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Urban Spatial Expansion, Urban Compactness, and Average Travel Demand in the US Urbanized Areas

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Abstract

This paper examines the impact of a wide variety of factors on spatial size, spatial compactness measured by population density, and average travel demand measured by daily vehicle miles traveled per capita. The simultaneous equation regression results indicate real average household income has a positive impact on spatial size and average travel demand while a negative impact on urban spatial compactness. Transportation cost measured by fuel cost per mile has a negative impact on spatial size while a positive impact on urban spatial compactness. Among the land use policy tools, urban growth boundary has a positive impact on urban compactness while minimum lot size has a positive impact on urban spatial size.

Keywords: urban compactness; average travel demand; simultaneous equation model; land use tools

1. Introduction

The last half of the twentieth century has witnessed a continuous growth of suburbs in the urbanized areas in the United States, which is accompanied by massive use of private vehicles. As more and more Americans move to the new homes in suburb areas, urban spatial size expands while urban compactness decreases. At the same time, people travel greater distances to work and make more frequent trips given the fact that public transit is either unavailable or poorly developed in the suburb areas. Although these phenomena have been studied extensively, they are examined separately despite the clear connection between them.

Urban economists focus on identifying underlying market forces and land use policy tools that contribute to the consistent urban expansion (Brueckner & Fansler, 1983; Baum-Snow, 2007; Su & DeSalvo, 2008; Geshkov & DeSalvo, 2012; McGrath, 2005; Song & Zenou, 2006; Glaeser & Kan 2004; Spivey, 2008; Paulson, 2012; Brueckner & Sridhar, 2012 (India);

Baum-Snow et al., 2013 (China), DeSalvo & Su, 2017, 2019) while urban planning scholars investigate the impact of state growth management on urban land use patterns. On the other side, transportation scholars examine the determinants of travel demand given the fact that travel demand is a derived demand to carry out other economic activities (for comprehensive reviews, see Ewing and Cervero, 2001; Cao et al. 2006; Bhat and Guo, 2007**).** Given the public concerns of externalities generated from growing travel demand (e.g. congestion) and environmental impact due to declining urban compactness, it is important for us to study these two phenomena jointly. It is very likely that the same underlying forces (observable or unobservable) could affect an area's spatial compactness and average travel demand. In other words, they could be jointly determined. This naturally raises an important question that has not yet answered satisfactorily: are there any common factors to explain these related phenomena and what role can urban public policies play if changing these phenomena is desirable?

This paper uses urban spatial size, population density (Galster et al., 2001; Malpezzi & Guo, 2001) and daily vehicle miles traveled per capita to measure inter-area variations in urban spatial size, urban compactness, and average travel demand. It adds to a sizable empirical literature, contributing three improvements. First, this paper applies the monocentric urban model to derive the comparative static results of household income, rural land rent, and transportation cost on urban compactness and average travel demand per capita. Second, in addition to the standard monocentric model variables used by many urban economists, land-use policies at both the local and state levels and political and geographic characteristics are also in included in the empirical analysis to reduce omitted variable bias. Third, this paper applies simultaneous equation model in the extended monocentric urban model framework to look for answers of two important questions: (1). Are there common contributors to these measures of different aspect of urbanized areas in the US? (2) Whether and how land use policies at the local and state level affect the different yet related land use and travel pattern in the US urban areas? The major findings of this paper help us better understand the causes of different land-use and travel patterns in the US and look for relevant policy tools to make changes if desirable.

2. Literature Review

While there is a growing literature examining growing urban spatial size, declining urban compactness, and increasing travel demand, the majority of earlier studies normally examine these issues separately. Given the large body of existing literature, this section highlights only those most relevant to this study.

Why have the urbanized areas in the US show a wide gap in terms of urban spatial size and compactness? Urban economists develop both the monocentric and polycentric models to explain expansion of urban areas and associated decline in urban compactness. The most obvious shortcoming of the monocentric model is the assumption that an area has one predetermined center. The polycentric urban model was developed to incorporate the reality that most urban areas have more than one employment center (Anas and Kim, 1996; Anas and Xu, 1999). Although the polycentric urban model incorporates more realistic factors, Anas (2007) leaves the empirical application of his theory as an extension while the monocentric model has clear testable hypotheses.

Brueckner (1987) provides a comparative static analysis of the monocentric urban model, which has been used as a standard model for extensions. The monocentric model assumes that there is one urban center: the central business district (CBD), to which all travel is made for work and other activities. The comparative static results from the closed monocentric city model indicate that an increase in population and household income as well as a decrease in transportation cost and rural land rent result in expansion of urban spatial size and decrease in population density, other things equal.

Majority of existing studies test the monocentric model based on this comparative static result. Estimated coefficients are mostly statistically significant and have the theoretically predicted signs in samples ranging from relatively small urbanized areas (Brueckner and Fansler, 1983; Su and DeSalvo, 2008; Geshkov and DeSalvo, 2012) to those including almost all urbanized areas (Song and Zenou, 2006; Spivey, 2008) and multi-year pooled cross-section data set of very large urbanized areas with multiple employment centers (McGrath, 2005, Deng et al. 2006, Paulsen, 2012).

Brueckner and Fansler (1983) and McGrath (2005) provide the empirical analyses of the un-extended model and their regression results are largely consistent with the theoretical prediction of the monocentric model. Other factors such as the property tax (Song and Zenou, 2006; Brueckner and Kim 2003), transportation subsidies (Brueckner 2005; Su and DeSalvo, 2008), and land-use controls (Geshkov and DeSalvo, 2012) have also been identified as important contributors. Despite differences in theoretical extensions and data samples, those papers find similar results regarding the basic variables of the un-extended model, which confirm the robustness of the monocentric urban model.

In addition to the factors identified in the general framework of monocentric model, Glaeser and Kahn (2003) identify automobiles and their lower travel costs as the primary forces behind cities' declining compactness. Their reasoning is straightforward based on a few facts. First, a majority of households in the US owned at least one car by 1952 (Glaeser and Kahn 2003) and vehicle ownership continues to grow. Growth in vehicle ownership and relatively low travel cost enables people live further and further away from their work. As a result, urban compactness declines. In the US, drive to work ratio was 64 percent in 1960. In the process of suburbanization, this ratio turned to be 84 percent in 1980 and 88 percent in 2000 (Bureau of Census, 2003).

Land use controls at the level of local government are also identified as factors affecting population density. Minimum lot-size zoning (Pasha 1996), maximum floor-area-ratio (Bertaud and Brueckner 2005), and maximum building heights (Bertaud and Brueckner 2005) are found to have a direct impact on the spatial size of an area. Maximum lot-size zoning (Pasha 1992), urban growth boundaries (Quigley and Swoboda 2007), minimum square-footage limitations (Bertaud and Brueckner 2005), and minimum number of persons per room (Geshkov and DeSalvo, 2012) are found to have an inverse effect.

Urban planning scholars focus on examining the impact of state growth management on urban land use patterns. Growth management is a general framework under which, local governments are either required or strongly encouraged to make their land use planning based on a formal review process with clear criteria. The local governments make plans related to such areas as infrastructure, environmental protection, and economic development. Their plans are expected be consistent and concurrent with state and regional plans and ensure adequate resources to public service of new development (Anthony 2004; Howell-Moroney 2007; Carruthers 2002; York et al. 2013). Various studies of the impact of state growth management on urban land use at the state level have mixed findings. Anthony (2004) find that state growth management programs don't have a statistically significant impact in curbing urban expansion while Carruthers (2002) and Howell-Moroney (2007) both find the only the states of the strongest growth management programs show promise in reducing urban expansion in size and increasing in population density.

2.1 Relevant Studies in Travel Demand

Many studies in the transportation field (Sweeney, 1978; Baltagi and Griffin, 1983, 1997) use urban-area level data in examining travel demand because of its policy relevance. In the United States, road capacity expansions and constructions are based on long-term plans at the state level. For these plans, traffic forecasts must be made and updated regularly.

To reduce growing externalities brought on by increasing dependence on automobile travel, transportation planners have turned to using density as a planning tool. They believe that people's travel demand may be reduced by modifying the design of the neighborhoods with a focus on increasing population density as well as transit-oriented development. Such a movement has been observed across the country during the past years (Cervero and Kockelman 1997, Chen et al. 2007). Empirical evidence on this issue, however, reveals an inconsistent picture on the role of urban density. Although some studies find a statistically significant negative relationship between density and the probability of using auto (Frank and Pivo 1994; Cervero 1994; Zhang 2004) and fuel consumption (Newman and Kenworthy 1989; Su 2011), others find density plays an ignorable role in affecting people's travel behavior and pattern (Mindali et al. 2004; Kockelman 1997; Schimek 1996; Miller and Ibrahim 1998, Bento et al., 2005).

Numerous studies in the past have tested the so-called induced travel hypothesis, namely, more road induces more travel. Fulton et al. (2000) use county-level data from Maryland, Virginia, North Carolina, and Washington, DC and find that average elasticities of VMT with respect to lane-miles range between 0.2 and 0.6. Other studies (Cervero 2000; Hansen 1997; Noland 2001) based on city-level data also verify that there is a positive relationship between road network capacity and travel demand.

Our discussion certainly does not exhaust the literature (for detailed reviews on the relationship between travel demand and population density and road network, please see Ewing and Cervero 2001, Cao, et al. 2006, and Bhat and Guo 2007), but it represents the major focus and results of such studies that are most relevant to our topic.

3. Theoretical Framework

In this section, a standard monocentric urban model similar to Brueckner (1987) is used as a framework to provide theoretical connection between urban spatial size, urban compactness, and average travel demand. Since the comparative static results of exogenous variables on spatial size of an urban area are the same as those derived by Brueckner, only mathematical derivations of those variables on population density and average travel demand are presented in Appendix A.

The monocentric model assumes a predetermined center, the central business district (CBD), to which all travel is made for work and other activities. Travel is along radial and dense transportation routes between the household's residential location and the CBD.

We assume only one mode of transportation, with total costs paid by the traveler given by the following equation:

(1) $$M = tx$$

where t is variable cost, which includes all costs that vary with distance traveled, x;

A household's quasi-concave utility function is

(2) $$v = v(c,q),$$

where q is housing consumption, which is a normal good, and c is non-housing, non-transportation expenditures. The household has the budget constraint

(3) $$y = c + pq + M,$$

which says the household spends its exogenous income, y, on non-housing, non-transportation goods, c; housing, pq, where p is the price of housing; and transportation.

The problem of the household is to maximize (2) subject to (3). Upon eliminating c, this problem gives rise to the first-order condition,

(4) $$\frac{v_q[y - pq - M, q]}{v_c[y - pq - M, q]} = p.$$

All urban households are assumed to be identical with respect to utility function and income. Consequently, for them to be in spatial equilibrium, in which no one wants to move, it is necessary that the following condition hold

(5) $$v[y - pq - M, q] = u,$$

where u is the urban-area-wide spatial equilibrium utility level. The catchall variable, c, plays

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no role in the analysis and is therefore ignored.

Housing is produced via a constant-returns-to-scale concave production function defined over land, l, and non-land inputs, N, as

(6) $$H = H(l, N),$$

but, because of constant returns to scale, this may be rewritten as

(7) $$\frac{H}{l} = H\left(\frac{N}{l}, 1\right) = H(S,1) = h(S) \text{ or } H = lh(S),$$

where S is the nonland-to-land ratio. Profit per unit of land is given by

(8) $$\pi = ph(S) - iS - r,$$

where i is the rental rate of the nonland input and r is the rental rate of the land input. Maximizing rent per unit of land produces the first-order condition

(9) $$ph'(S) = i.$$

Finally, the spatial equilibrium condition for housing producers is that land rent absorb profit, so all housing producers are equally well off at any location, or

(10) $$r = ph(S) - iS.$$

The urban boundary conditions are

(11) $$r(\bar{x}) = r_A,$$

where $\bar{x}$ is the distance from the CBD at which the urban area ends and the rural area begins and r_A is the rural land rent. The urban population condition is

(12) $$\int_0^{\bar{x}} \delta x D \, dx = L,$$

where δ is the number of radians in a circle available for urban residential use, $D = h/q$ is population density, and L is the urban population (assumed to be the same as the number of urban households). This condition ensures that the population of the urban area exactly fits inside the boundary of the urban area.

Based on this framework, we can easily extend it to derive average travel demand as follows

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(13) $$\text{ATD} = \frac{\int_0^{\bar{x}} \delta x^2 D dx}{L}$$

Table 1 summarizes the comparative static results of changes in exogenous variables on the spatial size of the urban area, population density, and average travel demand.

Table 1. Comparative Static Results

Exogenous Variable	L	y	r_A	t
Effect on $\bar{x}$	+	+	-	-
Effect on D		?	+	-
Effect on ATD		?	?	-

4. Data and Variables

Most variables used in this paper are from four major sources: US Bureau of Census, Census 2000; Burchfield, et al. (2006); Highway Statistics 2000, and Geshkov and DeSalvo (2012). Supplementary variables are from the Annual Urban Mobility Report, and the National Agricultural Statistics Service. Geshkov and DeSalvo's sample includes only those urbanized areas with one central city and located within a single county to be consistent with the monocentric urban model. After combining the variables from Geshknov and DeSalvo and Burchfield, the final sample includes 152 urbanized areas. While the existing literature identified many other variables that may be relevant to our paper, additional variables are selected based on availability due to the restriction of the sample of 152 areas that are medium or small in size. They are categorized into dependent variables and explanatory variables with sub-groups for better organization.

4.1 Dependent Variables

The variable used to measure urban spatial size is the total land area reported by Census 2000. The variable used to measure urban compactness is population density, which is also from Census 2000. It is derived by dividing an urban area's total land area by its total population. The variable used to measure average travel demand is daily vehicle miles traveled (DVMT) per capita. This variable is obtained from Highway Statistics 2000, Table HM 72 (Note 1). These two variables are measured at the urbanized area level. Since urbanized areas in the United States are identified based on criteria on population density and total population, the boundaries of the urbanized areas are not based on administrative units (e.g. cities or counties).

Explanatory variables are categorized in four groups: standard variables from the monocentric urban model; land use control variables; political, economic, and geographic characteristics; and other variables used to explain DVMT.

4.2 Standard Variables from the Monocentric Urban Model

There are four variables from the monocentric urban model that have been used in empirical work: number of households, mean household income, transportation cost, and rural rent at the urban fringe. The number of households in an urbanized area is obtained from Census 2000, SF3, Table P15. Mean household income (Note 2) in an urbanized area is reported by Census 2000 for 1999 in SF3, Table P54. For rural land rent, the mean estimated market value of farm land per acre for the county in which the urbanized area is located is used as a proxy. This variable is available from the National Agricultural Statistics Service. Since the Census of Agriculture is conducted every five years and in different years from the decennial census, we use the mean of the means reported for 1997 and 2002, which is meant to approximate land value for the year 2000. An alternative proxy is obtained from the National Agricultural Statistics Service's report on annual agricultural land values. The proxy measures the average farm land value per acre at the state level. We have used both proxies, and the major results of this paper remain unchanged.

Accurate measurement of transportation cost at the urban area level is not available. Following the most recent studies on travel demand measured by VMT based on area-level data (Small and Van Dender, 2007; Hymel, et al., 2010; Su, 2011), per-mile fuel price at the state level is used as a proxy variable for travel-cost per mile. This variable is obtained by dividing the product of the state's gasoline price and total gallons of gasoline consumed by total VMT.

Baum-Snow (2007, 2013) also identifies the highway network as a contributor to urban expansion. Small and Van Dender (2007) use the variable of road lane-miles per 1000 residents to capture the impact of road density. This variable, as discussed by Baum-Snow, may be endogenous, however. As an alternative, this paper uses the density of interstate and express road miles to capture the impact of the highway density. The variable is derived by dividing the sum of total interstate and express road miles (reported by Highway Statistics Table (2000) HM71) by the size of the urban area.

4.3 Growth Management at the State Level and Land Use Control at the Urbanized Area Level

According to Howell-Moroney (2007), growth management is regulations or legislatures designed by state to control and manage growth by requiring local governments to have and periodically review comprehensive planning in terms of land use. Following Howell-Moroney, two dummy variables are created to reflect the intensity of state growth management policies: moderate and strong. Those states with mandatory comprehensive planning and related policy tools aiming at controlling urban expansion are counted as strong growth management programs. Those states with mandatory comprehensive planning but without strong auxiliary policy tools are counted as moderate state programs. The base is those with such a policy or having a non-mandatory growth management.

The land-use control variables at the urbanized area level are from Geshkov and DeSalvo (2012). They use eight land use regulation variables: (1) minimum lot-size zoning; (2)

maximum lot-size zoning; (3) urban growth boundaries; (4) maximum floor-area-ratio restrictions; (5) minimum square-footage limitations; (6) maximum building permits; (7) minimum number of persons per room; and (8) impact fees. These land-use control variables are dummy variables indicating whether the urbanized area's central city or county have such land use regulations. These variables are pretty self-explanatory and definitions are thus not provided.

4.4 Geographic and Climate Characteristics of an Area

Four variables describing an area's geographic and climate characteristics used by Burchfield, et al. (2006), are also used in this paper as control variables (for detailed description, see Burchfield et al. (2006, pp. 609-615)): the range in elevation at the urban fringe; a terrain ruggedness index in the urban fringe; the number of cooling degree days and number of heating degree days. Following Burchfield, these variables are also treated as exogenous.

Table 1. Summary of Statistics on Selected Variables

Variable	Mean	Standard Deviation	Minimum	Maximum
Population Density	2124.69	835.75	811.1	5820.3
DVMT Per Capita	23.39	6.50	6	40.3
Households	71188.41	83512.51	17874	518614
Mean Household Income	48943.27	7448.18	35149	94957
Rural Rent	2345.86	1596.73	150	15064
Fuel Cost per Mile	0.063	0.0037	0.0571	0.078
Number of Vehicle per capita	0.472	0.072	0.31	0.64
Number of Bus per capita	.0028	.0011	.00057	.00570
Interstate and Express Highways Per Capita	0.00039	0.00049	0	0.00546
Land Use Variables (proportion)				
Minimum Lot Size Zoning	0.59		0	1
Maximum Lot Size Zoning	0.44		0	1
Urban Growth Boundary	0.45		0	1
Maximum Floor-Area-Ratio Restrictions	0.56		0	1
Minimum Square-footage Limitations	0.42		0	1
Maximum Building Permits	0.39		0	1
Minimum Number of Persons Per Room	0.61		0	1
Strong State Growth Management	0.066		0	1
Moderate State Growth Management	0.0592		0	1
Impact Fees	0.55		0	1
N	152			

4.5 Other Variables

We also draw variables from the literature investigating travelers' behavior. To reflect the inter-area difference in vehicle ownership (Note 3), we use the number of automobiles per capita at the state level. The number of buses per capita is also used as a proxy to control for the impact of public transit. Both variables are obtained from Highway Statistics 2000 (Table MV-1).

5. Empirical Specification

Our model specification is selected based on the following procedure: the first step is to run the OLS regressions with all the variables available for each equation; the second step is to run a variety of tests for joint significance for those variables that are not individually statistically significant at the level of at least 0.1 in different combinations. Based on the result of the second step, we dropped those variables that are not individually and jointly statistically significant at the level of at least 0.1 to obtain the basic specification. The third step is to examine the basic specification and identify potential endogenous variables and run the regression with relevant instrumental variables to see whether endogeneity of the suspected variable could be an issue. Instrument variables regressions are used and tests are conducted to reject the hypothesis that those variables are endogenous (see Appendix B for details). The final step is to run simultaneous equation model, which is more efficient and consistent when error terms of the equations are correlated. Given the empirical evidence that population density and urban area size are important factor in affecting people' travel demand, these two endogenous variables are included as explanatory variables in examining average travel demand in a simultaneous equation model.

The final model specification is as follows:

Spatial Size Equation:

$$\begin{aligned}\ln(SpatialSize) = {} & \beta_0 + \beta_1 \ln(Household) + \beta_2 \ln(RealIncome) + \beta_3 \ln(AverageFuelCostPerMile) \\ & + \beta_4 (\ln(RuralRent) + \beta_5 (MinimumLotSixe) + + \beta_6 (UrbanGrowthBoundary) \\ & + \beta_7 (ElevationIndex) + \beta_8 (\ln(RuggednessIndex) \\ & + \beta_9 (\ln(CentralCityViolentCrimeRate) + \beta_{10} (StrongStateGrowthManagement) \\ & + \beta_{11} (ModerateStateGrowthManagement) + \beta_{12} (California) \\ & + \beta_{13} (Michigan) + \beta_{14} (Illinois) + \beta_{15} (Texas)\end{aligned}$$

Urban Compactness Equation

$$\begin{aligned}\ln(PopD) = {} & \beta_0 + \beta_1 \ln(Income) + \beta_2 \ln(AverageFuelCostPerMile) + \beta_3 (\ln(RuralRent) \\ & + \beta_4 UrbanGrowthBoundary + \beta_5 ElevationRangeIndex \\ & + \beta_6 (\ln(CentralCityViolentCrimeRate) + \beta_7 (StrongStateGrowthManagement) \\ & + \beta_8 (ModerateStateGrowthManagement) + \beta_9 (California) \\ & + \beta_{10} (Michigan) + \beta_{11} (Illinois) + \beta_{12} (Texas)\end{aligned}$$

Average Travel Demand

$$\begin{aligned}\ln(DailyVMTPerCapita) = {} & \beta_0 + \beta_1 \ln(Income) + \beta_2 \ln(AverageFuelCostPerMile) + \beta_3(\ln(Rural\,\mathrm{Re}nt) \\ & + \beta_4(MinimumLotSize) + \beta_5(\ln(NumberofVehiclePerCapita) \\ & + \beta_6(\ln(Bus) + \beta_7(StrongStateGrowthManagement) \\ & + \beta_8(ModerateStateGrowthManagement) \\ & + \beta_9(\ln(ExpInterstateHighwayDensity) \\ & + \beta_{10}(CoolingDegreeDays) + \beta_{11}(California) \\ & + \beta_{12}(Michigan) + \beta_{13}(Illinois) + \beta_{14}(Texas) + \beta_{15}(\ln(PopD) \\ & + \beta_{16}(\ln(SpatialSize) + \beta_{17}(ElevationIndex)\end{aligned}$$

6. Regression Results

6.1 Spatial Size Equation

As shown in Table 2, the regression results indicate that the number of household in the area and real average household income both have a positive impact on the spatial size of an urbanized area. Other things equal, for every 10 percent increase in number of household, the spatial size of an area grows by around 9.4 percent. For every 10 percent increase in real average household income, the spatial size of an area expands by around 4.98 percent. The transportation cost, measured by fuel cost per mile, has a negative impact on the spatial size of an area. For every 10 percent decreases in fuel cost per mile, the spatial size of an area increases by around 1.3 percent.

Among all the available land use control variables at the urbanized area level, minimum lot size is the only one that has a statistically significant impact on the spatial size of an area. The regression results indicate that when either county or city of the urbanized area has the policy of minimum lot size in place, spatial size of such an area is 13 percent larger compared to those areas without such a policy in place. Evaluated by the mean value of spatial size, the impact of policy of minimum lot size increases spatial size of an area by around 10.88 square miles. The impact of growth management at the state level is captured by the two dummy variables: moderate and strong state growth management. Although the sign of strong state growth management is negative as predicted, the coefficient is not statistically significant.

Among the control variables, the regression results also indicate violent crime rate in the central city of an area has a positive impact on the spatial size. Among the state dummy variables, urbanized areas in the sample turn to have smaller spatial size in the states of California and Illinois.

6.2 Spatial Compactness Equation

Spatial compactness of an area is measured by population density. The regression results indicate that household income in an urban area has a negative impact on urban spatial compactness. Other things equal, for every 10 percent increase in real average household income, population density in an area decreases by around 6 percent. Rural land rent has a positive impact on population density, which is consistent with the prediction of the monocentric model. For every 10 percent increase in rural land rent, population density in an area increases by 1.5 percent. The measure of transportation cost, fuel cost per mile, has a negative impact on population density, as predicted. For every 10 percent increase in transportation cost, population density in an area decreases by 1.51 percent.

Among all the available land use control variables at the urbanized area level, urban growth boundary is the only one that has a statistically significant impact on population density. The regression results indicate that when either county or city of the urbanized area has the policy of urban growth boundary in place, population density of the area increases by around 13.65 percent, compared to those areas without such a policy in place. Evaluated by the mean value of population density, the impact of policy of urban growth boundary increases population density of an area by around 223 people per square mile. The two dummy variables capturing the impact of growth management at the state level don't have statistically significant impact on population density.

Among the control variables, the regression results also indicate that elevation range index at the urban fringe have a positive impact while violent crime rate in the central city of the urbanized area has a negative impact on population density. Among the state dummy variables, urbanized areas in the sample turn to have higher population density in the states of California and Texas.

6.3 Average Travel Demand Equation

Average travel demand is measured by natural log of daily average vehicle miles traveled per capita. The regression results indicate the impact of household income positive, suggesting travel as a normal and necessity good. Although the sign of per mile fuel cost is negative as expected and the coefficient is in the range of existing findings, this variable is not statistically significant. A potential explanation could be that there might be measurement errors in daily vehicle miles traveled due to the difference in measurement method and data collection by state transportation agencies.

Among the land use variables at the urbanized area level, the coefficient of the minimum lot size dummy variable is negative but not statistically significant at the level of 0.1. Among other control variables, the regression results indicate that interstate and expressway density has a positive impact on average travel demand. For every 10 percent increase in the road density, daily vehicle miles traveled per capita increases by 2.90 percent. The number of vehicles per capita and the number of bus per capita both have a negative impact on daily vehicle miles traveled per capita. Population density has a negative while urban area size has positive impact on daily vehicle miles traveled per capita, which is consistent with findings from Su (2010) and Kim and Brownstone (2013).

6.4 Robustness Check and Caveats

Given that our sample is restricted to only relatively small urban areas with one central city, a robustness check was conducted to test the sensitivity of the results to variable measurement and selection. Other possible limitations of our empirical analysis are also discussed in this section.

The first robustness check concerns measures of household income, transportation cost, and rural land rent. As discussed in the literature review, the monocentric urban model assumes all households have the same income. In addition, rural land rent should be measured at the urban fringe, and transportation costs should be measured at the urban area level. Proxies for these variables do not match their theoretical definitions because accurate measurements are not available. In the robustness check, alternative measures of these variables, specifically median family income, average farm land value at the state level, and average gasoline price per gallon at the state level, are used to check the sensitivity of the results.

The second robustness check is to test whether the major findings of this paper are sensitive to exclusion of variables based on joint insignificance. This robustness check is conducted using the method of Barslund, et al. (2007). The core variables are those used and reported in Tables 2. The testing variables include those excluded but for which we have data. The robustness check is conducted by running regressions including all the core variables and different combinations of the testing variables. The results indicate that the major findings of this paper remain unchanged.

The robustness of this paper's results is encouraging, but a few major caveats remain. The first major limitation involves the measure of daily vehicle-miles traveled per capita. The method used to collect data on vehicle miles traveled at the state and urban area levels has been long criticized for its inaccuracy since some states rely on direct, although sporadic, vehicle counts, while others rely on indirect imputation. A better approach to reduce the impact of imperfect data is panel-data estimation, accounting for state fixed effects, a focus for future research.

The second caveat stems from inaccuracy or potential measurement errors in the explanatory variables. Rural land rent is not measured at the immediate urban fringe while land-use policy variables are only represented by dummy variables, which cannot capture the impact of regulation details (e.g., minimum lot sizes may vary). The potential measurement errors may bias the results, given the small sample size. Ideally, panel dataset on all urbanized areas with better measurement of variables could be a direction for future research.

7. Conclusion

This paper examines the impact of a wide variety of factors on spatial size, spatial compactness measured by population density and average travel demand measured by daily vehicle miles traveled per capita. The simultaneous equation regression results indicate real average household income has a positive impact on spatial size and average travel demand while a negative impact on urban spatial compactness. Transportation cost measured by fuel cost per mile has a negative impact on both the spatial size and urban spatial compactness. Among the land use policy tools, urban growth boundary has a positive impact on urban compactness while minimum lot size has a positive impact on urban spatial size.

The findings from this paper may have important policy implications. It is worth mentioning that while the findings from this paper are based on the data on the urbanized area level, it is very likely that even in a small urbanized areas, there would be at least several local governments. Policy makers in many smaller communities (edge cities, township, independent school districts may have different policy goals from those in central cities and/or counties. For example, planners and policy makers in the central cities may be more concerned in congestion in the central business district since the boundaries of central cities are not likely to expand. For policy makers at the county level, their concern may be more related to decline in urban compactness and increase in travel demand, which requires higher expenditures on roads and public service. For planners in communities in urban fringe, their concern may be how to maintain or increase their attractiveness to others who has potential desire and ability to relocate to their areas.

If the policy goal is to address declining urban compactness or urban fragmentation, land-use policies may play an important role. Given the findings that urban growth boundary has a negative impact, urban growth boundary (similar to the one implemented in Portland, OR) or urban service boundary (namely, beyond certain boundary, not public service such as water will be provided) may be useful tools. Density based zoning (a zoning that assigns a total allowable number of residents units that may be built on any given parcel of land based on residential density and other applicable criteria) may also serve these purposes well. Given the finding that those areas with higher rural land rent have a higher urban compactness, local government at the urban fringe may buy land at the urban fringe as reserved greenbelt, which could reduce land supply at the urban fringe and increase overall urban compactness.

If the policy goal is to reduce travel demand and urban congestion, those policies that help increase in the overall population density may work given the negative impact of population density on average travel demand. Building new or change existing road into toll roads to city centers could be a used to reduce overall travel demand in congested areas. Land use regulation such as density based zoning and mixed land use policy to balance distribution of employment and population may also help reduce travel demand.

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Table 2. Simultaneous Equation Model Regression Results

Variable	Spatial Size	Spatial Compactness	Average Travel Demand
ln(Number of Households)	0.941*** (26.74)		
ln(Real Average Household Income)	0.498*** (2.82)	-0.616** (2.21)	0.378** (2.14)
ln(Fuel Cost Per Mile)	-0.127*** (3.25)	-0.151** (2.42)	-0.077 (0.18)
ln(Rural Rent)	0.035 (0.93)	0.150** (2.32)	0.055 (1.24)
Minimum Lot Size Zoning	0.122*** (3.25)		-0.068 (1.60)
Urban Growth Boundary	-0.066 (1.59)	0.128* (1.90)	
Elevation Range Index	-0.00003 (0.83)	0.0001** (2.10)	-0.00004 (1.15)
Terrain Ruggedness Index	-0.002 (0.83)		
ln(Violent Crime at the Central City of Urbanized Area)	0.103*** (3.57)	-0.117*** (2.83)	
Number of Vehicle Per Capita			-0.743** (2.20)
ln(Number of Buses Per Capita)			-0.101* (1.76)

ln(Interstate and Express Highway Density)			0.290**
			(4.20)
Strong Growth Management	-0.032	0.128	0.208**
	(0.37)	(0.88)	(2.32)
Moderate Growth Management	0.103	-0.333	-0.037
	(0.72)	(1.41)	(0.26)
State Dummies			
California	-0.223***	0.536***	0.268
	(2.79)	(4.07)	(1.34)
Michigan	0.100	0.055	0.174*
	(1.00)	(0.33)	(1.75)
Illinois	-0.283**	-0.115	-0.237*
	(2.50)	(0.61)	(2.08)
Texas	-0.089	0.603***	0.128
	(1.21)	(4.98)	(0.66)
Number of Cooling Degree Days			0.00009*
			(1.87)
ln(Population Density)			-0.388**
			(2.12)
ln(Spatial Size)			0.081*
			(1.94)
Constant	-5.088**	4.166	1.325
	(2.36)	(1.16)	(0.53)
"R^2"	0.87	0.43	0.41

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Notes.

Note 1. Although the population density can be measured using newer census data available (e.g. 2010), this table containing information on daily vehicle miles traveled is not available for 2010, which makes it impossible to use data in 2010 to run regressions.

Note 2. We also experimented with median household income, but the major results remained unchanged.

Note 3. We also experimented with number of drivers per capita, and the coefficient on this variable was statistically insignificant (z-values range between 0.001 and 0.005). We, therefore, dropped it from regressions.

Appendix A

The comparative static results for the monocentric model are the exactly the same as those obtained by Brueckner (1987), which will not be repeated here. The comparative static results for population density and average travel demand are presented below:

Preliminary Results

The first step in the comparative static analysis is to obtain the partial derivatives of p with respect to x, y, t, and u. Totally differentiating Equation (5), we have

$$v_c[(dy - tdx - xdt - pdq - qdp] + v_q dq = du.$$

Substituting $v_c p = v_q$ from Equation (4) into the above equation and rearranging terms produces

(A.1) $$-v_c qdp = du - v_c dy + v_c tdx + v_c xdt.$$

We derive the following from Equation (A.1)

(A.2) $$\frac{\partial p}{\partial x} = -\frac{t}{q} < 0,\ \frac{\partial p}{\partial y} = \frac{1}{q} > 0,\ \frac{\partial p}{\partial t} = -\frac{x}{q} < 0,\ \frac{\partial p}{\partial u} = -\frac{1}{v_c q} < 0.$$

Following Brueckner (1987, p. 825, n. 6) showing the effect of the spatial utility level on housing consumption, we have the following with appropriate notation change:

(A.3) $$\frac{\partial q}{\partial u} = \left(\frac{\partial p}{\partial u} - \frac{\partial MRS_{qc}}{\partial c}\frac{1}{v_c}\right)\eta,$$

where $\eta \equiv (\partial q / \partial p)_u$ is the Hicksian demand slope.

Our second step is to derive the effects of the above variables on *r* and on *S*, using the results in Equations (A.2) and (A.3). Upon totally differentiating Equations (8) and (9) with respect to φ, where φ stands for the variables *x*, *y*, *t,* and *u*, we get

(A.4) $$\frac{\partial p}{\partial \varphi}h' + ph''\frac{\partial S}{\partial \varphi} = 0$$

and

(A.5) $$(ph' - i)\frac{\partial S}{\partial \varphi} + \frac{\partial p}{\partial \varphi}h = \frac{\partial r}{\partial \varphi},$$

where $h \equiv h(S)$.

Upon substituting $ph' = i$ from Equation (9) into Equation (A.5), it becomes

(A.6) $$\frac{\partial r}{\partial \varphi} = h\frac{\partial p}{\partial \varphi}.$$

Equation (A.4), upon rearrangement, becomes

(A.7) $$\frac{\partial S}{\partial \varphi} = -\frac{h'}{ph''}\frac{\partial p}{\partial \varphi}.$$

We have

To derivate the comparative static results of the exogenous variables on population density D, we first substitute $D = h / q = -(\partial r / \partial x) / t$, then

(A.8) $$\frac{\partial D}{\partial \varphi} = \frac{\partial}{\partial \varphi}\left(\frac{h}{q}\right) = \frac{h'\frac{\partial S}{\partial \varphi}q - h\frac{\partial q}{\partial \varphi}}{q^2}$$

The impact of r_A on D is given as

(A.9) $$\frac{\partial D}{\partial r_A} = \frac{qh'\frac{\partial S}{\partial r_A} - h\frac{\partial q}{\partial r_A}}{q^2} > 0$$

The impact of y on D is given as

(A.10) $$\frac{\partial D}{\partial y}=\frac{qh'\frac{\partial S}{\partial y}-h\frac{\partial q}{\partial y}}{q^2}\gtreqless 0$$

The impact of t on D is given as

(A.11) $$\frac{\partial D}{\partial t}=\frac{qh'\frac{\partial S}{\partial t}-h\frac{\partial q}{\partial t}}{q^2}<0$$

Daily average travel demand is given by equation (13) as below

Upon totally differentiating Equation (13) with respect to φ, where φ stands for the variables x, y, t, and r_a, and rearrange terms, we get

$$\frac{\partial ATD}{\partial \varphi}=\left(\bar{x}^2\bar{D}\frac{\partial \bar{x}}{\partial \varphi}+\int_0^{\bar{x}} x^2\left(\frac{\partial D}{\partial \varphi}\right)dx-ATD\frac{\partial L}{\partial \varphi}\right)/L$$

The impact of y on ATD

(A.12) $$\frac{\partial ATD}{\partial y}\gtreqless 0$$

since $\frac{\partial \bar{x}}{\partial \varphi}>0$, $\frac{\partial D}{\partial \varphi}\gtreqless 0$, $\frac{\partial L}{\partial \varphi}=0$.

The impact of t on ATD

(A.13) $$\frac{\partial ATD}{\partial t}<0$$

since $\frac{\partial \bar{x}}{\partial t}<0$, $\frac{\partial D}{\partial \varphi}<0$, $\frac{\partial L}{\partial \varphi}=0$.

The impact of r_A on ATD

(A. 14) $$\frac{\partial ATD}{\partial r_A} \gtreqless 0$$

since $\frac{\partial \pi}{\partial r_A} < 0$, $\frac{\partial D}{\partial r_A} > 0$, $\frac{\partial L}{\partial \varphi} = 0$.

Appendix B: Test of Endogeneity of Certain Land Use Control Variables

The potential endogenous variables identified for spatial size are minimum lot size and urban growth boundary. The instrumental variable for minimum lot size is the standard deviation of decennial population growth between 1920 and 1970, a measure directly borrowed from Burchfield et al (2006). Based on their discussion, leapfrogging, which is greater as the increase in the level of uncertainty about future growth. The land use control tool such as minimum lot size could also be highly correlated to leapfrogging. Since the standard deviation of decennial population growth between 1920 and 1970 can be positive correlated to the minimum lot size control while not correlated to the error term of the spatial size equation, potentially a strong instrument variable if minimum lot size is endogenous.

The instrumental variables for the land use control of urban growth boundary are the member of Sierra Club (one of grass-root environmental protection organizations fight for the preservation of land and forest). The land use control of urban growth boundary is expected to be positively related to the number of Sierra Club. When the number of instrumental variables is the same as the number of potential endogenous variables, we cannot test whether the instrumental variables are exogenous. In order to do so, we borrow one more exogenous variable from Burchfield et al (2006): the number of restaurants and bars per 1000 residents, a proxy to measure the level of leisure activities in an area.

The potential endogenous variable for the average travel demand equation is expressway and highway density. The instrumental variable is the number of rays, directly borrowed by Baum-Snow (2005). This variable has been proved to be strong and appropriate instrument. The first stage regression results and related tests are presented in Table A1. Please note that the results of dummy variables of states are suppressed.

As we all know, the 2SLS estimator is less efficient than OLS when the explanatory variables are exogenous. It is, therefore, useful to test for endogeneity of those variables suspected to see whether 2SLS is even necessary. Following the method presented by Wooldridge (pp.532), the residuals are obtained from estimating the reduced form for each suspected endogenous variable by regressing it on all exogenous variables (including the state dummy variables). Those residuals are added to the equation and test for significance of the residuals using an OLS regression. The results of test are also reported in the Table B1. From which, we can conclude that we cannot reject the hypothesis that those suspected variables are exogenous.

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Table B1: First Stage Regression Results and Test Results *

Variable	Spatial Size Equation		Spatial Compactness Equation	Average Travel Demand Equation
Potential Endogenous Variable	Minimum Lot Size	Urban Growth Boundary	Urban Growth Boundary	Express and Highway Density
Standard deviation of decennial population growth between 1920 and 1970	**0.006 (2.12)**	-0.004(1.33)		
ln(Member of Sierra Club)	0.19(1.42)	**0.23(1.74)**	**0.12(1.89)**	
Number of Restaurants and Bars	0.18(1.25)	-0.23(1.68)	-0.20(1.61)	
Number of Rays				**0.36(7.23)**
ln(Household)	0.25(3.18)	-0.22(2.73)		
ln(Real Average Household Income)	0.17(0.48)	0.08(0.22)	-0.555 (1.59)	-0.60(3.52)
ln(Rural Land Rent)	-0.03(0.41)	-0.08(0.95)	-0.059(0.72)	-0.05(1.24)
ln(Fuel Cost Per Mile)	-0.06(0.69)	-0.007(0.02)	0.471(0.54)	0.15(0.33)
ln(Violent Crime Rate at Central City)	0.14(2.44)	-0.16(2.56)	-0.056(1.07)	
Strong Growth Control	-0.17(0.93)	0.52(2.74)	1.11(1.59)	-0.03(0.32)
Moderate Growth Control	-0.07(0.25)	0.38(1.25)	0.81(1.23)	0.04(0.29)
Elevation Range Index	-0.00001(0.88)	0.0002(1.62)	0.00004(0.48)	-0.00005(1.64)
Ruggedness Index	-0.0006(0.13)	0.00002(0.04)		
Number of Cooling Degree Days				-0.0001(4.11)
ln(Number of Bus Per Capita)				0.02(0.26)
Number of Vehicle Per Capita				-0.37(0.92)
Over-identifying Restrictions Test				
Sargan Test (P-Value)	1.271(0.2700)		0.724(0.39)	
Basmann Test (P-Value)	1.049(0.3058)		0.642(0.42)	
Test of Endogeneity of Suspected Endogenous Variables with Error Terms Included in the OLS regressions	F (2, 134) = 0.37 P-Value = 0.6924		F (1, 138) = 2.06 P-Value = 0.1533	F (1, 132) = 0.03 P-Value = 0.8628

Note. * the absolute t-value reported in parentheses while the coefficients of state dummies are suppressed.