to verify that effect empirically.[10]

It also is important to characterize the spatial variation in density within a city because although two cities may have identical overall densities, their costs of providing city services may differ if one is characterized by an extremely dense urban center surrounded by low-density suburbs and the other by a series of fairly dense subcenters. Let x_i be the density of land area i, which is smaller

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[9] Similarly, housing prices may be higher in the absence of HOV lanes and on-street parking regulations that restrict driving. However, those disincentives are difficult to measure in our context.

[10] Our specification will also allow the effect of density to vary with commute length, enabling its net benefits to fluctuate throughout the city.

than the entire city, and N be the number of land areas in the sample. A measure of entropy, which describes the extent of spatial variation, is given by

$$(1)\qquad Entropy = \left(\frac{1}{\ln(N)}\right)\left\{\sum_{i=1}^{N}\left(\frac{x_i}{\sum_{i=1}^{N}x_i}\right)\left(\ln\left(\frac{\sum_{i=1}^{N}x_i}{x_i}\right)\right)\right\}.$$

Entropy ranges from 0 to 1, with higher values implying more uniform density and greater sprawl and smaller values implying more variation in density and less sprawl.[11] For example, if every census tract in a city had exactly the same density, then the city would have entropy of 1. But if a city had a mix of densities, then the city's entropy would be lower.

Although it is possible to measure entropy, its a priori effect on home prices is not clear. Consider an increase in entropy, which means that density will be spread more evenly across neighborhoods in the city. Some suburban residents would benefit from the change because moderately dense neighborhoods, with their cultural and economic attractions, would become more accessible. But other residents might prefer to live in a low-density neighborhood and would find it more difficult to do so, while others might find that the benefits from very dense urban corridors had been diluted. Thus the net effect on home prices of greater entropy, which simultaneously increases access to certain attractions but limits the extent to which preference heterogeneity is accommodated, must be resolved empirically.[12]

Figure 2 presents some stylized density functions that characterize cities in our sample to illustrate how density and entropy interact to generate varied urban forms.[13] For example, Los Angeles, California, and Jersey City, New Jer-

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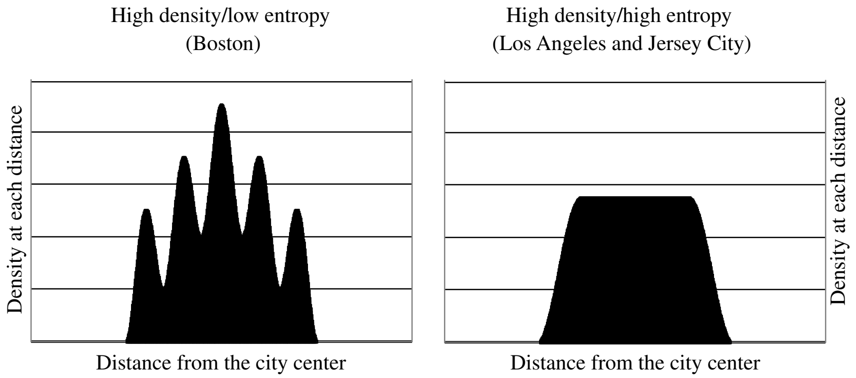
[11] The measure is similar to a Gini coefficient, but it has the advantage that it is independent of the number of observations. The Gini coefficient allows for observations with zero density, but such observations do not arise here**.** Tsai (2005) provides further discussion of the relative merits of measures of urban form.

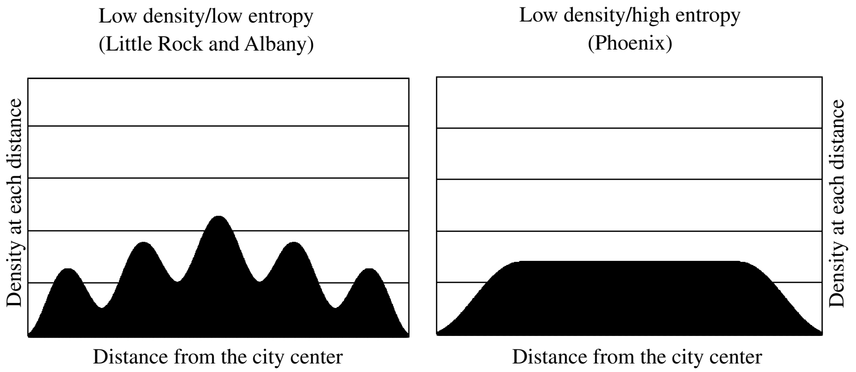
[12] It may be useful to identify also spatial variation that arises between cities with one dense core and those with multiple small subcenters. A measure of centrality, the Moran coefficient, can be used to characterize how close together the city's population is located spatially. In our empirical work, we found that we could not use the Moran coefficient because it exhibited little variation and did not have a statistically significant effect on home prices. Other land use measures that we explored in our empirical work but that did not perform as well as density and entropy were maximum density, density at the 90th percentile of census tract density, and a Geary coefficient (an alternative measure of centrality).

[13] Citywide density and entropy in the examples are not precisely derived from actual U.S. census data.

Figure 2. Representative Density Functions


High density/low entropy (Boston)

High density/high entropy (Los Angeles and Jersey City)


Low density/low entropy (Little Rock and Albany)

Low density/high entropy (Phoenix)

sey, exhibit high density and high entropy because they are moderately—but uniformly—dense throughout their metropolitan area. Their high densities are important because they indicate that these cities sprawl substantially less than a city such as Phoenix, Arizona, which is characterized by low density and high entropy and is commonly considered a sprawling city with few checks on development and no dense residential centers. We tended to find notable variation in density (low entropy) across census tracts in small cities with low average density, such as Little Rock, Arkansas, and Albany, New York, rather than in larger, more densely populated cities. In fact, our sample contains very few cities that are defined by very high density and low entropy. Boston, Massachusetts, is probably the best example of a nonsprawling, multicentric city, although it is not one of the ten lowest-entropy cities in our sample.

Land Use and Highway Congestion Models

Density and entropy cannot be treated as exogenous in our framework because both are likely to be affected by house prices (for example, the monocentric model predicts that a change in the bid-rent function influences population density) and to be correlated with unobserved influences on housing.

We are not aware of previous econometric models that seek to estimate the determinants of citywide density and entropy, but a plausible specification is that metropolitan land use measures are influenced by average home prices, highway congestion variables, and metropolitan area characteristics. An increase in all home prices throughout a metropolitan area is likely to reduce density but increase entropy as some households move further away from employment centers to reduce housing costs. We expect an increase in travel delays to increase density and decrease entropy as households move closer to work to avoid the higher costs of their commute time and possibly reduce the delays to and wait times for emergency and non-emergency services. Conversely, unpriced congestion reduces the total cost of driving for most drivers, encouraging people to live further from work; thus, it decreases density and increases entropy.

Land use variables are likely to be influenced by metropolitan area characteristics originating in historical development patterns that have imposed an underlying form on the city without necessarily affecting current home values. For example, certain features of a metropolitan area's climate affect the suitability of land for farming, which is likely to affect density, while the number of municipalities within the MSA reflects the historical development of subcenters that may affect population dispersion and entropy.

As noted, it is appropriate to treat the highway congestion variables—delay and unpriced congestion—as endogenous. Both variables are strongly related to the ratio of traffic volume to highway capacity, but they are distinct from each other and therefore are a function of metropolitan area characteristics, such as income and natural limits on road building, which affect that ratio.

Summary and Final Form of the Model

The model of housing prices, land use, and highway congestion variables that we have proposed can be summarized as follows:

Housing prices = *f* (*highway congestion variables, land use measures, housing stock attributes*, *metropolitan area characteristics*)

Land use = *g* (*highway congestion variables*, *housing prices*, *metropolitan area characteristics*)

Highway congestion variables = *h* (*metropolitan area characteristics affecting the volume-capacity ratio*).

Theory and empirical evidence suggest that commuters self-select into residential locations that can be classified by their proximity to places of employment. For example, Calfee and Winston (1998) and Calfee, Winston, and Stempski (2001) argue that in a given metropolitan area, commuters with the highest value of travel time live close to their workplaces (say, within a 5-minute commute) and those with lower values of travel time tend to live farther from their workplaces. When a house is sold, it is likely that the new homeowner's commute time will be similar to the previous owner's commute time if the cost of commuting has not changed. We therefore specify average housing price equations for each commuting time block within a metropolitan area (as indicated below, the time blocks are less than 5 minutes from the workplace, 5–19 minutes from the workplace, 20–45 minutes from the workplace, and greater than 45 minutes from the workplace), and we specify equations for density, entropy, delay, and unpriced congestion at the metropolitan level. Accordingly, the effect of road pricing on residential location is captured by residents' shifts to new commuting time blocks.

We stress that the commute time blocks are *not* proxies for a commuter's distance from the city center; therefore a resident with a commute of less than 5 minutes from the workplace lives close to work but does not necessarily live close to the central business district. In addition, by using commute time rather than distance from the central city, we are able to generalize from the monocentric city model and allow for more realistic commuting patterns, including commuting between subcenters. We also are able to use the Census Five Percent Public Use Microdata Sample (PUMS), which includes information on households' commute time but does not include information on the exact location of each household and workplace. Unfortunately, data are not available that would enable us to disaggregate density, entropy, and the volume-capacity ratio by time group.

Specifying commute time blocks does not affect the expected signs of the highway congestion variables, as average delay should have a negative effect and unpriced congestion should have a positive effect on housing prices for all time blocks. For the land use variables, density should have a positive effect on housing prices for all time blocks while entropy's effect is unclear and may vary across time blocks. To understand why, consider an increase in entropy. Residents in the farthest time blocks will benefit most from greater access to certain attractions in dense neighborhoods, while residents in the closest time block may not be affected much because they live in dense neighborhoods close to employment centers, regardless of any change in citywide entropy.

The effects of housing prices on the land use variables also will vary to some extent by commute time block. Households may be influenced to move closer to or further from employment centers when housing prices in their commuting time block increase. We expect households to move farther from places of employment if the savings in housing prices exceed the increase in (total) commuting costs. We expect households to move closer to places of employment if the increase in housing prices is less than the savings in (total) commuting costs.

Given these considerations, we can analyze how changes in home prices within each commuting time block would be expected to affect density and entropy, ceteris paribus. We expect density to decrease if housing prices for the shortest commuting time block increase because households will move to less dense areas farther from employment centers. The effect on density of a change in housing prices in the two middle commute time blocks (5–19 minutes and 20–45 minutes) will depend on the volume of households that shift to time blocks closer to and further from employment centers. If housing prices for the longest commuting time block increase, we expect density to increase because households from that time block will move closer to employment centers.

Entropy measures the relative variation in density. If low-density areas gain proportionately more households than high-density areas do, the variation in density will decrease and entropy will increase. That occurs when housing prices in the farthest commute time block increase because households move marginally closer to employment centers, thereby increasing the below-average density in the 20–45 minute time block. We therefore expect an increase in housing prices in the farthest commute time block to increase entropy.

An increase in housing prices in the closest commute time block will cause households that have the longest commute in that block to move because they are more likely than other households to find that the savings in housing costs exceed the increase in commuting costs. The population density where such households lived is undoubtedly lower than the population densities in other parts of the commute time block because it is furthest from the employment center, so those households' relocation increases the variation in density in the time block (decreases entropy). Entropy in the rest of the city is likely to change very little because density will increase the most in those areas that have the shortest commute lengths in each commute block, which is where density is relatively high. In sum, we expect an increase in housing prices in the closest commute time block to decrease citywide entropy by decreasing entropy in that block and leaving entropy unchanged elsewhere in the city.

Table 1. Expected Signs of Model

	Left-hand side variable		
Right-hand side variable	*Housing prices*	*Density*	*Entropy*
Average delays	-	+	-
Unpriced congestion	+	-	+
Density	+	…	…
Entropy	?	…	…
Housing prices (closest in)	…	-	-
Housing prices (middle blocks)	…	?	?
Housing prices (farthest out)	…	+	+

The effect on entropy of a change in housing prices in the two middle blocks is ambiguous, but we can see from the preceding cases that the variation in citywide density tends to decline (entropy increases) as housing prices in commute blocks further from employment centers increase. Therefore, we would expect that compared with an increase in housing prices in the 5- to 19-minute commute time block, an increase in housing prices in the 20- to 45-minute commute time block will cause entropy either to decline by a smaller amount or to increase by a greater amount.

Accounting for the inclusion of commuting time blocks, we summarize the important expected signs of the model in table 1.

Identification of Equations

The land use and highway congestion equations can be identified by certain attributes of the housing stock that affect housing prices but have no theoretical reason to affect land use, delays, and unpriced congestion. It appears difficult to identify the housing price equations on purely theoretical grounds because they are likely to be influenced by the same type of variables that influence the land use measures. But, as noted, it is reasonable to expect that some of the metropolitan area characteristics that help explain land use may not affect housing prices and vice versa. In any case, the exclusion restrictions that ultimately identify the housing price equations are based on statistical significance or the lack thereof rather than an unambiguous theoretical exclusion requirement.

Sample and Variables

We identified the 100 largest metropolitan statistical areas in the nation and constructed a sample based on the 98 largest MSAs in the 48 contiguous states (excluding Honolulu, Hawaii, and San Juan, Puerto Rico) for the year 2000. The MSAs account for a large fraction of U.S. highway congestion and exhibit a wide range of land use patterns.[14]

Endogenous Variables

Data on average reported prices for owner-occupied housing are from the 2000 U.S. decennial census. As noted, we divided residents into average commuting time blocks of less than 5 minutes, 5–19 minutes, 20–45 minutes, and greater than 45 minutes.[15] We obtained less satisfactory statistical fits using other commuting time blocks. Roughly 24 percent of owner-occupied housing did not include have any members who worked outside the home. The PUMS data do not allow us to place those households in a commute time group. However, the value of their homes will be affected by changes in highway congestion variables because home prices are determined by demand and supply in the entire metropolitan area housing market. As discussed later, our simulations account for changes in the prices of homes owned by people who do not work outside the home.

To ease the interpretation of our parameter estimates and simulation results, we annualize housing prices by drawing on estimates of the annual "user cost" of housing in Himmelberg, Mayer, and Sinai (2005). The authors estimate the annual cost of owning a home—that is, the percent of housing that is consumed each year—in cities across the United States, accounting for the opportunity cost of owning a home, the change in house prices, and federal income and local property tax rates. We apply the authors' user cost estimates for forty-six cities to annualize home values for the same cities in our sample and use the average annual user cost in their sample of medium and small cities, roughly 5.85 percent, to annualize home values for the remaining cities in our sample.

Table 2 presents the current or, put more accurately, present value and the annualized value of houses in our sample by commute time block. Households pay a substantial premium to live close to their workplaces, and the large standard deviation indicates that some homes in this time block are quite expensive.

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[14] The Texas Transportation Institute limits its annual assessment of congestion in the United States to 85 major MSAs because they find that congestion falls sharply as city size declines. Thus, our omission of MSAs outside of the top 100 should have little effect on our findings. Although some MSAs include rural areas of predominantly urban counties, some residents in rural areas that are not included do commute into the city. Such problems are unavoidable when using MSAs to define cities in a national analysis.

[15] Average commuting times were based on the average commute time of all household members who work outside the home. Commuters who walk to work are placed in the closest time group regardless of the time it takes them to get to work.

Table 2. Population Weighted Housing Values in the Sample by Commute Time Block
2000 dollars

	Present value		*Annualized value*	
Commute time block	*Average*	*Standard deviation*	*Average*	*Standard deviation*
Less than 5 minutes	231,860	95,060	12,687	4,020
5–19 minutes	195,720	80,470	10,731	3,425
20–45 minutes	188,930	75,810	10,366	3,203
More than 45 minutes	185,760	74,320	10,195	3,163

Source: Authors' calculations.

As expected, average housing prices decline as households live farther from their workplaces. Note, however, that the averages reported in the table control only for commute time and not for other attributes, such as lot and house size; therefore, the bid-rent function may be steeper than implied by our summary data.

Citywide density, measured as population per unit of land, and entropy, as specified in equation 1, are constructed from U.S. census data on the population and land area of each census tract in the city. We use census tracts to determine urban subunits in the entropy formula. Census tracts have similar populations because they are defined so that they include roughly 4,000 people living contiguously, although their land area can vary greatly. Las Vegas, Bakersfield, and Tucson have the lowest densities in our sample; Jersey City, New York City, and Orange County (California) have the highest. Harrisburg, Ann Arbor, and Syracuse have the lowest entropy (that is, their density varies greatly) because they have pockets of densely populated land surrounded by areas with very few people. Fort Lauderdale, Orange County, and San Jose have the highest entropy because they have moderately high density over a broad area. Density and entropy clearly are capturing distinct aspects of land use because their correlation is 0.28.

The highway congestion variables that we include in the model are travel delays and the benefits of unpriced congestion. We measure the delay per mile on highways in the city during the peak travel hour using data on traffic volume and road capacity reported in the Federal Highway Administration's *Highway Statistics*.[16] We estimate the difference between actual and free flow speeds using a speed-flow curve developed by the Bureau of Public Roads (a

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[16] We determined peak hour traffic volume by using data in *Highway Statistics* on the average amount of daily travel on freeways and making plausible assumptions regarding the share of daily traffic that occurs during the peak hour. We determined highway vehicle capacity by using data in *Highway Statistics* on freeway lane miles and assumed 2,000 vehicles per lane per hour (2,200 for Los Angeles and San Francisco).

derivation is provided in the appendix).[17] The benefit to road users of unpriced congestion is measured by the difference between the average cost per mile (including the monetary value of travel time) and the marginal social cost per mile (a derivation is provided in the appendix). In our sample, Orange County has the greatest average delay per mile (41 seconds) and therefore the largest benefit of unpriced congestion per mile (36 cents), while Scranton has the lowest average delay per mile (0.5 seconds) and the smallest benefit of unpriced congestion per mile (0.34 cents).

We specify delay per mile in minutes instead of multiplying it by an assumed value of time and expressing it as a cost because we wish to allow the model to determine the implicit value of travel delays. However, unpriced congestion is measured as the difference between marginal social costs and average private costs and must include a value of time. This variable is also used to set the efficient congestion toll faced by all road users. Following Small (1992), we assume that the value of time is half of the average wage in the city and later discuss how our main findings would change based on alternative assumptions.

Finally, although we use highway delay and unpriced congestion in our model, we are not assuming that all road users travel entirely on freeways. Rather, we are assuming that the variation in highway delay and unpriced highway congestion across MSAs is a good indicator of the variation in delay and unpriced congestion on all major thoroughfares servicing MSAs.

Exogenous Variables

The housing stock attributes in the annualized housing price equations for each commuting block include the percent of homes with a cellar and the percent of homes with missing tiles or other damage to the roof.[18] Metropolitan area characteristics include the office vacancy rate, average annual household income, mean number of days per year below 32 degrees Fahrenheit (obtained

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[17] Following the Texas Transportation Institute, we assume a free flow speed of 60 miles per hour for urban highways. We obtained similar results using alternatives to the Bureau of Public Roads speed-flow curve, such as the Metropolitan Transportation Commission's Bay Area speed-flow curve.

[18] Data for the percent of homes with a cellar and with missing tiles or other damage to the roof are from the Census Bureau's American Housing Survey. We assign to these variables the average value in the sample for those cities in which the census did not conduct a housing survey between 1997 and 2003. Variables such as the number of bedrooms and the number of rooms in the house are likely to be endogenous and their exclusion had little effect on our main findings. We also tried including several additional variables from the American Housing Survey, but they were statistically insignificant. The variables, as described in the survey, were the percent of houses with a "major problem," porch, fireplace, washer and drier, rodents, garage, or structural damage, such as a crumbling foundation, cracks in the wall larger than a dime, or sloping walls.

from the National Oceanographic and Atmospheric Administration), and the percent of the state that is classified as urban.[19] We expect home prices to be higher if houses have a cellar and if they are located in cities with affluent residents. We expect home prices to be lower if houses have a damaged roof and if they are located in cities that experience a lot of cold weather, have vacant office space, and, as indicated by the extent of the state's urbanization, compete with other cities in the state to attract residents. Finally, we include state fixed effects to capture variation in state taxes and government services that may influence home prices.[20]

It is appropriate to include in the density equation metropolitan area characteristics that affect the availability of land outside the city to facilitate expansion. Therefore we specify a coast dummy to indicate whether development was limited by a large body of water, such as an ocean or a gulf. We also specify a dummy to indicate whether the MSA contains a traffic bottleneck (for example, a bridge over a body of water) that might encourage or discourage development before or beyond a major point of congestion. Finally, we include average annual precipitation in the MSA as a proxy for the historical reasons for the original development of an MSA, which was determined to a certain extent by whether the climate was conducive to local agriculture.[21]

We include the number of municipalities (obtained from the Office of Management and Budget) as a metropolitan area characteristic in the entropy equation. We expect MSAs with a large number of municipalities to have more dispersed populations and greater entropy than MSAs with fewer municipalities have. We also include the coast dummy and a dummy that indicates whether the MSA has an interstate running through it, both of which we expect to increase entropy.[22]

[19] Household income and the percent of the state that is classified as urban are from the decennial census. The office vacancy rate is from CB Richard Ellis. Other metropolitan area characteristics that we tried to include in the model but found to be statistically insignificant were the cost of living in the city, number of high–air pollution days, annual precipitation, and the average number of extremely warm days (warmer than 90 degrees Fahrenheit) per year. Variables such as crime rate, foreign-born residents, and the like were not included because they are likely to be endogenous.

[20] Taxes and government services tend to vary at the state and municipality level. Because an MSA contains many municipalities and a state may contain more than one MSA, state fixed effects are more appropriate than MSA fixed effects to control for the variation in taxes and government services. For those states that have only one major city, state and MSA fixed effects are equivalent.

[21] In the density equation, we also explored other ways of capturing limits on a city's development, including a combined MSA (CMSA) dummy to indicate whether the city is part of a larger metropolitan area with less land, but it was statistically insignificant. We also tried geographical variables, including the mean and standard deviation of a city's elevation and slope, but they also were insignificant.

[22] In the entropy equation, we found that the interstate dummy fit better than the bottleneck dummy that we include in the density equation. One possible explanation is that transportation is less expensive along interstate highways, causing dense areas to be dispersed along highways rather

And we include the range of elevation in the MSA as a topographical characteristic. We expect a greater range of elevation to decrease the variation in population density—that is, to have a negative effect on entropy—because most residents will tend to live in flat areas where it is cheaper to build housing and to live close to sea level in coastal cities. We measure the range of elevation in the half-degree longitude-latitude square including the city.[23]

We include the state fixed effects in the density and entropy equations. We include a dummy variable for New York City in the density equation because the city is distinguished from others in the sample by its island geography. We also include "major city" dummy variables in the entropy equation, which denote large cities that are located in a state that has more than one city in our sample.[24] The dummy variables capture the likelihood that large cities in a given state may have unobserved differences from other cities in the state.

Delays and unpriced congestion should be influenced by the MSA's population and economic vitality, as indicated by the income of its residents, and by road network characteristics that may exacerbate congestion (for example, an interstate highway carrying through traffic) and that may limit capacity expansion (for example, close proximity to a large body of water). We also include the standard deviation of elevation. Although the range of elevation captures whether there are especially high peaks and low valleys near an MSA, the standard deviation of elevation indicates whether there are many of such peaks and valleys or just a few. A high standard deviation of elevation could call for additional road capacity to enhance vehicle safety, thereby reducing delays and unpriced congestion. Finally, we include the state fixed effects and the "major city" dummy variables. Major cities in the same state may share congestion-related influences that they do not share with other cities in the state.

Estimation Results

We specified a linear functional form for the annualized housing price, density, entropy, delay, and unpriced congestion equations and jointly estimated

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than concentrated in one area, which would increase the variation in density across the metropolitan area.

[23] To capture the range of elevation over the area covered by the MSA, not just the central city, we needed a measure of the range of elevation surrounding the city. The best publicly available data for this measure are from the International Satellite Land-Surface Climatology Project (ISLSCP), which provides the range of elevation for the half-degree longitude-latitude square including the city. The actual data were from ISLSCP's Initiative II Data Archive.

[24] Major cities are New York City, Philadelphia, Boston, Detroit, Dallas, Houston, and Los Angeles.

the system by three-stage least squares to account for the endogenous influences and contemporaneous correlation of the errors.[25] The estimation results presented in table 3 indicate that most of the variables were estimated with good precision and had the expected sign.

Housing Price Equations

The effects of average delay and unpriced congestion on annualized home values are central to our analysis. As noted, these variables capture all aspects of highway travel, including commuting, nonwork trips, and emergency and non-emergency services. In all likelihood, residents are likely to place the greatest weight on changes in highway travel that affect their commute.

Interestingly, we find that the pattern of coefficients exhibits a U-shape (in absolute value), because the prices of homes where residents have the shortest and longest commuting times are more responsive to average delay and unpriced congestion than are the prices of homes whose residents have commuting times between the extremes.[26] We expect households that have self-selected into residential locations where they are close to work to place a high value on travel time and to attach a large disutility to delay. We also expect households that have self-selected into residential locations where they have a long commute to place a much lower value on travel time. But given that average delay is measured on a per-mile basis, we find that such households attach a high disutility to an increase in average delay in the metropolitan area because it will have the greatest cumulative effect on the duration of their commute and on other vehicle travel. Given their disutility from the cost of delay, households that have the shortest and longest commutes experience the largest decrease in home values for a given increase in delay; they therefore have the highest willingness to pay to reduce delay. These households also experience the largest increase in home values from a given increase in the benefit of not having to pay out-of-pocket for the congestion that they cause. Households that live close to work avoid being charged for delaying a large flow of motorists, some of whom have a high value of time, while households that live far from work avoid being charged for contributing to congestion during a lengthy commute.

[25] We also estimated models using log-linear functional forms for all the equations and for the housing price and land use equations and semi-log-linear functional forms for the highway congestion equations. These functional forms did not fit the data as well as the linear functional forms did.

[26] We tried interacting the highway congestion variables with indicators of a city's population to see whether their effects varied for large and small cites and with indicators of high and low volume-capacity ratios to see whether their effects varied by traffic density. We did not find any notable changes in the estimates.

Table 3. Three-Stage Least Squares Parameter Estimates[a]

	Dependent variable							
	Annualized owner-occupied housing value by time group (in thousands of dollars)							
Independent variable	*Less than 5 minutes*	*5–19 minutes*	*20–45 minutes*	*More than 45 minutes*	*Average MSA population density*	*MSA population entropy x 1,000*	*Delay (minutes per mile)*	*Unpriced congestion (dollars per mile)*
Average delay (minutes per mile)	-30.38	-17.58	-15.79	-20.75	33.41	. . .	. . .	. . .
	(6.11)	(3.66)	(3.22)	(3.55)	(5.74)			
Highway congestion distortion (marginal cost per mile minus average cost per mile in dollars per mile)	83.83	40.56	35.69	47.04	-67.31	. . .	. . .	. . .
	(12.20)	(7.24)	(6.36)	(6.99)	(12.94)			
Average MSA population density (thousands of people per square mile)	1.03	0.70	0.65	0.47	. . .	. . .	. . .	. . .
	(0.21)	(0.13)	(0.11)	(0.12)				
MSA population entropy	-3.74	10.28	8.46	11.38	. . .	. . .	-0.53	-0.45
	(12.46)	(7.29)	(6.25)	(7.06)			(0.54)	(0.26)
Annualized value for housing owned and occupied by working households with commutes of less than 5 minutes (thousands of dollars)	. . .	. . .	. . .	. . .	-0.98	-8.31	. . .	. . .
					(0.24)	(2.62)		
Annualized value for housing owned and occupied by working households with commutes of between 5 and 19 minutes (thousands of dollars)	. . .	. . .	. . .	. . .	0.59	-7.72	. . .	. . .
					(0.46)	(5.53)		
Annualized value for housing owned and occupied by working households with commutes of between 20 and 45 minutes (thousands of dollars)	. . .	. . .	. . .	. . .	1.21	13.30	. . .	. . .
					(0.49)	(5.70)		

Annualized value for housing owned and occupied by working households with commutes of more than 45 minutes (thousands of dollars)	. . .	. . .	. . .	. . .	-0.10 (0.24)	5.24 (2.57)	. . .	. . .
Percent of homes in MSA with a cellar	1.44 (0.55)	0.88 (0.39)	1.13 (0.34)	1.41 (0.37)	. . .	. . .	. . .	. . .
Percent of homes in MSA with tiles missing from roof	-44.66 (18.00)	-27.48 (12.21)	-29.84 (10.60)	-25.81 (11.91)	. . .	. . .	. . .	. . .
Mean number of days per year with minimum temperature under 32 degrees Fahrenheit	-0.042 (0.009)	-0.026 (0.006)	-0.020 (0.005)	-0.022 (0.006)	. . .	. . .	. . .	. . .
Percent of state classified as urban	-0.62 (0.11)	-0.34 (0.07)	-0.30 (0.06)	-0.25 (0.07)	. . .	. . .	. . .	. . .
Average annual income in each time group for working households that own and occupy their housing (thousands of dollars)	0.053 (0.012)	0.115 (0.009)	0.106 (0.007)	0.100 (0.006)	. . .	. . .	. . .	. . .
MSA office vacancy rate	-0.041 (0.016)	-0.032 (0.012)	-0.042 (0.010)	-0.046 (0.011)	. . .	. . .	. . .	. . .
Bottleneck dummy variable (1 if city contains a bottleneck; 0 otherwise)	. . .	. . .	. . .	. . .	0.81 (0.34)	. . .	. . .	. . .
Coast dummy (1 if MSA is located on an ocean or the Gulf of Mexico; 0 otherwise)	. . .	. . .	. . .	. . .	1.00 (0.40)	17.5 (3.8)	0.06 (0.02)	0.03 (0.007)
Average annual precipitation in the MSA (hundreds of inches)	. . .	. . .	. . .	. . .	4.19 (2.53)	. . .	. . .	. . .
Interstate dummy (1 if MSA has an interstate highway ending in 0 or 5; 0 otherwise)	. . .	. . .	. . .	. . .	. . .	5.94 (3.17)	0.0379 (0.0149)	0.0208 (0.0065)
Number of municipalities in the MSA	. . .	. . .	. . .	. . .	. . .	0.23 (0.04)	. . .	. . .

Table 3 (continued). Three-Stage Least Squares Parameter Estimates[a]

	Dependent variable							
	Annualized owner-occupied housing value by time group (in thousands of dollars)							
Independent variable	*Less than 5 minutes*	*5–19 minutes*	*20–45 minutes*	*More than 45 minutes*	*Average MSA population density*	*MSA population entropy x 1,000*	*Delay (minutes per mile)*	*Unpriced congestion (dollars per mile)*
Range of elevation within a half-degree longitude-latitude square containing the MSA (feet)	. . .	. . .	. . .	. . .	. . .	-0.012 (0.004)	. . .	. . .
Average annual income in the MSA for working households that own and occupy their housing (thousands of dollars)	. . .	. . .	. . .	. . .	. . .	. . .	0.0034 (0.0006)	0.0029 (0.0003)
Standard deviation of elevation within a half-degree longitude-latitude square containing the MSA	. . .	. . .	. . .	. . .	. . .	. . .	-1.81 E-4 (7.37 E-5)	-8.30 E-5 (3.17 E-5)
New York City dummy variable	No	No	No	No	Yes	No	No	No
Major city dummy variables	No	No	No	No	No	Yes	Yes	Yes
State dummy variables	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
R^2	0.80	0.92	0.93	0.93	0.47	0.74	0.79	0.82

Source: Authors' calculations.

a. Sample consists of 98 of the 100 largest metropolitan statistical areas in 2000 that were located within the continuous 48 states. Standard errors are in parentheses. All dollar amounts are in 2000 dollars.

Additional perspective on the delay coefficients is typically provided in mode choice studies by using them to calculate the implied value of travel time. However, it is difficult for us to do that here for two reasons. First, as noted, the coefficients reflect delay that the household experiences from its work and nonwork trips and from highway travel by service providers who affect the household's welfare. We do not know what proportion of delay costs can be attributed to each type of trip. Second, the coefficients capture the effect of delay on the *household*, not on a single commuter, and it is not clear how to properly apportion the costs of delay to various household members.

The total annual miles traveled for which households that live in a given time block are directly or indirectly subjected to some congestion are captured by the coefficients for unpriced congestion.[27] As expected, these miles significantly exceed a household's annual vehicle miles traveled, especially for households that live close to employment centers and tend to "consume" a disproportionate share of the city's amenities.[28]

Turning to the other coefficients, the effect of MSA density on annualized housing prices becomes stronger the closer homes are located to employment centers. This finding appears to reflect preference heterogeneity: residents who choose to enjoy the benefits of living close to employment centers are also more likely to place a relatively higher value on those benefits and a lower value on the negative aspects of density, such as crime and noise. Residents who live farther from employment centers may place a somewhat lower value than other residents on the positive aspects of density and a higher value on the negative aspects. The effect of entropy on annualized home prices is highly insignificant for the closest time block, and it has a positive effect that does not vary much across the other time blocks. The closest time block is likely to be densely populated in most MSAs; therefore home values in that block are likely to be insensitive to changes in entropy over the entire MSA. The positive effect for the remaining time blocks reflects their residents' preferences for access to areas

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[27] Note that the units of annualized housing costs are dollars and units of unpriced congestion are dollars per mile.

[28] If we ignore the complications of trying to apportion the costs of delay to various household members, we can obtain a rough estimate of the value of travel time by dividing the delay coefficients by the total annual miles for which the household is exposed to some congestion (note that annualized housing costs are expressed in dollars and delay is expressed in minutes per mile). This procedure yields values of time that cluster around $20 per hour, which align with the estimates for Los Angeles households found in Bajari and Kahn (2004) and in Small, Winston, and Yan (2006) but which may be above the value that might be expected for the nation as a whole based on work trips. On the other hand, our estimate is based on working households that own a home and have incomes that generally exceed the incomes of commuters in general. Average income in our sample is just under $40 per hour, which would imply a value of time that is roughly equal to half of the wage.

with the average density. Although the a priori effect of entropy involves a trade-off between accessibility and accommodating preference heterogeneity, our empirical findings indicate that residents place a higher value on greater access to the attractions of higher-density neighborhoods.

The magnitudes of the positive coefficient for a cellar and the negative coefficient for a damaged roof do not vary greatly across commute time blocks. But the negative effect on housing prices of cold weather is noticeably greater for the shortest commuting time block than for other commuting time blocks, possibly because more people who live in the shortest commuting time block may walk to work and run errands on foot, thereby experiencing greater disutility from cold weather than other residents do. We also find that the negative effect of competition from other urban areas in the state is somewhat greater for the shortest commuting time block while the positive effect of income is smaller.[29] An increase in office vacancy rates reduces home prices fairly uniformly across commuting time blocks.

Land Use Equations

We find, as expected, that average delay increases density and that the failure to price congestion decreases density. (The highway congestion variables had insignificant effects on entropy.) *Thus, holding home prices constant, the failure to price highway congestion contributes to sprawl, while the resulting delays reduce sprawl.* And given that the increase in density from pricing congestion is greater than the expected decrease in density from reducing delay, inefficient highway policy results in an increase in sprawl.[30]

Annualized home prices have varying plausible effects on density and entropy. An increase in home prices for the shortest commuting time block reduces density and entropy as residents move to time blocks that are farther away from employment centers. An increase in home prices for the two middle commute blocks increases density as residents move to time blocks that are closer to employment centers. In the case of the 5–19 minute time block, that

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[29] As noted in our conceptual framework, we do not account for the long-run response of household moves to new MSAs in response to road pricing. Average household income is therefore taken as exogenous here, although we acknowledge that it could be correlated with unobserved attributes of the city, such as cultural offerings that may attract certain residents and affect home prices. However, our simulations—which keep the estimated parameters and value of income fixed during predictions of the base case without road pricing and during predictions that capture the economic effects of road pricing—will net out any possible bias from the correlation.

[30] At the average levels of the congestion distortion and delay in our sample, marginal cost congestion pricing would increase density by more than 800 people per square mile. To offset that effect, delays would have to decrease more than 70 percent, which seems unlikely given the magnitude of optimal congestion tolls.

reduces entropy, but in the case of the 20–45 minute time block, entropy increases because areas of the city whose density is close to the average gain the most population. Finally, an increase in home prices in the farthest commuting block has an insignificant effect on average MSA density but a positive effect on entropy because households move to a time block whose density is closer to the MSA average.

Density increases if an MSA has a bottleneck, is located along a coast, and experiences a relatively high level of precipitation. Entropy increases if an MSA is located along a coast, has an interstate running through it, and includes a large number of municipalities, while it decreases if its elevation varies greatly (that is, the MSA includes large, flat areas along with mountains or valleys) because the bulk of residents will live in the flat areas.

The highway congestion variables are explained by parsimonious specifications that include the same influences. Delays and the cost of unpriced congestion are greater if an MSA is located along a coast, has an interstate running through it, and if its residents earn relatively high incomes.[31] An interesting finding is that the congestion variables were more affected by population entropy than by average population density. Specifically, delays and the costs of unpriced congestion are *higher* as density becomes more varied throughout the MSA (that is, as entropy decreases). Policymakers may be better able to increase highway capacity to match average density over the metropolitan area than to adjust capacity to ameliorate congestion related to extremely high density in certain parts of the MSA. Finally, a high standard deviation of elevation (that is, the MSA consists of a series of hills and valleys) reduces delays and the costs of unpriced congestion, possibly because additional road capacity is likely to be constructed to accommodate slower traffic and to allow vehicles to pass each other safely.

We have acknowledged that our model is identified by exclusion restrictions. But we can report that the key parameter estimates capturing the effect of the transportation and land use variables on housing prices tended to be robust to alternative specifications that were estimated to determine statistically significant influences on the endogenous variables in our model. In the final specification, the housing price equations are identified by certain metropolitan area characteristics, including a bottleneck dummy, coast dummy, interstate dummy, annual precipitation, and number of municipalities. Given our aggregate approach and the fact that these variables are determined by an MSA's geography or history, they are plausible instruments.

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[31] As indicated in footnote 29, we treat household income as exogenous.

Simulating the Effects of Road Pricing

The central finding of our model is that policymakers' failure to charge motorists for the congestion that they cause has raised all home prices in metropolitan areas while also contributing to sprawl. We use the model to simulate the welfare effects of instituting marginal cost congestion tolls on the nation's urban highways to capture two major effects. The first is that the tolls will generate toll revenues while causing home prices (and property tax revenues) to decline because, on average, residents' higher out-of-pocket highway costs will exceed their value of the reduction in travel time.[32] The increase in toll revenues is a welfare gain, assuming that the revenues are used for socially desirable purposes, but the decline in home prices represents a welfare loss. The reason is that, on net, congestion pricing reduces the attractiveness of homes and lowers their price by decreasing consumer demand. Alternatively, if the price of housing dropped because the supply of homes increased, the price decline would be associated with a welfare gain from an increase in the housing stock.

The second effect is that congestion pricing will cause certain residents to move, thereby increasing metropolitan area density and partially offsetting the initial reduction in home prices as home prices rise in response to the decreased cost of city services and greater access to urban amenities. At the same time, because the prices of homes in the shortest commute time groups will fall more than the prices of homes that are farther from employment centers, entropy will increase, which feeds back to further increase home prices, especially those in the farthest time groups. We point out that our model does not capture other benefits of congestion pricing associated with reducing sprawl, such as preserving the natural habitat, discouraging wasteful suburban expansion of rail transit, and weakening restrictive land use regulations. We discuss those and other effects later.

We make the following assumptions to perform a base case simulation and then, where possible, conduct sensitivity analysis or discuss an assumption's likely effects in the conclusion. First, tolls will reduce the average delay per mile in accordance with motorists' long-run elasticity of vehicle miles traveled with respect to commuting costs. We assume that this elasticity is -0.3 and that

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[32] Glazer and Van Dender (2002) develops a theoretical model that predicts that introducing congestion tolls without allowing residents to relocate will reduce property values. Home values could increase if the government uses the toll revenues to increase government services or reduce property taxes. Our model includes state fixed effects to control for the variation in government services. Those effects do not change in the simulation. Thus, the initial change in home prices caused by congestion tolls is unambiguously attributable to the change in out-of-pocket costs and travel time.

the pre-toll private cost of driving is $0.40 per mile.[33] Although optimal congestion tolls vary both across different highways and by time of day, our aggregate approach enables us to calculate one congestion toll per city. Thus, the congestion toll calculations can be interpreted as representing the average congestion toll paid by a city's motorists, and our results reflect the toll's average effect on home prices in each commute time block and on overall urban land use. Second, zoning regulations and physical constraints on the provision of housing are likely to limit the extent that density can increase in response to tolls. We assume that a city's density can increase no more than 50 percent or that it cannot exceed the density of the Chicago MSA, whichever is greatest.[34] We do not think that it is likely that small, sparsely populated cities would become denser than New York City or Northern New Jersey (the two densest MSAs in the sample). In fact, in our analysis, New York City and Jersey City are the only MSAs that are able to increase their density beyond the level that is currently observed in our sample. The Chicago metro area is a mix of a high-density center and very low-density suburbs, so its density offers an appropriate limit. Third, our simulation assumes that residents do not change their place of work. Finally, our simulation assumes that residents do not move to another metropolitan area—in terms of the monocentric city model, we are employing a "closed-city" instead of an "open-city" model.

The welfare effects of congestion tolls are obtained by calculating an iterated equilibrium. First, we determine the optimal congestion toll in each MSA in our sample. To do that, we calculate the current full cost of driving, which includes private costs of $0.40 per mile and average travel time costs (see the appendix). We then calculate the marginal cost congestion toll based on current vehicle miles traveled (VMT) and road capacity, and recalculate VMT given the introduction of the toll and an elasticity of -0.3. The process is repeated until the change in VMT and in the congestion toll is very small. At that point we obtain the toll revenues for each MSA by multiplying the optimal toll per mile times the exposure of each household to congested vehicle miles.[35]

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[33] The elasticity is consistent with the estimate in Mannering and Winston (1985) of the long-run elasticity of vehicle use with respect to operating costs. The private cost of driving, including gasoline and vehicle capital costs, is slightly above the IRS tax deduction for driving a personal vehicle for business use.

[34] Ten percent of the cities in our sample had an initial density that was greater than the density of Chicago.

[35] As noted, the exposure of households by commute distance block to congested *passenger* miles can be obtained from the coefficients capturing the effect of the highway congestion distortion on home prices. Dividing this value by average vehicle occupancy, 1.25 people (following the Texas Transportation Institute), generates the household's congested *vehicle* miles.

Table 4. Population Weighted Average Annualized Value of Housing and Land Use Variables before and after Congestion Pricing[a]

Item	*Before congestion pricing*	*After congestion pricing*
Annualized housing value (dollars per year)		
Less than 5 minutes	12,636	7,515
5–19 minutes	10,697	8,878
20–45 minutes	10,352	8,790
More than 45 minutes	10,169	7,668
Average annualized housing value in the MSA (dollars per year)	10,545	8,656
Average population density (people per square mile)	1,552	2,527
Population density entropy	0.929	0.945

Source: Authors' calculations.
a. In 2000 dollars.

We then calculate the changes in home values and the land use variables by predicting home values in each time group, assuming the optimal congestion toll is implemented but keeping the land use variables at their current values. The predicted home values and the optimal congestion toll are then used to predict new values of the land use variables. The process is repeated until the change in the predicted home prices and land use variables is small, at which point we calculate for each MSA the change in annualized home prices, density, entropy, annual toll revenues, and annual property tax revenues.[36]

Table 4 presents the (predicted) average changes in annualized housing values, density, and entropy that result from efficient road pricing. Annualized housing values decline for homes in all commute blocks, especially for those closest to and farthest from places of employment. The average decline in housing values over all MSAs in the sample is 18 percent.

It is useful to recall our previous discussion of a household's constrained utility maximization problem to understand our findings. This problem can be reformulated as a household maximizing an indirect utility function, where the relevant "prices" for our discussion are the price per unit of housing, travel time costs, and the out-of-pocket costs of driving, including the toll. Note that the price per unit of housing is negatively related to the commute distance from the workplace and that the travel time and out-of-pocket costs are positively related to the commute distance.

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[36] Average implied property tax rates for each city are generated by using the self-reported property tax payments in the Census Bureau's Public Use Microdata. These rates are applied to the pre- and post-simulation home values to generate expected property tax revenues.

Congestion pricing reduces the relative attractiveness of homes that require less than a 5-minute commute because some commuters who tend to have the highest value of time can choose to live somewhat farther from their workplace, consume more house per dollar, and experience little, if any, increase in their commute time without having to pay excessive out-of-pocket costs. Recall from table 2 that those households have been paying a premium in housing prices to live extraordinarily close to work—and in all likelihood for the benefits of a dense living environment—and they no longer have to pay this premium under road pricing. That is, road pricing has *lowered* the rate at which their (total) commute costs rise with increasing distance from their workplaces, enabling them to seek more distant and relatively less expensive residential locations.

Residents who live far from their workplace are able to get to work faster, but the relative attractiveness of homes that require more than a 45-minute commute is significantly reduced for some of these residents because they have to pay a very high toll per trip and they tend to place a lower value than other residents do on the travel time savings. Thus road pricing has *increased* the rate at which their (total) commute costs rise with increasing distance from their workplace, causing them to seek closer residential locations even if they are more expensive. Note, however, that it is unlikely that these households are now willing to pay a housing premium to live in a very dense neighborhood. Given these adjustments, it is plausible that congestion pricing would cause the values of homes located in the two middle commuting time blocks to decrease by smaller amounts than the values of homes located in the extreme commuting blocks and that the value of the homes in the middle blocks exceeds the value of homes located in the extreme commute time blocks.

To put the finding somewhat differently, households that used to experience higher housing costs to live extremely close to work are now able to live in a neighborhood with less expensive housing (relative to the cost of their original home) that is farther from work but that suits their tastes for urban land use. The movement of such households from the shortest commute time block is not offset by the movement of households that do not like paying higher out-of-pocket costs but at the same time are not willing to pay a premium for living in a dense neighborhood close to an employment center.

Our findings contrast with conventional theory based on the monocentric model, which predicts that congestion tolls will cause the bid-rent function to become steeper throughout the metropolitan area.[37] The reason that this does not occur here is because we allow for *preference heterogeneity*, whereby res-

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[37] Segal and Steinmeier (1980).

idents with high values of time sort into housing close to employment centers and residents with low values of time choose to live farther from work. Preference heterogeneity implies that residents in different commuting time blocks will react differently to the introduction of congestion pricing.

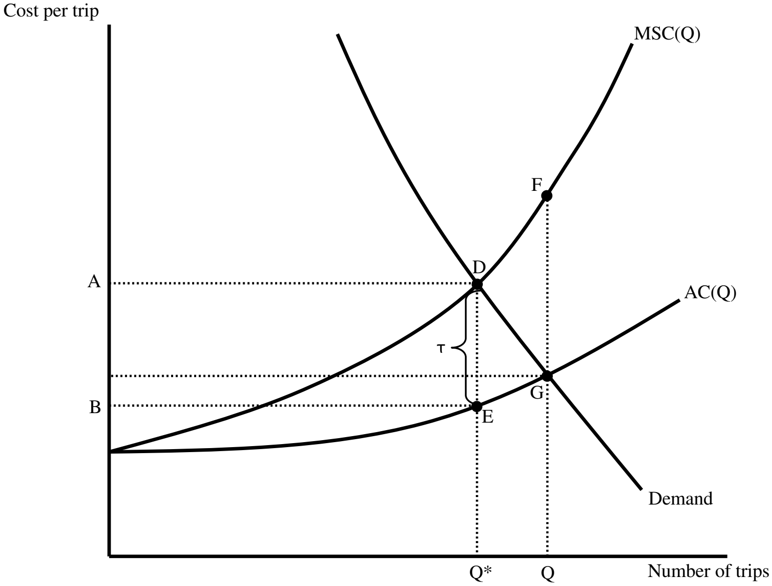
The dramatic change in the structure of home prices caused by road pricing is associated with a significant change in land use. Table 4 reports that cities would become much denser and that density would be somewhat more uniformly distributed across the urban area. The former result is consistent with conventional theory. Overall, road pricing has encouraged residents to move closer to places of employment, including city subcenters. In terms of figure 2, the change in land use has reduced the low-density, leap-frog development that characterizes urban sprawl by transforming low-density/high-entropy functions to high-density/high-entropy functions. In the process, residents' losses from road pricing because of lower housing values are mitigated to a certain extent by changes in land use that reduce the cost of sprawl.

Before presenting our empirical estimates of the welfare effects of road pricing that account for the changes in land use, we provide some perspective on why, in theory, the effects differ from those in previous analyses of road pricing that do not account for changes in land use. Figure 3, panel A reproduces the conventional diagram presented in Lindsey (2006). In this framework, the average cost (AC) of drivers' trips is less than the marginal social cost (MSC) of the trips because drivers do not pay for their contribution to congestion and delays. An optimal congestion toll, τ, reduces travel from its inefficient level, Q, to the optimal level Q*. In response to the toll, some motorists no longer use the road during peak periods while others continue to use the road and pay the toll. The loss to both groups is given by the area ADGEB. The toll raises revenue equal to ADEB. The toll also reduces but does not eliminate the social cost of delay; this gain is given by the area DFGE. Comparing the areas yields a welfare gain of FDG. That gain is also obtained as the integral of the marginal social cost minus the marginal social benefit of trips that would have been taken without congestion pricing but that are not taken after the toll is imposed. Note that the direct loss in consumer surplus is relatively large and exceeds the gain in revenues and that the welfare gain is small relative to the loss in consumer surplus and the gain in revenues.

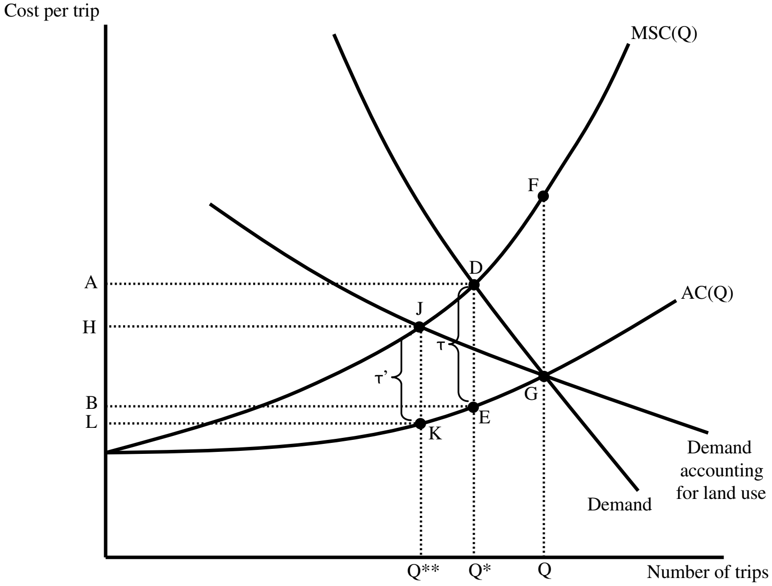
An important effect of accounting for changes in land use is that motorists' demand for travel will become more elastic because households have an additional response—namely, changing their residence—to the introduction of the toll. This is shown in figure 3, panel B by modifying the conventional diagram to include a more elastic demand curve that intersects the average cost curve

Figure 3. Welfare Effects of Congestion Pricing

A. Conventional diagram



B. Conventional diagram accounting for land use



at point G and yields the pre-toll equilibrium number of trips Q. The introduction of a congestion toll now generates a welfare gain, FGJ, which exceeds the original welfare gain and results in less redistribution. Note that consumer surplus losses, HJGKL, and revenue gains, HJKL, are smaller than they were without land use adjustments and that both the optimal toll τ', and the optimal quantity of trips, Q**, are smaller than the optimal toll and quantity of trips when housing locations are held fixed. However, the modified graph accounts only for changes in transportation costs and does not include the benefits from more efficient land use, which will further increase the welfare gain of the toll and reduce adverse redistribution.

The welfare effects of the changes induced by road pricing on residents and the government are shown in table 5. At the national level, the annualized value of owner-occupied housing declines $56.6 billion (2000 dollars). Because we do not know the value of renter-occupied housing, we assume that the annualized value of renter-occupied housing is equal to twelve times the monthly rent reported in the U.S. census. We then assume that the value of housing occupied by working renters declines at the same percentage as the value of housing occupied by working owners in the same commute time group. Thus, we find that the value of renter-occupied housing declines $18.6 billion (2000 dollars). Finally, as noted, we do not know where nonworking (that is, noncommuting) households live. But given that those households do not make peak-hour commutes, it is likely that they select residential locations where housing values are less affected by congestion tolling than the values of housing occupied by working households. So, for example, they tend to live in the two middle commute blocks instead of in the closest block. We therefore assume that annualized housing values for nonworking households decrease by half the percentage decrease of the housing values of working households, which results in an additional $3.5 billion loss in the annualized value of the housing stock.[38]

Thus, the reduction in the annual value of the entire housing stock from the introduction of road pricing is $78.7 billion. The loss in property tax revenue associated with the decline in the value of the housing stock is $0.9 billion, which raises the annual cost from road pricing to $79.6 billion. At the same time, toll revenues amount to $120.4 billion, indicating that implementing congestion pricing in the nation's congested metropolitan areas would yield an annual welfare gain of $40.8 billion (2000 dollars).[39]

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[38] As an upper bound, if we assume that these homes lose the same percentage as working households' homes lose, the loss to nonworking households is $7 billion. The additional loss does not alter our basic findings very much.

[39] Some plausibility checks on our estimates are as follows. In our sample, housing occupied by working owners accounts for more than $300 billion in annualized housing value and $56.6

Table 5. Annual Effect of Congestion Tolling

Billions of 2000 dollars

Costs and revenues	*Dollar change*
Costs	
Working households that own and occupy their housing	
Decrease in annualized housing value	56.6
Decrease in tax revenue	0.7
Working households that rent their housing	
Decrease in annualized housing value	18.6
Decrease in tax revenue:	0.2
All nonworking households	
Decrease in annualized housing value	3.5
Decrease in tax revenue	0.04
Total costs	79.6
Revenues	
Working households that own and occupy their housing	
Toll payments	63.6
Working households that rent their housing	
Toll payments	40.2
All nonworking households	
Toll payments	16.6
Total toll revenues	120.4
Annual social benefit	40.8

Source: Authors' calculations.

Consistent with the preceding theoretical discussion, our estimate of the net benefits of adopting road pricing nationwide is much greater than previous estimates that do not account for changes in land use. For example, based on estimates in Lee (1982), Small, Winston, and Evans (1989) reports that a nationwide policy of congestion pricing would yield annual revenues of $54 billion (1981 dollars) and, accounting for road users' out-of-pocket losses and travel time savings, an annual welfare gain of $6 billion (1981 dollars). Winston and Shirley (1998) estimates that the annual welfare gain from nationwide congestion pricing would amount to $3.2 billion (1990 dollars), but the authors' estimate includes the losses from additional transit subsidies generated by auto users who shift to bus or rail. (Our analysis does not account for how road pricing may

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billion in losses—or an 18.8 percent drop in annualized housing value—from congestion pricing. Turning to toll revenues, the cities in our sample have nearly 3 trillion annual vehicle miles traveled on freeways. Our analysis indicates that owner-occupied housing accounts for slightly more than half of total toll revenues and owners pay congestion tolls on approximately 1.2 trillion vehicle miles annually. Therefore, residents of all housing pay congestion tolls on 2.4 trillion vehicle miles annually, or 80 percent of freeway vehicle miles. Alternatively, the $120 billion in toll revenues that we estimate could account for less than 80 percent of freeway vehicle miles and some percentage of congested arterial miles.

Table 6. Results of Sensitivity Analysis[a]

Billions of 2000 dollars

VMT elasticity	**-0.3**	-0.3	-0.3	-0.5	-0.5	-0.5	-0.1	-0.1	-0.1
Density limit (percentile)	**0.9**	0.8	0.95	0.9	0.8	0.95	0.9	0.8	0.95
Working owner-occupiers									
Decrease in annualized home value	**56.6**	63.1	47.7	47.4	53.9	38.5	70.0	76.5	61.0
Decrease in tax revenue	**0.7**	0.8	0.6	0.6	0.7	0.5	0.8	0.9	0.7
Working renters									
Decrease in annualized home value	**18.6**	20.1	16.6	14.9	16.4	12.9	24.1	25.7	22.1
Decrease in tax revenue	**0.2**	0.2	0.2	0.2	0.2	0.1	0.3	0.3	0.2
Nonworkers									
Decrease in annualized home value	**3.5**	3.9	3.0	2.8	3.2	2.3	4.5	4.8	3.9
Decrease in tax revenue	**0.04**	0.04	0.03	0.03	0.04	0.03	0.05	0.05	0.04
Annual decrease									
Tax revenue	**0.94**	1.04	0.83	0.83	0.94	0.63	1.15	1.25	0.94
Home value	**78.7**	87.1	67.3	65.1	73.5	53.7	98.6	107.0	87.0
Total costs	**79.6**	88.1	68.1	65.9	74.4	54.3	99.8	108.3	87.9
Annual toll revenue	**120.4**	120.4	120.4	102.4	102.4	102.4	146.2	146.2	146.2
Annual social benefit	**40.8**	32.3	52.3	36.5	28.0	48.1	46.4	37.9	58.3

Source: Authors' calculations.

a. Base case results are in boldface type. Minor discrepancies are due to rounding.

affect transit finances.) As indicated in figure 3a, the welfare gains from congestion pricing in these studies are small relative to the redistributive effects.

To be sure, our welfare gain exceeds previous estimates partly because of the growth in traffic congestion during the past two decades. But as indicated by figure 3b and the discussion of additional benefits, our welfare gain is also greater because our model allows residents to change their residential location, which increases the net benefits of road pricing. Although the benefits from road pricing still entail considerable redistribution, they are so large that the government could retain a sizable amount of toll revenues to maintain and, where appropriate on cost-benefit grounds, to expand the road system and use part of the revenues to offset residents' losses by, for example, reducing property taxes or supplementing reduced tax revenues or both. Thus, in addition to reducing congestion, policymakers would have a stable long-term source of funding to prevent the nation's road system from deteriorating.

As noted, our simulations are based on certain assumptions. Table 6 shows the sensitivity of our findings to various assumptions about the elasticity of vehicle miles traveled with respect to congestion tolls and limits on the increase in density in our sample. We allow the elasticity of vehicle miles traveled to range from –0.1 to –0.5 and allow the density constraint of each city to range from the 80th percentile in the sample (the density of Milwaukee) to the 95th percentile in the sample (the density of Los Angeles) or 1.5 times the city's current density, whichever is greater. Even under the least favorable assumptions, congestion pricing generates an annual welfare gain of $28 billion.[40] Finally, it should be kept in mind that we have estimated an average congestion toll for each city that is used in the simulations. If we allowed congestion tolls to vary both by roadway and time of day, commuters would be charged more precisely for the marginal cost of their trips, which would increase the annual welfare gain from congestion pricing.

Qualifications and Discussion

Many authors who have written about road pricing have asserted that it may have important effects on land use. Almost independently, a literature has recently developed that suggests that sprawl causes significant social costs; however, it has rarely quantified those costs. Surprisingly, no one, to the best of our knowledge, has attempted to analyze empirically how road pricing might lower the costs of sprawl by improving land use.

We have applied a methodology to account for the effects of road pricing on land use and found that road pricing's net benefits are substantial, in part because of improvements in land use. Thus the government obtains an efficiently generated source of funding for the road system and is better able to address distributional concerns that have long been identified as a political obstacle to adopting road pricing. Note that certain renters would directly gain from the policy because lower housing prices would be reflected in lower rents. In the process, more affordable housing would be available for renters, whose incomes tend to be lower than those of homeowners.

Our findings should be qualified because certain households would incur lump-sum transaction costs from selling their homes and moving into existing

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[40] An additional area of sensitivity is the assumed value of time used to measure the unpriced congestion variable and the optimal tolls (and thus the toll revenues). We assumed an average value of time equal to half of the average wage. If we assumed a higher value, the net welfare gains would be larger. This direction would be justified because we do not account for the improvements in travel time reliability that would result from road pricing (Small, Winston, and Yan 2006). Of course, there is a *distribution* of the value of travel time that is likely to reveal differences in behavior within a given commute time group. However, the preceding conclusion based on the average value of time would still hold if our analysis were based on such a distribution.

or newly constructed housing.[41] At the same time, our findings are understated because although we assume in our simulations that households are able to move to locations within their own MSA, we assume that they are not able to take a different job in the MSA or relocate to a different MSA. Accounting for job and intercity mobility would enable households to optimize their response to road pricing even further. From a distributional perspective, road pricing is likely to cause congested cities to gain population and increase property values at the expense of less congested cities. But as pointed out in Winston and Langer (2006), the growth in delays during the past twenty years in the United States is to a notable extent accounted for by cities that experienced little congestion in the early 1980s but now experience measurable congestion. Hence, many small, low-density areas are likely to benefit in the future from adopting road pricing.

We also do not explicitly account for how the private sector would respond to and how it would be affected by road pricing.[42] Our revenue estimates do include higher out-of-pocket costs incurred by truckers, which are largely passed on to consumers. On the other hand, those losses are likely to be offset, because by reducing delays, congestion pricing reduces truckers' operating costs and enables firms to hold lower inventories—savings that in large part are passed on to consumers.[43]

Finally, we have indicated that the government could use the toll revenues to soften the distributional effects of road pricing. In addition, if part of the revenues was used to finance efficient infrastructure investments, such as expanding highway capacity in a dense corridor, another round of land use adjustments would result and produce additional welfare gains.[44] We also must acknowledge that like a notable share of recent transportation expenditures, the additional revenues generated by tolls could also result in wasteful spending.[45]

In the final analysis, we appear to obtain plausible benefits from improvements in land use caused by road pricing. For example, Burchell and others (1998) concluded that compared with "sprawling" development, "compact" development roadway infrastructure costs are 25 percent lower, utility costs are 20 percent lower, and school infrastructure costs are 5 percent lower. Such figures suggest that the annual cost savings from reduced infrastructure costs that are internalized in home prices could be substantial.

[41] The transaction costs are transfers to real estate agents, movers of household goods, and the construction industry.

[42] An issue that has arisen in London's road pricing experiment is its effect on retail sales. Quddus, Carmel, and Bell (2007) found that the congestion charge raised the sales for a specific store located in the priced zone but that it did not affect overall retail sales in central London.

[43] Shirley and Winston (2004).

[44] Deakin (1994).

[45] Winston (2006).

We also point out that by improving land use, road pricing may produce additional social benefits that we have not been able to quantify. First, increasing density and decreasing entropy could promote social interactions and strengthen the bonds that underpin a healthy society.[46] In particular, changes in land use could reduce the distance between poor and affluent residents and make it harder for the wealthy to ignore the problems of those less well off.[47] Recall that in response to congestion pricing, we found that households that live in the most expensive homes in an MSA (and in many cases, that have the highest incomes) move from homes in the central city and subcenters that are basically within walking distance of work to neighborhoods that are between 5 and 45 minutes from work, while households that live more than 45 minutes from work move to neighborhoods that are less than 45 minutes from work. Overall, the city will become denser, indicating that poor and rich people will be living closer together.

Second, reducing sprawl could enhance the protection of natural habitat at the urban boundary. Third, increasing density could encourage the use of vehicles that are more fuel efficient and that produce fewer emissions than vehicles used in less dense metropolitan environments.[48] Finally, reducing congestion and sprawl weakens the ostensible rationale for policymakers to use inefficient policies to address these problems, such as zoning laws,[49] urban growth boundaries,[50] transit-oriented development,[51] and various taxes and fees that are intended to raise money for transportation improvements.[52] Similarly, with the recent interest in reducing carbon emissions in the United States, congestion pricing would reduce vehicle miles traveled for most households, thus decreasing the nation's vehicle emissions of all pollutants. By efficiently raising the price, on average, of urban travel, policymakers could potentially reduce the size of any future carbon taxes that might inefficiently seek to tax travel instead of taxing carbon emissions directly. Hopefully, policymakers would be less inclined to pursue inefficient approaches.

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[46] Brueckner (2000).

[47] Kahn (2006).

[48] Fang (2006).

[49] Glaeser and Gyourko (2003).

[50] Anas and Rhee (2006); Brueckner (2007).

[51] Winston and Maheshri (2007).

[52] For example, Virginia lawmakers recently gave the Northern Virginia Transportation Authority the power to impose new taxes and increase existing vehicle registration and safety inspection fees with the expectation of raising some $325 million for roads and transit. More than half of the money will be accounted for by a "congestion relief fee," which is actually a real estate seller's tax of 40 cents per $100 of assessed valuation on the sale price of a house. The constitutionality of the new levies is currently being challenged before the Virginia Supreme Court.

If subsequent work confirms that road pricing's appeal extends far beyond congestion mitigation, then it would appear that the policy community has substantially underestimated pricing's social benefits and may have exaggerated its undesirable distributional features. Eventually, opposition to road pricing may wear thin.

APPENDIX

This appendix derives the measures of delay per mile and unpriced congestion. We use the Bureau of Public Roads (BPR) speed-flow curve,

$$\text{Congested speed} = \frac{FreeFlowSpeed}{1+.15*(V/C)^4},$$

where V is volume of traffic and C is capacity. We assume a free flow speed (FFS) of 60 miles per hour. Using this equation, delay per mile is equal to the inverse of congested speed (CS) minus free flow speed (FFS).

Unpriced congestion is the difference between the social marginal cost of delay and the average cost of delay. The average cost of delay (in dollars per mile) to a motorist is equal to the average value of travel time (in dollars per hour) times the delay per mile:

$$(1) \quad \text{Value of time} * \left(\frac{1}{CS} - \frac{1}{FFS}\right) = \text{Value of time} * \left(\frac{1+.15*(V/C)^4}{FFS} - \frac{1}{FFS}\right).$$

$$(2) \quad = \text{Value of time} * \left(\frac{.15*(V/C)^4}{FFS}\right).$$

Thus, the total cost of all driving on a given mile of road is

$$\text{Value of time} * \left(\frac{.15*(V/C)^4}{FFS}\right) * V = \text{Value of time} * \left(\frac{.15}{FFS*C^4}\right) * V^5.$$

The marginal cost of driving is

$$(3) \quad \frac{\partial TC}{\partial V} = MC = 5 * \left(\frac{ValueOfTime * .15}{FFS}\right) * \left(\frac{V}{C}\right)^4 .$$

Thus, the distortion from unpriced congestion is obtained by subtracting the average cost given in equation (2) from the marginal cost in equation (3) and plugging in FFS = 60:

$$\text{Distortion} = 4 * \left(\frac{ValueOfTime * .15}{60}\right) * \left(\frac{V}{C}\right)^4 = \text{Value of time} * .01 * \left(\frac{V}{C}\right)^4 .$$

Comment

Nathaniel Baum-Snow: Langer and Winston perform an impressively detailed analysis of the aggregate welfare implications of imposing optimal congestion pricing in all metropolitan areas throughout the United States. Their final estimate of about $40 billion per year is intuitively reasonable. In this comment, I argue that the estimate, while valuable, is probably fairly rough. To make my case, I first discuss the conditions under which the methodology used to arrive at the welfare estimate is reasonable. I then discuss the potential difficulties and distributional consequences associated with implementing a broad-based congestion pricing scheme such as the one that Langer and Winston claim would fully internalize congestion externalities.

The strategy employed by the authors to evaluate the costs of congestion includes two steps. First, they estimate from metropolitan area data a structural relationship between the spatial distribution of the population, housing prices by commuting time interval, and commuting delay due to congestion. They then impose adjustments to the cost of travel and travel speeds that represent changes from the current state of affairs to optimal congestion pricing in each metropolitan area. Finally, they calculate the implied toll revenues and change in housing values from their structural model, allowing them to recover an estimate of the social benefit of congestion pricing nationwide that takes into account endogenous changes in the spatial distribution of the population.

In order to assess the value of this approach, I examine the conditions under which a standard land use model would imply that the change in aggregate housing prices fully capitalizes the change in social welfare associated with congestion pricing. For the purpose of this comment, I primarily consider a simple monocentric city with a fixed residential lot size.

Consider a city on a strip of land that emanates in one direction from the work location and has width 1. There are N residents of the city who each earn a wage w and are constrained to consume one unit of land. The opportunity cost of land is R_a. Individuals have preferences only with respect to consumption. Therefore, we can represent money-metric utility as the dollar value of income net of rent and commuting cost. Commuting time per unit distance is given by $t(c)$, where c is the pecuniary congestion toll paid per unit distance. This function is decreasing and convex in c. Therefore, an individual living at location r has utility $w[1\text{-}t(c)r]\text{-}cr\text{-}R(r)$, where $R(r)$ is R_a at the urban fringe (location N) and $R_a+N[wt(c)+c]$ at the work location.

Given this very simple environment, some basic geometry shows that aggregate rent in the city is given by the following expression:

$$H = NR_a + \frac{1}{2}N^2[wt(c)+c]. \tag{1}$$

Similarly, equilibrium utility in the city is given by the following expression:

$$U = w - N[wt(c)+c] - R_a. \tag{2}$$

It is evident that the same optimal level of congestion toll per mile traveled that maximizes utility also *minimizes* aggregate housing values. The intuition for this result is that as travel speeds increase, there remains less competition to live near the work location, driving down land prices. Indeed, in the extreme case of 0 commuting costs and no congestion toll, aggregate housing value in the city would be NR_a while utility would be $w - R_a$.

Implementing the utility-maximizing congestion toll of

$$c^* = t'^{-1}(-\frac{1}{w}),$$

we can see the implications for welfare. The total amount in tolls collected is

$$\frac{1}{2}N^2c^*.$$

The change in aggregate rent totals

$$\frac{1}{2}N^2[wt(c^*) - wt(0) + c^*],$$

an expression that is negative. Finally, the utility change, which in this case equals aggregate willingness to pay, for renters who do not receive a congestion charge rebate totals $N^2[wt(0) - wt(c^*) - c^*]$ and is greater than 0. Renters are better off with the congestion charge because they face lower rental costs and shorter commutes. They are willing to pay the congestion charge to facilitate those gains.

Imposition of the congestion charge generates three sources of welfare change: aggregate utility, rent, and collected tolls. If landlords are absentee and the congestion tolls are not rebated back in lump sum, the aggregate reduction in land values equals exactly half the willingness to pay for the congestion charge. If, however, all rent changes and congestion charges are paid back to residents, the total willingness to pay for the new regime is the absolute value of the decline in rent plus the aggregate toll paid. Langer and Winston calculate the aggregate welfare benefit as the change in rent plus the congestion charge. Therefore, this simple analysis implies that they understate the true welfare gain implied by the simplest model. Increased commuting speed leads to both a decline in competition for central space and a pure income effect.

The set of calculations done above is based on a very simple model that does not capture reality in many ways. Indeed, Langer and Winston take seriously the possibility that land use patterns may adjust endogenously in response to changing travel speeds. Such an adjustment would only loosen the connection between aggregate rent decreases and welfare improvements since it implies an increase in equilibrium utility and aggregate rent over the case in which lot size is fixed.

It is not hard to see how adding wage heterogeneity into the simpler model would lead us to more complicated conclusions than those exacted above. The fact that the poor have a low value of commuting time means that they are willing to pay less for a reduction in commuting time than the rich. Those with the highest value of time and lowest utility value of money are the ones for whom congestion pricing is most onerous.

To develop this point, suppose that we have a city with αN high-income and $(1-\alpha)N$ low-income individuals with wages w_H and w_L respectively. Fixed lot size implies that the high income individuals outbid the others to live closer to the work location.[1] The equilibrium rent function in this city is kinked at work location distances αN and N. Under this scenario, it is clear that the optimal congestion charge is different for each income group. Assuming that no price discrimination is possible, it is a straightforward process to derive the utility of both groups:

$$\begin{aligned} U_H &= w_H - Nt(c^*)[(1-\alpha)w_L + \alpha w_H] - Nc^* - R_a \\ U_L &= w_L[1 - Nt(c^*)] - Nc^* - R_a \end{aligned} \tag{3}$$

From these expressions, it is clear that the poor group could actually be worse off with the socially optimal congestion toll without price discrimination, even if the poor group consists only of renters.

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[1] This location pattern is not what is seen in the data. It is beyond the scope of this comment to formulate a model that matches that pattern. All of the main ideas come through regardless.

An additional theoretical issue that is not addressed by Winston and Langer is the potential for migration between metropolitan areas. Indeed, if N were endogenous, congestion pricing would need to be implemented in all cities at once and result in the same uncongested level of utility for the calculation in the paper to have a meaningful interpretation. Absent such coordination, endogenous migration would serve to mitigate the welfare benefits of congestion pricing.

There are three broad lessons in my brief theoretical treatment. First, the analysis of the imposition of a congestion charge on a particular roadway analyzed in partial equilibrium using standard tools does not easily generalize to the general equilibrium case. Second, it matters very much for the analysis who the landowners are and who receives the congestion toll. (The most cynical may assume that the majority of this money is wasted by the government.) Finally, incidence is very important. While in theory there may be way to implement lump-sum transfers across income groups so as to achieve Pareto improvements, that may in practice be quite difficult because of the considerable amount of distortion that it would entail.

To recover the change in aggregate housing values that would occur with congestion pricing, Langer and Winston require estimates from a system of structural equations with endogenous house prices, land use, and travel speeds. They use those estimates to simulate house prices once congestion pricing is implemented. In order to identify causal relationships in this system of equations, some exclusion restrictions are required. Langer and Winston include the percent of homes in the MSA with a cellar and the percent with missing roof tiles in the housing equations but not in the land use or travel time equations. Ideally, one would want these variables to provide random variation in housing prices that could be leveraged to recover causal relationships between them and the remaining variables in the structural system. Short of that ambitious goal, the identifying assumptions for causal inference are that there are no unobservables correlated with the variables that themselves influence housing prices, conditional on controls, and that these house-quality variables and their unobserved correlates do not belong in either of the other two equations.

While the estimation results are plausible and intuitive, it is not clear whether these identifying assumptions have been fully satisfied. MSAs containing many houses without a cellar or with missing roof tiles are probably on the decline relative to others. Therefore, those MSAs may be poorer or have lower expected housing prices for that reason. Unobservables correlated with these features of the housing stock may belong in the density and travel equations. The fact that the estimated parameters of the structural system look reasonable, however, gives credence to the authors' claim that these housing variables are validly excluded from the land use and travel time equations.

Understanding the full welfare effects of congestion pricing is a valuable exercise. Langer and Winston deserve considerable credit for their ambitious and extensive analysis. While the identification issues confronted by the authors are difficult, they are able to recover intuitively plausible estimates of the structural relationships between housing values, land use, and commuting speeds. For many reasons, the resulting estimate of the social value of congestion pricing should be viewed as rough. Nevertheless, this study provides us with a valuable starting point for further investigation into this important topic.

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