Do HOV Lanes Save Energy? Evidence from a General Equilibrium Model of the City

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Abstract

High-occupancy vehicle (HOV) lanes have been promoted to encourage carpools, reduce traffic congestion, save energy, and improve air quality. At the partial equilibrium level, commuting with three workers per automobile clearly uses less energy and reduces highway congestion compared to three single drivers. This paper develops a numerical urban simulation model to generate the general equilibrium effects of HOV lanes on urban spatial structure, energy use, and greenhouse gas emissions. The major findings are that HOV lanes reduce the cost of long distance commuting and lower commuting energy consumption. However, the reduction in transportation costs induces urban sprawl, which results in higher dwelling and numeraire good energy consumption. Overall, the introduction of HOV lanes has little effect on total energy consumption. This is another classic case of general equilibrium effects reversing the partial equilibrium effects of an urban policy. In contrast, an alternative policy that imposing congestion tolls is more effective in reducing energy consumption and preventing urban sprawl.

JEL Codes: R14, R21, R31, R40, R48

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1 Introduction

Traffic congestion is a serious problem in many urban areas because it lengthens travel time, increases energy consumption, and worsens air quality. To reduce traffic congestion and air pollution, policy makers have implemented several strategies. One popular policy tool is the implementation of high-occupancy vehicle (HOV) lanes. An HOV lane is reserved for the exclusive use of certain vehicles, including carpools, vanpools, and transit buses. The minimum occupancy level is 2 or 3 occupants. The implementation of HOV lanes began in the early 1970s. The Clean Air Act Amendments of 1990 included HOV lanes as a measure to improve air quality. In the United States, over 2,500 lane-miles of HOV lanes have been built and over 130 HOV facilities have been implemented in more than 27 metro areas. The popularity of HOV lanes is based on the belief that they encourage carpooling, thus relieving traffic congestion in general purpose lanes and reducing automobile emissions. However, these are only short term direct effects of HOV lanes.

Although HOV lanes have been evaluated by government agencies as effective in reducing traffic congestion and improving air quality, this has been based on partial equilibrium analysis. This paper derives the long run general equilibrium effects of HOV lanes on urban spatial structure, energy use, and greenhouse gas (GHG) emissions . These effects are twofold: first, after the HOV lane is introduced, workers living further away from the city center shift from using low to high occupancy vehicles to save commuting costs. By carpooling, workers can share gasoline costs and maintenance costs of the car. All workers save commuting time because the traffic volume in both the HOV lane and the general purpose lane will be reduced. Second, the fall in transportation costs for both HOV lane users and general purpose lane users reduces workers incentives to live near the Central Business District (CBD), thus causing urban sprawl. This sprawl effect of HOV lanes lowers structure density while increasing housing consumption and the length of the average commute. These indirect, general equilibrium effects increase energy consumption and greenhouse gas emissions.

Thus far, there is no literature studying the long run general equilibrium effects of HOV lanes. Current research focuses on the short term partial equilibrium effects. Hanna et al. (2017) show that HOV policies can be effective in the short run in relieving traffic congestion using data from the unexpected lifting of Jakartas HOV policy. There is no consensus regarding the effects of HOV lanes on congestion, air quality, and welfare in the literature. Boriboonsomsin and Barth (2007) find that HOV lanes are effective in reducing vehicle emissions, while Johnston and Ceerla (1996) report that new HOV lanes have little emission reduction benefit. These studies on HOV lanes focus on the commuting behavior of households without taking into account changes in household location and consumption after HOV lanes are created. The short run partial equilibrium analysis may overestimate or underestimate the energy and environmental effects of HOV lanes, potentially misleading policy makers.

This paper is the first to study the long run general equilibrium effects by taking into account the effects of HOV lanes on households location decisions and consumption behaviors. Based on the standard urban model of Alonso et al. (1964), Mills (1967), and Muth (1969), this paper develops a general equilibrium model of land use, the housing market, and commuting with endogenous congestion. This model generates predictions regarding the effects of HOV lanes on urban spatial structure, energy consumption, and GHG emissions. The model is calibrated and simulated numerically to show the long run general equilibrium effects of HOV lanes following Muth (1975), Altmann and DeSalvo (1981), Sullivan (1985), Bertaud and Brueckner (2005), and Rappaport (2014).

This numerical simulation approach enables counter-factual experimentation and is able to generate rich insights that are thus far prohibitively difficult to test empirically. The long run treatment effect of HOV lanes is difficult to identify using empirical methods for several reasons. First, the adoption of HOV lanes is endogeneous. Larger cities with severe traffic congestion problems are more likely to adopt HOV policies. In addition, the adjustment of housing markets and commuting patterns over time is based on many factors other than the number of HOV lanes, raising the likelihood that empirical tests would suffer from omitted variable bias.

Simulation results show that HOV lanes encourage carpooling, cause urban sprawl, and have little effect on energy consumption and GHG emissions. Households living farther away from the city center choose to carpool to use HOV lanes to save commuting costs and time while those living closer continue to use general purpose lanes. After HOV lanes are created, households increase housing consumption and move farther away from the city center, which leads to urban sprawl. HOV lanes are indeed effective in relieving traffic congestion and lowering commuting time by reducing the number of cars on the road. Even though cars travel a longer distance due to urban sprawl, commuting energy consumption falls. Due to the lower transportation cost, housing and numeriare good consumption increases, causing both dwelling and numeraire good energy consumption to rise. Overall, the conversion of general purpose lanes to HOV lanes has little effect on total energy consumption and GHG emissions. The comparison between the general equilibrium analysis and the partial equilibrium analysis suggests that the partial equilibrium estimation overestimates the effects of HOV lanes on traffic congestion, energy consumption, and GHG emissions.

A policy alternative to combat traffic congestion and poor air quality is imposing congestion tolls. The comparison between these two policy alternatives is highly relevant because they are substitutes. The simulation shows that imposing congestion tolls is more effective in preventing urban sprawl and saving energy.

The remainder of the paper is organized as follows. Section 2 describes the theoretical framework and solution method in detail. Section 3 discusses the parameter calibration and the simulation of the model. Section 4 presents the simulation results of several counterfactual scenarios. Section 5 concludes the paper.

2 Model Structure

The model framework in this paper closely follows the urban energy footprint model developed by Larson, Liu, and Yezer (2012). In the urban energy footprint model, the commuting and dwelling energy consumption can be derived based on the simulation output of the standard urban model of Alonso et al. (1964), Mills (1967), and Muth (1969). It provides a general framework that can be used to investigate the energy implications of different public policies. For example, Larson and Yezer (2015) develop an open city version of the urban energy footprint model to explore the energy implications of city size. Larson and Zhao (2017) incorporate telework into the standard urban model to investigate the long run effects of teleworking on urban form, energy use, and carbon emissions. Adopting a similar approach, this paper incorporates HOV lanes into the standard urban model to address the long term effects of an HOV lane policy on the city, energy use, and GHG emissions.

2.1 The Standard Urban Model with HOV Lanes

The city is monocentric and lies on a featureless plane without geological constraints and housing regulations. Firms are located in the city center, the Central Business District (CBD), and pay the same wage rate to identical workers. Workers, who commute to the CBD to work every day, reside between the CBD edge and city edge. Beyond the city edge is agricultural land, which determines the reservation land rent at the city boundary. Land and housing prices vary across locations so that households are indifferent across all locations within the city. Housing producers use land and structure inputs to maximize profit and receive zero economic profit at every location inside the city. The city is radial and uniform at each radius.

HOV lanes are incorporated in this model by assuming that a fraction of highway capacity is allocated to HOV lanes.

Housing Production

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

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

where H is housing production, S is structure inputs that are perfectly elastically supplied, and L is land inputs.

Households

Homogeneous households consume housing and a composite commodity to maximize a CES utility function:

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

where h is housing consumption, y represents numeraire good consumption, β_1 and β_2 are consumption share parameters, and $1/(1-\eta)$ represents the constant elasticity of substitution between housing and the numeraire good. For households living at distance k from the city center, income, w, is spent on the numeraire good, $y(k)$, housing, $r(k)h(k)$, and transportation, $T(k)$. Housing expenditure depends on housing rental price $r(k)$ and housing size $h(k)$. The price of y is normalized to unity.

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

Households' utility is identical at each distance, k, from the the CBD.

The total number of households in the city is N,

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

where $D(k)$ is the households density, θ is the fraction of land devoted to housing, k_{CBD} is the CBD edge, and $\bar{k}$ is the outer extend of the city.

Land Used for Highways

In each annulus, a constant fraction of land area, $R(k)$, is allocated to highway. The fraction of highway capacity used for HOV lanes is ψ. Therefore, the highway capacity allocated to HOV lanes is $\psi R(k)$ and the highway capacity allocated to general purpose lanes is $(1-\psi)R(k)$.

Cost of Commuting Using General Purpose Lanes

Workers commute to the CBD via automobile through general purpose lanes. Annual transportation costs for a household living at radius k using general purpose lanes is the sum of the following: fixed costs of owning and operating an automobile m_0 (e.g. insurance, licensing), costs proportional to distance traveled (e.g. vehicle depreciation, maintenance) m_1, gasoline costs, and time cost of commuting. The gasoline cost is determined by the fuel efficiency of the car G and the price per gallon p_g. The time-cost of commuting depends on the travel time and the value of time as a fraction, τ , of the wage rate, W . The gasoline consumption per mile G^{-1} depends on vehicle velocity, V. The velocity is determined jointly by the number of commuters using general purpose lanes and the general purpose lane capacity. Taken together, the total commuting cost is given by:

$$T_{GP}(k) = m_0 + \left[m_1 k + p_g \int_{k_{CBD}}^{k} \frac{1}{G(V(M_{gp}(\kappa)))} d\kappa + \tau W \int_{k_{CBD}}^{k} \frac{1}{V(M_{gp}(\kappa))} d\kappa \right] \tag{5}$$

Both fuel and commuting time are related to the velocity of the automobile at various locations in the city. The velocity is a function of the ratio of traffic volume to roads. Following Bureau of Public Roads specification, the function of velocity is

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

where $M_{gp}(k) = \overrightarrow{N_{pg}}(k)/(\psi R(k))$. $N_{pg}(k)$ represents the number of commuters using general purpose lanes and $\psi R(k)$ represents the general purpose lane capacity. a, b, and c are congestion parameters.

Cost of Commuting for HOV Lane Users

If workers decide to carpool to use HOV lanes, each car has to meet the minimum occupancy level. It is assumed that each carpool using HOV lanes has n riders. By carpooling, variable costs and gasoline costs are shared among riders. As a result, variable costs related to distance traveled become m_1/n per rider and shared price per gallon is lowered to p_g/n. However, in order to carpool, drivers have to pick up and drop off carpoolers. This incurs an extra time cost of carpooling for each rider. It is assumed that carpooling coordination time is $t_{carpool}$, and thus the time cost of carpooling is $t_{carpool} * \tau * W$. The total commuting cost is

$$T_{HOV}(k) = m_0 + t_{carpool} * \tau * W + \left[(m_1/n)k + (p_g/n) \int_{k_{CBD}}^{k} \frac{1}{G(V(M_{hov}(\kappa)))} d\kappa + \tau W \int_{k_{CBD}}^{k} \frac{1}{V(M_{hov}(\kappa))} d\kappa \right] \tag{7}$$

HOV lane users have the option to switch lanes. If the speed on general purpose lanes is higher, carpoolers will use general purpose lanes. As general purpose lanes get congested, carpoolers will switch back to HOV lanes.

Velocity depends on the number of workers using HOV lanes and the road capacity for HOV lane users.

$$V(k) = \frac{1}{a + bM_{hov}(k)^c} \tag{8}$$

where $M_{hov}(k) = \overrightarrow{N_{hov}}(k)/R_{hov}(k)$. $R_{hov}(k)$ is the road capacity for HOV lane users in each annulus. $\overrightarrow{N_{hov}}(k)$ is the number of cars using HOV lanes.

HOV Lane Usage Decision

HOV lanes help workers to save monetary commuting costs and the time cost due to cost sharing and lower traffic congestion as a result of carpooling. However, carpooling incurs an additional time cost of coordination. The decision about whether to use HOV lanes depends on whether the commuting cost saving outweighs the additional incurred carpooling cost. The variable costs, gasoline costs, and the time cost of commuting increase with the driving distance, therefore the commuting cost saving through carpooling rises with the distance from the CBD. As a result, the commuting cost saving is greater than the incurred carpooling cost for workers living farther away from the CBD. Thus workers living farther away from the city center will choose to carpool to use HOV lanes. Workers living closer to the CBD will choose to use general purpose lanes because the commuting cost saving through carpooling is low and outweighed by the incurred carpooling cost.

Figure 1 shows the simulation of commuting costs for using HOV lanes and general purpose lanes respectively. The commuting cost using HOV lanes is higher than that using general purpose lanes for workers living closer to the CBD. For workers who live farther away from the city center, the commuting cost using HOV lanes is lower. The intersection of the two commuting cost curves is the HOV lane boundary k_{hov} where the commuting cost saving using HOV lanes is offset by the incurred carpooling cost, that is, the commuting cost using HOV lanes is the same as that using general purpose lanes. Within the boundary k_{hov} , where workers live between the CBD edge and the boundary k_{hov}, workers will choose to use general purpose lanes, while workers who live between the boundary k_{hov} and the city edge $\bar{k}$ will choose to use HOV lanes.

Therefore, workers using general purpose lanes are those living within the boundary k_{hov}:

$$TN_{pg} = \int_{k_{CBD}}^{k_{hov}} 2\pi\theta k D(\kappa) d\kappa \tag{9}$$

The traffic volume using general purpose lanes at radius k, $N_{pg}(k)$, is

$$\overrightarrow{N_{gp}}(k) = TN_{pg} - \int_{k_{CBD}}^{k} 2\pi\theta k D(\kappa) d\kappa \tag{10}$$

where the second term is the number of workers living inside radius k.

The traffic volume using HOV lanes at radius k, $\overrightarrow{N_{hov}}(k)$, is

$$\overrightarrow{N_{hov}}(k) = (N - \int_{k_{CBD}}^{k} 2\pi\theta k D(\kappa) d\kappa)/n \tag{11}$$

2.2 Model Solution

The solution method is based on Muth (1975), Altmann and DeSalvo (1981), and McDonald (2009). Two simultaneous nonlinear differential equations with initial values are derived from the model for both general purpose lane users and HOV lane users.

The two-equation system of nonlinear differential equations for general purpose lane users includes marginal commuting costs and the household density at radius k.

$$\begin{bmatrix} \frac{dT(k)}{dk} \\ \frac{dN(k)}{dk} \end{bmatrix} = \begin{bmatrix} \left[(m_1 + p_g \frac{1}{G(V(M_{gp}(k)))} + \tau w \frac{1}{V(M_{gp}(k))})\right] \\ 2\pi\theta k D(T(k)) \end{bmatrix} \tag{12}$$

with initial values

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

The two-equation system of nonlinear differential equations for HOV lane users is:

$$\begin{bmatrix} \frac{dT(k)}{dk} \\ \frac{dN(k)}{dk} \end{bmatrix} = \begin{bmatrix} \left[(m_1/n + (p_g/n)\frac{1}{G(V(M_{hov}(k)))} + \tau w \frac{1}{V(M_{hov}(k))})\right] \\ 2\pi\theta k D(T(k)) \end{bmatrix} \tag{13}$$

with initial values

$$\begin{bmatrix} T(k_{hov}) \\ N(k_{hov}) \end{bmatrix} = \begin{bmatrix} m_0 + m_1 k_{hov} + p_g \int_{k_{CBD}}^{k_{hov}} \frac{1}{G(V(M_{gp}(\kappa)))} d\kappa + \tau W \int_{k_{CBD}}^{k_{hov}} \frac{1}{V(M_{gp}(\kappa))} d\kappa \\ \int_{k_{CBD}}^{k_{hov}} 2\pi\theta k D(\kappa) d\kappa \end{bmatrix}$$

After solving this system numerically, housing prices, land prices, housing demand, lot size, and structure/land ratios are solved as a function of commuting costs and housing density.

In order to achieve the locational equilibrium, two conditions must be met. First, the land price at the edge of the city must be equal to the agricultural land rent $p_L(\bar{k}) = p_L^a$. Second, the total population must fit inside the city. If either of these equilibrium conditions is not met, the simulation will be re-initialized and simulated until subsequent iterations achieve an equilibrium solution.

3 Calibration and Simulation

3.1 Parameter calibration

Parameter calibration is performed following the literature on numerical urban simulations. In order to be consistent with model assumptions, four cities including Charlotte, Indianapolis, Kansas City, and San Antonio are selected to provide calibration target values. These four cities have low land use regulation based on the Wharton Residential Land Use Regulatory Index (WRLURI; Gyourko, Saiz, and Summers, 2008) and low topographical constraints with over 90% of area topographically available for development. The calibration is evaluated by comparing simulation outputs with the average characteristics of the four cities. Table 1 shows the parameter values selected for the calibration.

Table 2 compares the simulation output with the average characteristics of the four cities.

Overall, the simulated baseline city matches the average characteristics of the four cities well. The simulated average lot size, 0.16 acre, is lower than the average lot size of the four cities, 0.28 acre. This is because the lot size data for higher density units such as multifamily units are missing in the American Housing Survey. The simulated city radius, 9.91 miles, is slightly lower than the average radius of the four cities, 12.2 miles. This is due to the fact that simulations with one household type tend to produce cities with a smaller land area than those in the real world.

The solid line in Figure 2 displays the simulated urban form pattern. Housing prices, land prices, household density, structure land ratio, and traffic volume decrease with the distance from the CBD, while housing demand, lot size, velocity, and commuting time increase with the distance from the city center. These simulation results are consistent with past simulations in the literature.

3.2 Simulating Energy Demand and Greenhouse Gas Emissions

The simulation method for computing energy consumption and GHG emissions follows Larson, Liu, and Yezer (2012) and Larson and Zhao (2017). Energy consumption and GHG emissions are calculated based on the simulation outputs on expenditures, housing consumption, and commuting behavior. Total energy consumption, $E(k)$, is categorized into three types: commuting energy, $E^C(k)$, dwelling energy, $E^D(k)$, and numeraire good energy, $E^N(k)$. Commuting energy consumption is based on gasoline consumption, dwelling energy consumption is based on electricity consumption in dwellings, and numeraire energy consumption embodies the energy consumption from all other goods consumption. Energy is measured in terms of British thermal units (BTUs).

$$E(k) = E^C(k) + E^D(k) + E^N(k) \tag{14}$$

The gasoline consumption while commuting is estimated by the following equation according to Larson, Liu, and Yezer (2012).

$$G(V(k)) = .822 + 1.833V(k) - .0486V(k)^2 + .000651V(k)^3 - .00000372V(k)^4 \tag{15}$$

This 4th degree polynomial function gives an appropriate representation of commuting fuel use in the simulation.

Energy used in commuting through general purpose lanes is given by

$$E_{pg}^{C}(k) = E_g \int_{k_{CBD}}^{k} \frac{1}{G(V(M_{pg}(\kappa)))} d\kappa \tag{16}$$

where E_g is the energy embodied in a gallon of gasoline in BTUs. Based on the data published by the Energy Information Administration, the total energy embodied in 1 gallon of gasoline is $150,602$ BTUs. Thus, $E_g = 150,602$.

Energy used in commuting through HOV lanes is given by

$$E_{hov}^{C}(k) = (E_g \int_{k_{CBD}}^{k} \frac{1}{G(V(M_{hov}(\kappa)))} d\kappa)/n \tag{17}$$

The numerator represents the commuting energy consumption per car. Given that each car has n commuters, each commuter using HOV lanes consumes $1/n$ fraction of the commuting energy per car. This demonstrates that HOV lanes effectively reduce the commuting energy consumption per commuter who carpools. The total commuting energy consumption is

$$E^{C}(k) = E_{pg}^{C}(k) + E_{hov}^{C}(k) \tag{18}$$

The equation for estimating dwelling energy consumption is borrowed from Larson, Liu, and Yezer (2012). There are three major factors determining dwelling energy consumption: the income of the household, the square feet of interior space, and the structure type. The structure type is determined by the floor area ratio, which is the ratio of housing square footage over lot size, denoted $q = H/L$. The critical value of q for each structure type is borrowed from Larson and Zhao (2017). The structure type is single-family detached if $q \in [0, 0.6]$, single-family attached if $q \in (0.6, 0.7]$ 2-4 unit multifamily if $q \in (0.7, 0.8]$ and 5+ unit multifamily when q is above 0.8. In order to simplify the calculation, it is assumed that all energy consumed in the dwelling is from electricity. Each kilowatt hour of electricity consists of $3,412$ BTUs of energy. After taking into account the energy embodied in production and distribution of electricity, the electricity efficiency parameter E_e is 0.303. (Federal Register, 2000).

Therefore, the function for dwelling electricity demand is

$$E^{D}(k) = E_e \exp\left[\gamma_1 + \gamma_2 \ln w + \gamma_3 \ln p_e + \gamma_4 \ln h(k) + s(q(k))'\Gamma\right] \tag{19}$$

where p_e is the price of electricity.

The numeraire energy consumption is estimated using the following equation:

$$E^N(k) = E_N \left(w - p_g E^C(k)/E_g - p_e E^D(k)/E_e\right) \tag{20}$$

where E_N is the the energy embodied in \$1 of numeraire good consumption, which is set at 7,470 BTUs (Energy Information Administration, 2011).

The solid line in Figure 3 displays the energy consumption for the baseline city. Dwelling energy consumption increases with the distance from the CBD because households live in larger houses as they move farther away from the city center. The jumps in this gradient are due to structure type changes based on floor area ratios. As the distance from the city center increases, the structure type changes from large multifamily (5+ units), to small multifamily (2-4 units), to single-family structures. The energy efficiency of housing falls with structure density. However, commuting energy consumption increases with commuting distance. As households live farther away from the CBD, they spend more of their incomes on housing and commuting. Therefore, numeraire good consumption falls with the distance from the CBD and thus numeraire energy consumption falls with the distance from the city center. Overall, the total energy consumption rises with the distance from the CBD.

GHG emissions are calculated based on three different types of energy consumption. Each type of energy consumption is multiplied by a carbon dioxide (CO_2) emissions coefficient reported by the Energy Information Administration. CO_2 is the only greenhouse gas considered because other greenhouse gases including methane (CH_4), hydrofluorocarbons, and nitrous oxide (N_2O) account for less than 5% of all greenhouse gas emissions from gasoline consumption and electricity generation.

According to the data from the Energy Information Administration in 2016, the combustion of one gallon of gasoline results in 157 pounds of CO_2 per million BTUs. The weighted average of CO_2 emissions for electricity generation is 115 pounds of CO_2 per million BTUs. It is assumed that the CO_2 emissions coefficient for numeraire energy consumption is the same as that for dwelling energy consumption.

4 Results

After the model is calibrated, various counter-factual experiments are performed by altering model parameters. Scenarios are designed to uncover general equilibrium effects of HOV lanes. In general, a comparison of general equilibrium effects with partial equilibrium effects demonstrates the importance of taking into account long term effects when imposing policy change. The ineffectiveness of HOV lanes in saving energy is further demonstrated by increasing the fraction of highway capacity allocated to HOV lanes. The comparison between the HOV lane policy and the optimal congestion toll policy suggests that imposing congestion tolls is more effective in preventing urban sprawl and saving energy. These scenarios provide rich predictions regarding the commuting, urban form, energy, and environmental effects of HOV lanes.

4.1 General Equilibrium Effects of Creating HOV Lanes

In the baseline, it is assumed that all road capacity is used for general purpose. The city with HOV lanes is simulated by allocating 15% of highway capacity for HOV. It is assumed that in order to use HOV lanes, the minimum occupancy level is three. Each carpool using HOV lanes has three riders. On average, the extra time spent in coordinating carpooling is 10 minutes in each round trip. The general equilibrium effects of creating HOV lanes are readily observable in Figure 2 and Figure 3. The direct effect is that workers living farther away from the CBD shift from solo driving to carpooling, which reduces the number of cars on the road and relieves traffic congestion. However, the fall in transportation costs causes a rotation of the house price gradient and reduces households incentive to live closer to the city center, which lowers housing density and leads to urban sprawl.

Table 3 shows that 33% of households choose to use HOV lanes. These HOV lane users live at least 6.45 miles away from the city center. After HOV lanes are created, the city radius increases from 9.9 miles to 11.48 miles. This provides strong evidence for the sprawl effect of HOV lanes. Households at every distance from the city center increase housing consumption and on average, the housing size increases by 40 square feet of interior space (2.71%). The city becomes less dense as structure density decreases almost everywhere in the city. The floor area ratio at the CBD edge falls by 16.8%, the fraction of 5+ housing unit structures decreases by 33%, and the share of single family, detached units increases by 18%.

The creation of HOV lanes does relieve traffic congestion. Figure 2 shows that after HOV lanes are created, the commuting time is reduced for every commuter. On average, the commute time is reduced by 4.3 minutes (17%).

These effects combined increase dwelling energy consumption by 3.3%, decrease commuting energy consumption by 36%, and increase numeraire energy consumption by 0.27%. From Figure 3, after HOV lanes are introduced, the commuting energy consumption especially for households using HOV lanes has dramatically decreased. This is not only due to reduced traffic congestion but also due to the fact that households who use HOV lanes only consume one third of the gasoline per car through carpooling. However, both dwelling and numeraire energy consumption have increased because by saving commuting costs, households spend more on housing and other goods. The surprising results, after taking into account the households' long term location change and housing consumption change, are that HOV lanes have little effect on energy consumption. The total energy consumption is reduced by only 0.65% after HOV lanes are implemented.

CO_2 emissions from gasoline are reduced by 36% after HOV lanes are imposed due to gasoline sharing and relieved traffic congestions. However, carbon emissions from electricity increase by 1.24% due to the increase in the consumption of housing and other goods. In total, carbon emissions per household are reduced by 1.24%.

4.2 Comparison of Partial Equilibrium Effects with General Equilibrium Effects of Eliminating HOV Lanes

HOV lanes are believed to relieve congestion, reduce energy use, and lower carbon emissions. However, this belief is too simplistically based on the partial equilibrium effects and implicitly assumes that households location decisions and consumption behaviors do not change in response to policy changes.

To demonstrate the importance of conducting a general equilibrium analysis and that the partial equilibrium analysis overestimates the effects of eliminating HOV lanes, simulations are conducted to compare general equilibrium effects with partial equilibrium effects of lifting HOV lanes.

Partial equilibrium effects are simulated by holding housing consumptions and location decisions constant after the HOV lane policy is lifted. After the HOV policy is eliminated, households lose incentives to carpool. As a result, more cars are on the road, which worsens traffic conditions. In the short run, households do not change their location decisions and housing consumptions in response to the change in the HOV policy. Table 4 shows that after the HOV policy is lifted, commuting is delayed by 33%, commuting energy consumption increases by 70%, total energy consumption rises by 1.8%, and carbon emissions increases by 2.55%.

In contrast, in the long run, households move closer to the CBD to save commuting cost, reduce housing consumption, and consume less numeriare goods in response to the lift of the HOV policy. As a result, under the general equilibrium context, commuting is delayed by 27%, commuting energy is increased by 56.7%, and dwelling energy consumption is reduced by 3.2%. Overall, lifting HOV lanes has little effect on energy consumption.

The comparison shows that lifting the HOV policy has negative effects on traffic congestion and causes delay in commuting. However, these effects are overestimated under the partial equilibrium analysis.

Table 4 captures the interesting phenomenon that under the general equilibrium context, eliminating HOV lanes makes the city smaller and denser which leads to a lower dwelling energy consumption, while under the partial equilibrium context, the change in the HOV policy has no effect on the urban spatial structure and dwelling energy consumption.

The comparison demonstrates that the partial equilibrium analysis overestimates the effects of HOV lanes on commuting, energy consumption, and carbon emissions. After taking into account general equilibrium effects, HOV lanes are not as effective as what is commonly believed. They are more effective in relieving traffic congestion and saving energy in the short run. Thus, it is especially important to analyze the general equilibrium effects of public policies when policy makers propose changes.

4.3 Effects of Increasing HOV Lanes

The above analysis shows that converting 15% of highway capacity to HOV lanes has little effect on energy consumption. It is possible that converting more highway capacity to HOV lanes can save more energy because more HOV lanes encourage more people to carpool. In order to test whether creating more HOV lanes saves more energy, in this counter-factual scenario, the fraction of highway capacity converted into HOV lanes is increased from 15% to 25%.

Table 5 shows that as more roads are converted into HOV lanes, the fraction of people using HOV lanes increases from 33% to 45% and people living closer to the city center start to switch from solo driving to carpooling. More HOV lanes encourage more people to carpool and thus are more effective in relieving traffic congestion. The commuting time is reduced from 16 minutes to 14.5 minutes. The greater reduction in transportation cost leads to a greater urban sprawl. The city radius increases from 11.48 miles to 11.71 miles. More HOV lanes lead to a lower commuting energy consumption and a higher dwelling energy consumption. Surprisingly, the overall energy consumption and carbon emissions are stable as HOV lanes increase. Increasing HOV lanes has little effect on total energy consumption and carbon emissions.

4.4 Comparison of Imposing Optimal Congestion Tolls with the HOV Lane Policy

In this counter-factual scenario, the HOV policy is compared with another policy, congestions tolls, which have been proposed for urban highways as an alternative approach to combat traffic congestion. Singapore, London, Milan, and other cities have implemented congestion tolls on cars on certain roads or areas to relieve traffic congestion and improve air quality. The topic of congestion pricing on highways has long been the object of research in economics. Studies such as Liu and McDonald (1998, 1999) have shown that congestion tolls are effective in relieving traffic congestion.

In this simulation, it is assumed that optimal congestion tolls are imposed on all drivers. Following the congestion model in McDonald (2004), optimal congestion tolls are calculated based on externalities created by each additional driver on the highway. Each additional driver delays every commuter who is already on the highway, thus increasing the marginal commuting cost of each driver. Optimal tolls are calculated as the following:

$$toll(k) = \overrightarrow{N}(k) * \frac{dMC(k)}{d\overrightarrow{N}(k)} \tag{21}$$

where $MC(k)$ is the marginal commuting cost of each driver in annulus k, which is equal to $m_1 + p_g \frac{1}{G(V(M(k)))} + \tau W \frac{1}{V(M(k))}$. $\overrightarrow{N}(k)$ is the traffic volume at radius k. The effect of an additional vehicle on the marginal commuting cost is

$$\frac{dMC(k)}{d\overrightarrow{N}(k)} = p_g \frac{d(1/G(V(M(k))))}{d\overrightarrow{N}(k)} + \tau W \frac{d(1/V(M(k)))}{d\overrightarrow{N}(k)} \tag{22}$$

After congestion tolls are imposed, the total commuting cost for each driver becomes

$$T(k) = m_0 + \left[m_1 k + p_g \int_0^k \frac{1}{G(V(M(\kappa)))} d\kappa + \tau W \int_0^k \frac{1}{V(M(\kappa))} d\kappa + \int_0^k toll(\kappa) d\kappa \right] \tag{23}$$

Figure 4 shows that imposing congestion tolls effectively reduces city radius, increases housing density, and lowers commuting time. In contrast, the HOV lane policy causes urban sprawl and reduces structural density. However, HOV lanes are more effective in relieving traffic congestion and reducing commuting time. Figure 5 shows that after congestion tolls are imposed, dwelling energy, commuting energy, and total energy consumption decrease, while HOV lanes lead to a greater reduction in commuting energy consumption but increases dwelling energy consumption.

Table 6 shows that congestion tolls reduce the city radius by 6.5% and increase the structure land ratio at the CBD edge by 58%. The fraction of apartment buildings increases by 17%. The commuting time is reduced by 3.5%. In contrast, HOV lanes increase the city radius by 15.8% and reduce the structure land ratio (CBD) by 16.8%. The fraction of apartment buildings is reduced by 33%. HOV lanes decrease commuting time by 21%. For energy use, congestion tolls reduce dwelling energy consumption by 3.2% and commuting energy consumption by 5.7%. Overall, the total energy consumption is reduced by 1%. HOV lanes decrease commuting energy consumption by 36% while increasing dwelling energy consumption by 3.3%. Overall, the total energy consumption is lowered by only 0.65%.

For carbon emissions, imposing congestion tolls reduces carbon emissions from both gasoline and electricity by 1.1%. In contrast, the HOV lane policy decreases carbon emissions from gasoline and increases emissions from electricity. Overall, the HOV lane policy reduces carbon emissions by 1.2%. The results imply that imposing congestion tolls is a more effective policy tool in preventing urban sprawl and reducing energy use.

5 Conclusion

HOV lanes have been created and promoted in 27 metropolitan areas so far in the United States. The growth of HOV lanes is due to the belief that they reduce traffic congestion by encouraging carpooling, thus saving energy and protecting the environment. However, the indirect effects or unintended consequences of HOV lanes are urban sprawl, lower structure density, and an increase in housing consumption.

In contrast to previous literature, the numerical simulation model presented in this paper takes into account the general equilibrium effects of HOV lanes on urban form, energy consumption, and GHG emissions. After the HOV lane policy is implemented, in the long run, households will change their location decision and consumptions in housing and other goods.

The simulation results establish rich predictions that are not intuitive. It is true that HOV lanes encourage carpooling and improve traveling speed. Households living farther away from the city center choose to carpool to use HOV lanes to save commuting costs while households living closer to the city center continue to use general purpose lanes. However, the reduction in transportation cost reduces households' incentives to live closer to the city center. As a result, households move to live farther away from the city center and consume a larger house, which leads to urban sprawl and lower structure density. The overall energy and environmental implications are that HOV lanes have little effect on overall energy consumption and carbon emissions. In addition, the surprising result is that increasing HOV lanes has little effect on total energy consumption and carbon emissions.

The comparison between the general equilibrium analysis and the partial equilibrium analysis suggests that the partial equilibrium analysis overestimates the effects of HOV lanes on energy and carbon emissions. In order to help guide policy makers to choose among different policy alternatives, the HOV lane policy is compared with the congestion toll policy. The simulation results show that imposing congestion tolls is more effective in preventing urban sprawl and reducing energy consumption.

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Figure 1: Comparison of Commuting Cost Using Different Lanes

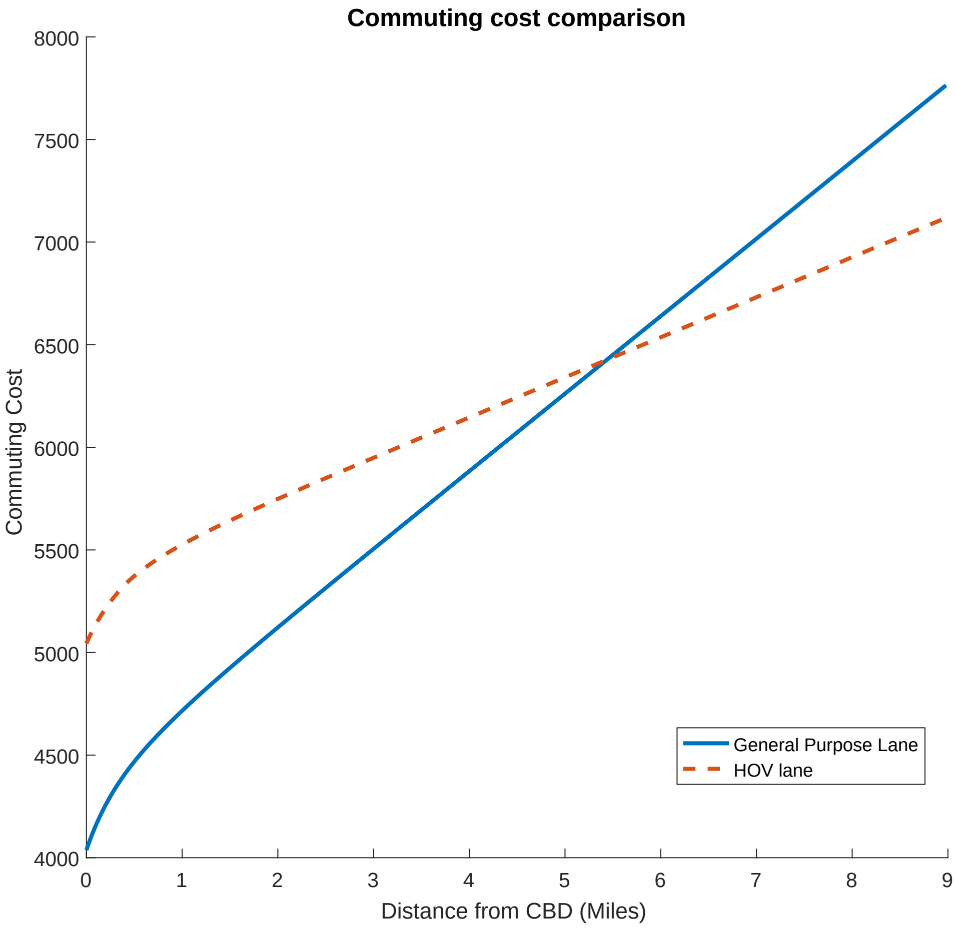

Figure 2: Baseline and HOV lanes Simulations - Urban Form

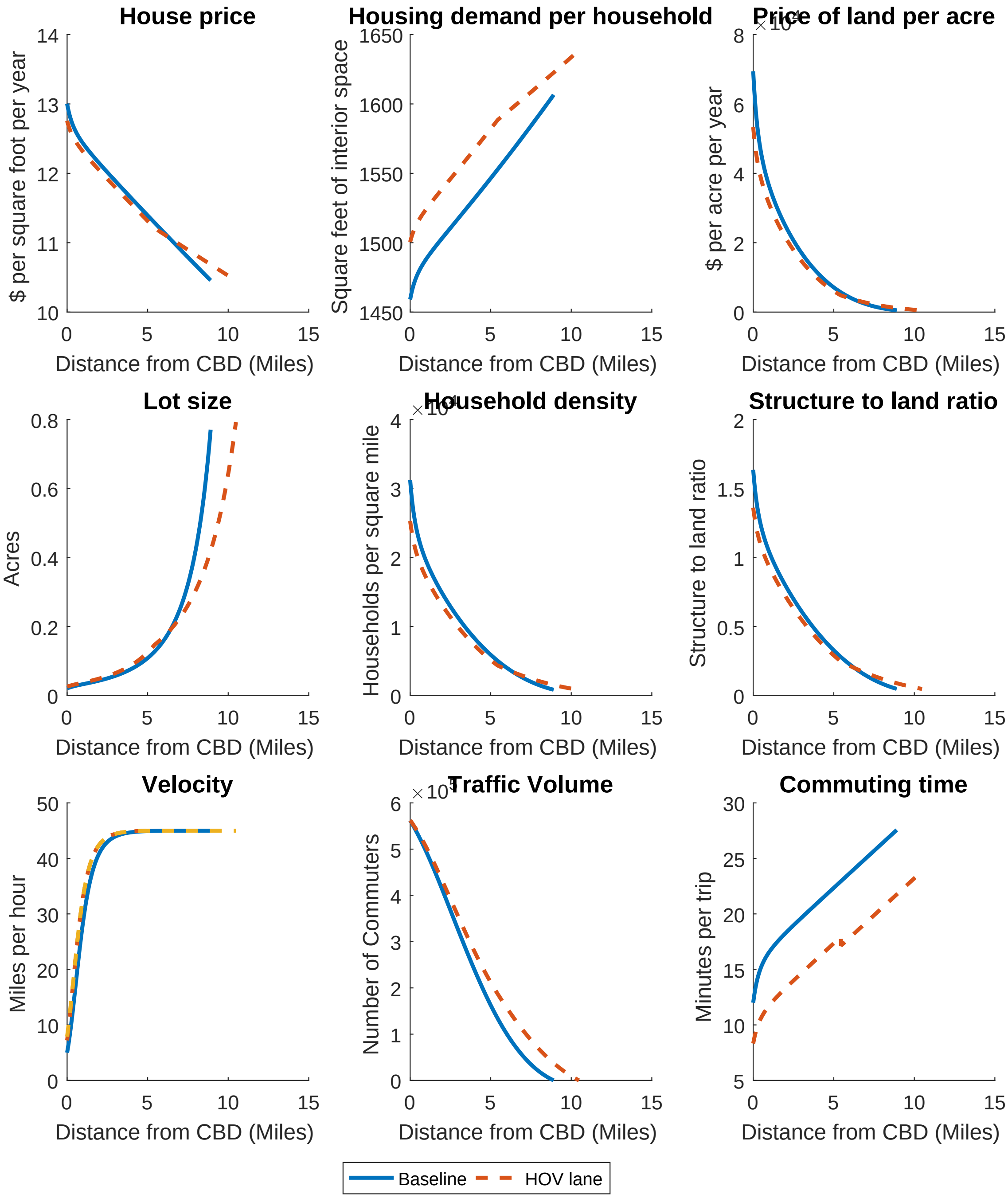

Figure 3: Baseline and HOV lanes Simulations - Energy Consumption

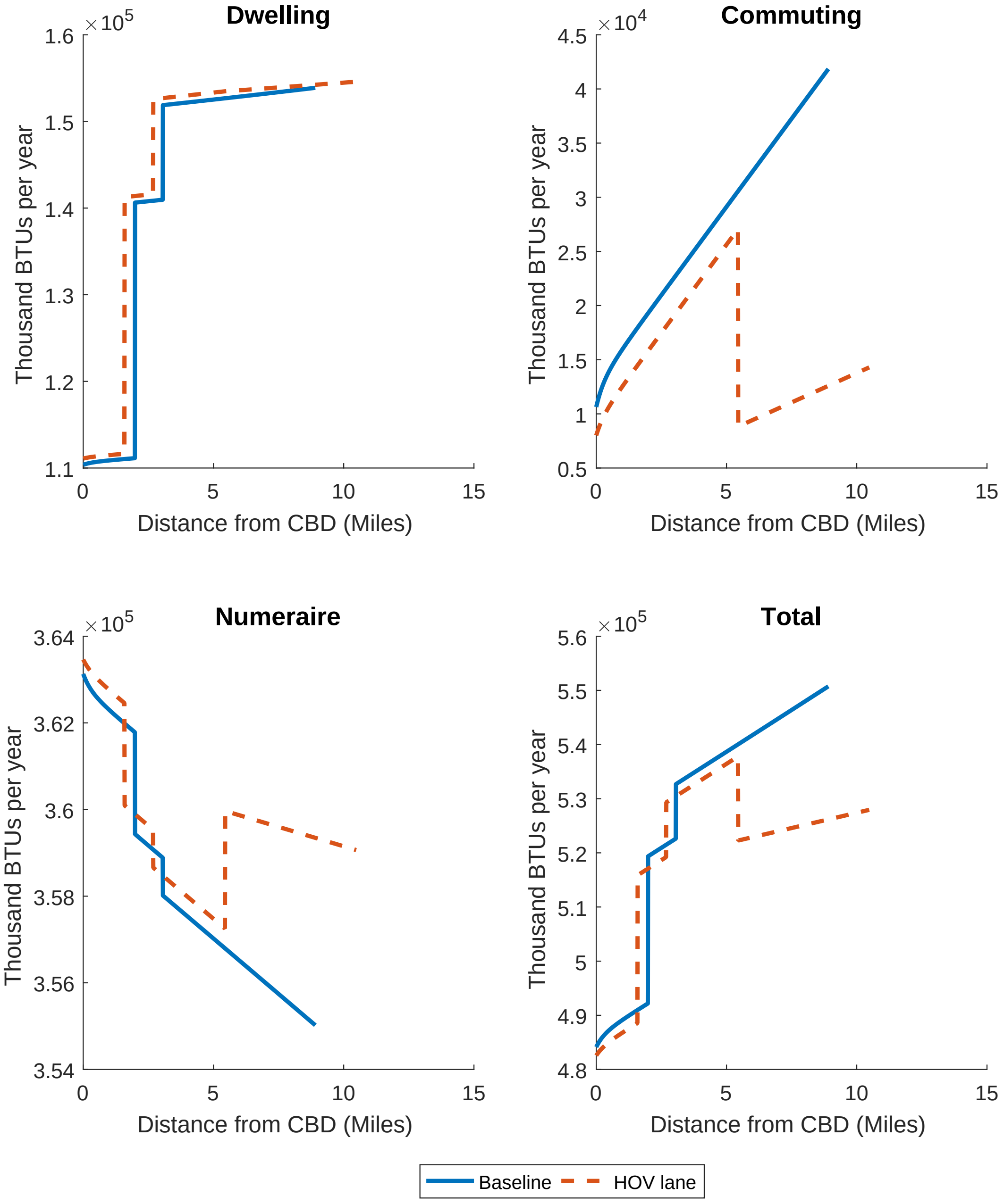

Figure 4: Comparison of HOV Lanes with Optimal Congestion Toll - Urban Form

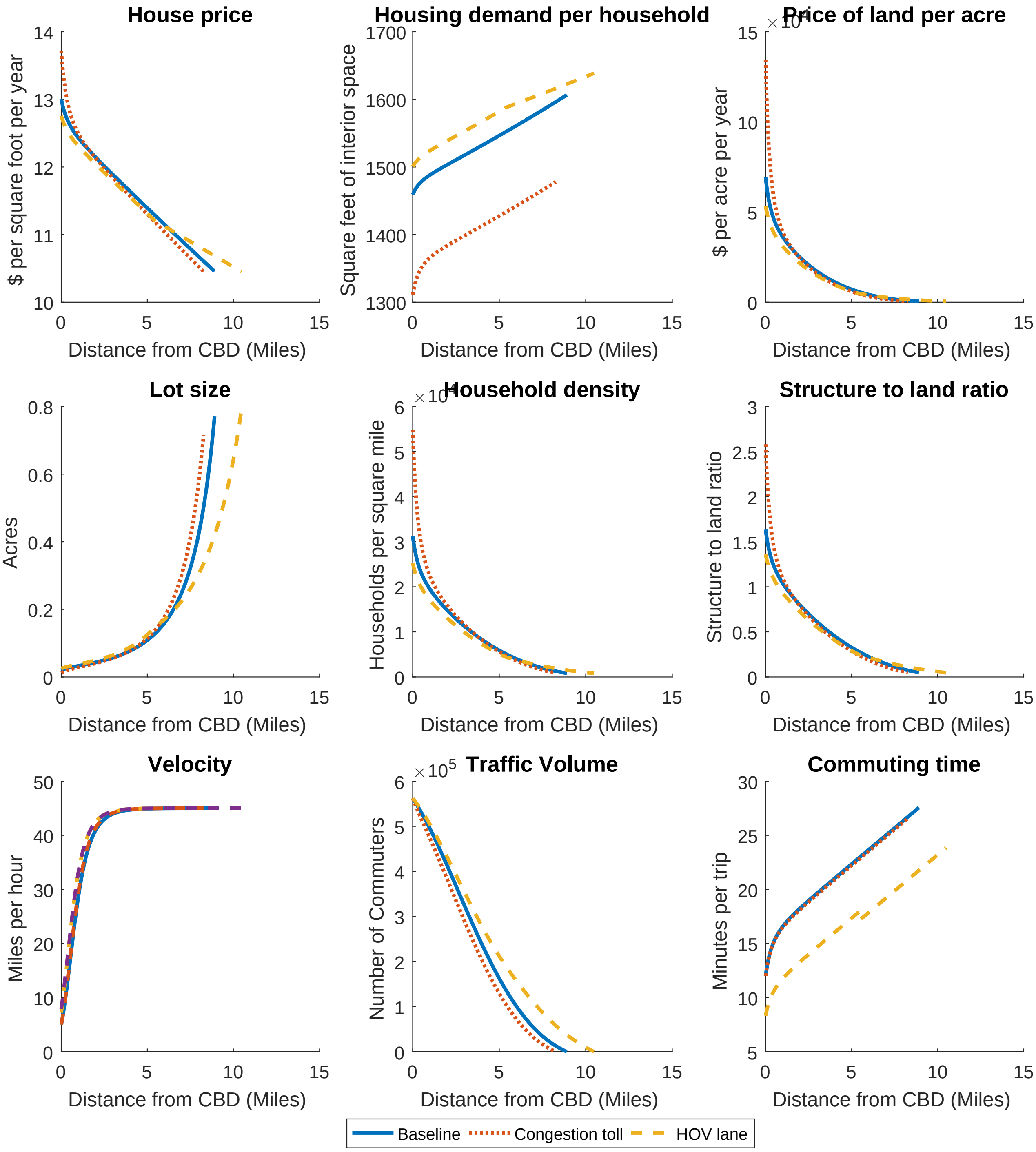

Figure 5: Comparison of HOV Lanes with Optimal Congestion Toll - Energy Consumption

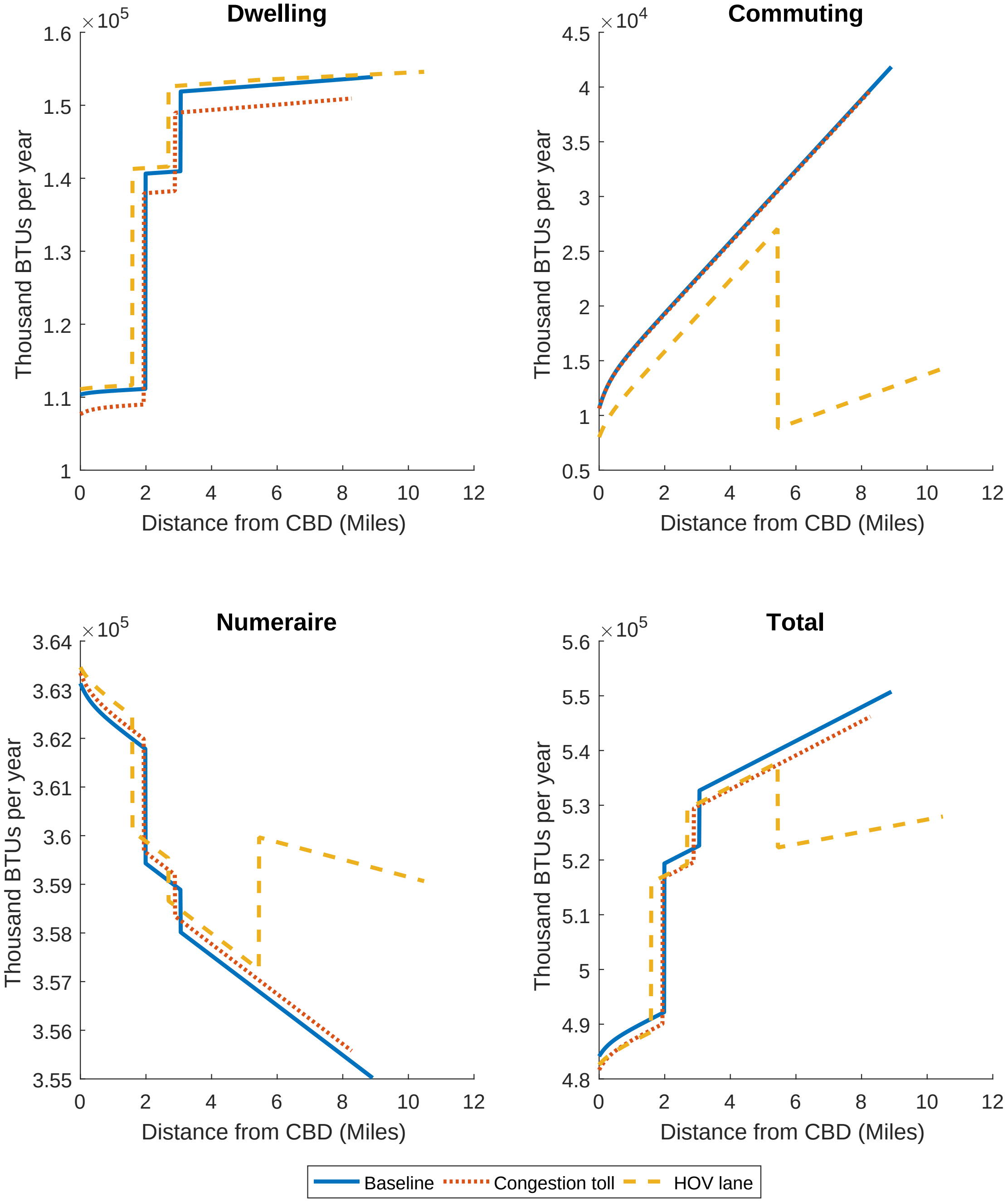

Table 1: Simulation Parameters

Parameter	Baseline Value	Description	Source
City Income and Size			
W	50,000	Annual earnings	American Community Survey
N	450,000	Households	American Community Survey
Housing Production			
$1/(1-\rho)$	0.75	Elasticity of substitution	Altmann and DeSalvo (1981)
α_1	1	Structure share	Muth (1975); Altmann and DeSalvo (1981)
α_2	0.03	Land share	Muth (1975); Altmann and DeSalvo (1981)
A	0.105	Technology parameter	Calibrated
Household Utility			
$1/(1-\eta)$	0.75	Elasticity of substitution	
β_1	1	Numeraire share	Numeraire
β_2	0.27	Housing share	Altmann and DeSalvo (1981)
Land Use			
θ	0.25	Fraction of land used for housing	Muth (1975)
k_{CBD}	1	Radius of the CBD	Muth (1975)
p_L^a	500	Reservation agricultural land rent per acre	Bertaud and Brueckner (2005)
Transportation			
v_{low}	5	Minimum commuting speed	Muth (1975)
v_{high}	45	Maximum commuting speed	Muth (1975)
c	1.75	Parameter in speed function	Muth (1975)
τ	0.5	Commuting time cost fraction of income	Bertaud and Brueckner (2005)
p_g	3.5	Gasoline price (USD) per gallon	Energy Information Administration
m_0	2,654	Fixed cost of commuting	American Automobile Association
m_1	0.222	USD per mile of depreciation	American Automobile Association
V_c	0.822	Miles per gallon constant term in polynomial	American Automobile Association
Housing			
q_0	0.8	5+ unit building cut-off	Calibrated
q_1	0.7	2-4 unit building cut-off	Calibrated
q_2	0.6	S. f. attached cut-off	Calibrated
γ_1	5.709	Dwelling energy demand, constant term	Larson et al. (2012)
γ_2	0.07	Dwelling energy demand, log income	Larson et al. (2012)
γ_3	-0.743	Dwelling energy demand, log price	Larson et al. (2012)
γ_4	0.23	Dwelling energy demand, log square feet	Larson et al. (2012)
Γ_2	-0.07	Dwelling energy demand, s. f. attached FE	Larson et al. (2012)
Γ_3	-0.31	Dwelling energy demand, multifamily FE	Larson et al. (2012)
Numeraire Consumption			
p_e	0.035	Electricity price per BTU	Energy Information Administration
E_N	7,470	BTU/GDP Ratio	Energy Information Administration
Physics Constants			
C_g	157	pounds of CO2 per million BTUs of gasoline	Energy Information Administration
C_e	115	pounds of CO2 per million BTUs of electricity	Energy Information Administration
E_g	150.6	thousand BTUs per gallon of gasoline	Energy Information Administration
E_e	0.303	Electricity production and transmission efficiency	Energy Information Administration

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

Table 2: Simulation Calibration

City CBSA Code	Charlotte 16740	Indianapolis 26900	Kansas City 28140	San Antonio 41700	Average	Simulation
Lot Size (acre) – Occupied Units[1]	0.36	0.31	0.25	0.20	0.28	0.16
Unit (square feet) – Occupied Units[1]	1,694	1,668	1,655	1,382	1,599	1,528
Area (sq. miles)[2]	444	409	515	505	468	308
Radius (assuming circle)[2]	11.9	11.4	12.8	12.7	12.2	9.91
Wharton Regulatory Index (WRLURI, 2008)	-0.53	-0.74	-0.79	-0.21	-0.57	-
Unavailable Land (Saiz, 2010)	5%	1%	6%	3%	4%	0%
Median Income[2]	$ 50,702	$ 46,970	$ 49,001	$ 43,586	$ 47,565	$ 50,000
Total Occupied Units[2]	412,445	410,594	360,109	547,627	432,694	450,000
Time to work[2]	25.1	23.8	22.3	24.6	23.9	20.42
Fraction housed in 1 unit structures[2]	71%	71%	70%	54%	66%	56.8%
Fraction housed in 2-4 unit structures[2]	12%	12%	15%	14%	13%	16.8%
Fraction housed in 5+ unit structures[2]	16%	17%	15%	32%	20%	26.5%

[1] Source for actual values: AHS (2011)

[2] Source for actual values: ACS (2010)

[3] Source for actual values: RECS (2009) households with 100% electricity consumption

Table 3: Simulated Effects of the HOV Lanes

Scenario	**Baseline**	**15% HOV Lanes**	%Δ
Urban Form			
Total Occupied Units	450000	450000	
Lot Size (acre) – Detached Units	0.16	0.20	21.69%
Unit (square feet) – All Units	1527.55	1568.96	2.71%
City Area (sq. miles)	308.53	414.03	34.20%
City Radius (assuming circle)	9.91	11.48	15.84%
House Price per Sq. Ft. (CBD)	13.00	12.76	-1.90%
Land Price per Acre (CBD)	69401.68	53281.26	-23.23%
Residential Struct./Land ratio (CBD)	1.64	1.36	-16.79%
Residential Density (hh per sq. mile)	1473.53	1095.18	-25.68%
Time to work	20.42	16.08	-21.24%
Fraction housed in 1 unit structures	56.75%	67.21%	18.43%
Fraction housed in 2-4 unit structures	16.79%	15.08%	-10.16%
Fraction housed in 5+ unit structures	26.47%	17.71%	-33.07%
HOV boundary		6.45	
Fraction of population using HOV		33.24%	
Energy Consumption per Household (million BTUs)			
Total	523.09	519.70	-0.65%
Commuting	24.81	15.83	-36.17%
Dwelling	139.59	144.20	3.31%
Numeraire	358.69	359.66	0.27%
Carbon Emissions per Household (tons)			
Total	30.71	30.33	-1.24%
Gasoline	1.95	1.24	-36.17%
Electricity	28.76	29.08	1.12%
Welfare			
Income	50000.00	50000.00	
Utility	5225.56	5329.15	1.98%

Table 4: Partial Equilibrium Effects vs. General Equilibrium Effects of Eliminating HOV Lanes

Scenario	**HOV**	**Partial Eqm effects, Eliminating HOV**	%Δ	**General Eqm effects, Eliminating HOV**	%Δ
Urban Form					
Total Occupied Units	450000	450000.00		450000	
Lot Size (acre) – Detached Units	0.20	0.20	0.00%	0.16	-17.83%
Unit (square feet) – All Units	1568.96	1568.96	0.00%	1527.55	-2.64%
City Area (sq. miles)	414.03	414.03	0.00%	308.53	-25.48%
City Radius (assuming circle)	11.48	11.48	0.00%	9.91	-13.68%
House Price per Sq. Ft. (CBD)	12.76	12.76	0.00%	13.00	1.94%
Land Price per Acre (CBD)	53281.26	53281.26	0.00%	69401.68	30.26%
Residential Struct./Land ratio (CBD)	1.36	1.36	0.00%	1.64	20.18%
Residential Density (hh per sq. mile)	1095.18	1095.18	0.00%	1473.53	34.55%
Time to work	16.08	21.34	32.68%	20.42	26.97%
Fraction housed in 1 unit structures	67.21%	67.21%	0.00%	56.75%	-15.56%
Fraction housed in 2-4 unit structures	15.08%	15.08%	0.00%	16.79%	11.31%
Fraction housed in 5+ unit structures	17.71%	17.71%	0.00%	26.47%	49.41%
HOV boundary	6.45				
Fraction of population using HOV	33.24%				
Energy Consumption per Household (million BTUs)					
Total	519.70	529.11	1.81%	523.09	0.65%
Commuting	15.83	26.89	69.81%	24.81	56.67%
Dwelling	144.20	144.20	0.00%	139.59	-3.20%
Numeraire	359.66	358.02	-0.46%	358.69	-0.27%
Carbon Emissions per Household (tons)					
Total	30.33	31.10	2.55%	30.71	1.26%
Gasoline	1.24	2.11	69.81%	1.95	56.67%
Electricity	29.08	28.99	-0.33%	28.76	-1.11%

Table 5: Effects of Increasing HOV Lanes

Scenario	**15% HOV Lanes**	**20% HOV Lanes**	**25% HOV Lanes**
Urban Form			
Total Occupied Units	450000	450000.00	450000.00
Lot Size (acre) – Detached Units	0.20	0.20	0.20
Unit (square feet) – All Units	1568.96	1575.18	1579.81
City Area (sq. miles)	414.03	424.19	430.79
City Radius (assuming circle)	11.48	11.62	11.71
House Price per Sq. Ft. (CBD)	12.76	12.71	12.68
Land Price per Acre (CBD)	53281.26	50820.64	48896.27
Residential Struct./Land ratio (CBD)	1.36	1.32	1.28
Residential Density (hh per sq. mile)	1095.18	1068.76	1052.27
Time to work	16.08	15.20	14.50
Fraction housed in 1 unit structures	67.21%	69.36%	71.16%
Fraction housed in 2-4 unit structures	15.08%	14.60%	14.19%
Fraction housed in 5+ unit structures	17.71%	16.04%	14.65%
HOV boundary	6.45	5.99	5.62
Fraction of population using HOV	33.24%	39.71%	45.12%
Energy Consumption per Household (million BTUs)			
Total	519.70	519.34	519.12
Commuting	15.83	14.48	13.45
Dwelling	144.20	145.07	145.78
Numeraire	359.66	359.79	359.89
Carbon Emissions per Household (tons)			
Total	30.33	30.28	30.24
Gasoline	1.24	1.14	1.06
Electricity	29.08	29.14	29.19
Welfare			
Income	50000.00	50000.00	50000.00
Utility	5329.15	5344.69	5356.14

Table 6: Comparison of Imposing Optimal Congestion Tolls with the HOV Lane Policy

Scenario	**Baseline**	**Optimal congestion toll**	%Δ	**15% HOV Lanes**	%Δ
Urban Form					
Total Occupied Units	450000	450000		450000	
Lot Size (acre) – Detached Units	0.16	0.15	-8.04%	0.20	21.69%
Unit (square feet) – All Units	1527.55	1400.46	-8.32%	1568.96	2.71%
City Area (sq. miles)	308.53	269.97	-12.50%	414.03	34.20%
City Radius (assuming circle)	9.91	9.27	-6.46%	11.48	15.84%
House Price per Sq. Ft. (CBD)	13.00	13.72	5.50%	12.76	-1.90%
Land Price per Acre (CBD)	69401.68	134527.46	93.84%	53281.26	-23.23%
Residential Struct./Land ratio (CBD)	1.64	2.58	57.81%	1.36	-16.79%
Residential Density (hh per sq. mile)	1473.53	1686.50	14.45%	1095.18	-25.68%
Time to work	20.42	19.70	-3.54%	16.08	-21.24%
Fraction housed in 1 unit structures	56.75%	53.35%	-5.98%	67.21%	18.43%
Fraction housed in 2-4 unit structures	16.79%	15.69%	-6.51%	15.08%	-10.16%
Fraction housed in 5+ unit structures	26.47%	30.95%	16.95%	17.71%	-33.07%
HOV boundary				6.45	
Fraction of population using HOV				33.24%	
Toll expenditure (Average)		3518.39			
Energy Consumption per Household (million BTUs)					
Total	523.09	517.81	-1.01%	519.70	-0.65%
Commuting	24.81	23.40	-5.67%	15.83	-36.17%
Dwelling	139.59	135.15	-3.18%	144.20	3.31%
Numeraire	358.69	359.26	0.16%	359.66	0.27%
Carbon Emissions per Household (tons)					
Total	30.71	30.37	-1.09%	30.33	-1.24%
Gasoline	1.95	1.84	-5.67%	1.24	-36.17%
Electricity	28.76	28.54	-0.78%	29.08	1.12%
Welfare					
Income	50000.00	50000.00	0.00%	50000.00	0.00%
Utility	5225.56	4806.98	-8.01%	5329.15	1.98%