The Effects of Changes in the Transportation Infrastructure on Suburbanization: Evidence from the Construction of the Interstate Highway System

Nathaniel Baum-Snow

University of Chicago[1]

[1]I thank Alberto Abadie, Gary Becker, Mark Duggan, Austan Goolsbee, Jonathan Guryan, Matthew Kahn, Steven Levitt, Edwin Mills, Casey Mulligan, Chad Syverson and especially Derek Neal for their helpful comments and suggestions. I also thank participants in the Applications Workshop, Micro Lunch and the Emprical Workshop at the University of Chicago and participants in a seminar at Tufts University for their comments. All errors are mine.

Abstract

Between 1950 and 1990, the aggregate population of center cities in the U.S. declined by 16 percent despite national population growth of 64 percent. This paper assesses the extent to which the construction of new limited access highways has contributed to center city population decline. Using planned portions of the interstate highway system as a source of exogenous variation, empirical estimates indicate that the population living in center cities would have grown by 6 percent had the interstate highway system not been built. Calibrations of a land use and commuting model imply that one new highway passing through a center city reduces the center city population by about 18 percent, a magnitude that is consistent with estimates from the data. Further, observed changes in the spatial distribution of the population in metropolitan areas following new highway construction are consistent with theoretical predictions from the model.

1 Introduction

In 1956 Congress passed two pieces of legislation that would forever change the urban American landscape. The Federal Aid Highway and Highway Revenue Acts of 1956 represented the beginning of a major federal funding commitment to highways that would eventually pay for the construction of over 40,000 miles of limited access roads. Meanwhile, despite robust population growth in metropolitan areas, the aggregate population in 1950-definition center cities declined by 16 percent between 1950 and 1990. The primary goal of this paper is to assess the extent to which we can attribute this change in the spatial distribution of the population to the construction of new road infrastructure. Key to the analysis are unique time-series data on the construction of the interstate highway system and on the evolution of the spatial distribution of the urban population in all metropolitan areas in the United States. Estimates indicate that the construction of the interstate highway system alone can account for the full decline in center city population between 1950 and 1990. Had the interstate highway system not been built, estimates indicate that the aggregate population in constant area center cities would have risen by at least 6 percent.

Table 1 documents the evolution of the spatial distribution of the population in metropolitan areas between 1950 and 1990. Despite the facts that the U.S. population grew by 64 percent and that there was net migration from rural areas to metropolitan areas, the population in constant-area center cities fell dramatically during this period. This decrease in 1950-definition center city population was slightly more pronounced in larger cities and considerably more pronounced in cities farther away from physical boundaries like coasts and borders.

There is a wide range of models that could be used to explain falling urban density. For comprehensive overviews, see Glaeser & Kahn (2004) and Mieszkowski & Mills (1993). Two broad strands of literature are most frequently cited as providing important explanations. The first is the local public goods literature. In general terms, it states that heterogenous demand for locally provided services have caused many to flee decaying center cities in search of a different bundle of public goods in the face of an increasing burden being placed on center cities to provide for the poor and disadvantaged. Negative shocks to public goods such as forced school desegregation, housing project ghettoes and increasing crime rates have precipitated such center city decline leading to flight of the more affluent[1]. Because center cities are less politically divisible than surrounding communities, the argument goes, such Tiebout (1956) sorting has led people to the suburbs. This effect may have become exacerbated as the income distribution has become more unequal, increasing demand for more differentiated public goods. Epple & Sieg (1999), Nechyba (1997) and Fernandez & Rogerson (1996) are examples from this Tiebout literature.

The second strand of literature revolves around the land use theory first developed extensively by Alonso (1964), Mills (1967), and Muth (1968) of which Fujita (1989) gives a detailed overview. In its simplest form, this theory assumes all employment occurs at a central location and the rental rate of land adjusts as a function of distance from the center to compensate for different commuting times of identical agents. A standard extension allows for heterogeneity in various factors that affect the demand for space and the value of commuting time. The model predicts, for example, that increases in nonlabor income or family size are forces pushing people away from the center because both push up the demand for space without changing the value of commuting time. Rising wages cause a more dispersed spatial distribution of residences if the income elasticity of demand for space is greater than the income elasticity of marginal transportation cost, which is near 1[2]. Higher commuting speed also implies lower population density in this model.

The patterns in Table 1 suggest that a significant fraction of the population dispersion away from center cities is independent of boundaries determining the provision of public goods. The fact that constant area central city population fell significantly faster than central city population within political boundaries implies that space is an important factor needed to explain falling urban population density. Over one-half of center cities in all samples more than doubled in area between 1950 and 1990; over half of those that did not expand are constrained by existing surrounding communities and are located near a coastline. As seen in Panel D, center cities that

[1] For example, Detroit went from 16 percent black in 1950 to 76 percent black in 1990 with median family income falling from $28,000 to $25,000 (1999 dollars) over this period.

[2] There is little empirical evidence to suggest that the income elasticity of demand for space is greater than 1. Wheaton (1977) and Gleaser et al. (2000) estimate this parameter.

grew fastest in population had the sharpest decrease in central population density. Of the four samples in Table 1, the sample in Panel D also had the largest average increase in center city area. Tiebout sorting models imply that people moving further from the core would endeavor to form new communities that provide different levels of public services, not relocate within the same political jurisdiction[3]. Inspection of maps of incorporated cities and towns reveals that coastal metropolitan areas are more politically fractured than the metropolitan areas of the South and West. Yet Table 1 shows that they have experienced less population dispersion.

While there is no lack of theories that can be used to explain urban population decentralization, there is little empirical consensus as to the relative importance of these theories. Part of the lack of consensus is due to the difficulty of constructing relevant data and part is due to a paucity of sources of exogenous variation in potential explanatory variables. The empirical strategy used in this paper exploits the fact that an observable portion of the national road network was designed to link far away places and not to facilitate local commuting. As a result, some metropolitan areas received more interstate highways than others simply because they are more centrally located. I take several approaches in tandem to exploit this variation in interstate highway assignment. The first is to perform an adjusted difference in difference comparison in suburbanization rates between metropolitan areas with many highways and those with fewer. In this approach, I instrument for the total number of highways built with the number of highways in a 1947 national interstate highway plan. Secondly, I estimate MSA fixed-effects regressions using the full 1950-1990 panel. In the panel estimation, I instrument for the stock of highways in each year with rays in the 1947 plan times the fraction of federally funded interstate mileage completed in that year in the state of the MSA's center city. 1990 is used as the end point of the analysis because construction of the planned interstate system was complete by this time and ample time had been available for individuals to relocate in response to changes in the transportation infrastructure. The measure of "highways" used is the number of "rays" emanating from center cities. This measure is convenient in that it is somewhat comparable between urban

[3]There are clearly some public goods, like crime, that are more neighborhood based than city based. This argument could only be applied to citywide services such as schools.

areas, is easily verifiable by looking at a map and can be simply incorporated into existing urban theory.

This paper proceeds as follows. Section 2 describes some relevant institutional details about how the interstate highway system was planned, Section 3 outlines a theoretical mechanism for suburbanization and presents some simulation results, Section 4 describes the data, Section 5 discusses some patterns in the data, Section 6 presents estimation results, Section 7 discusses interpretation, robustness and implications of the results and Section 8 concludes.

2 The Planning and Construction of The Interstate Highway System

Significant federal involvement in the planning and construction of limited access highways did not begin until during World War II. Before WWII, the federal Bureau of Public Roads (BPR) and later the Public Roads Administration (PRA) were largely limited to advising, serving as an information clearinghouse, and enforcing federal standards on the small quantity of roads constructed with federal funding. The state of the national road network in 1950 was such that there were only 341 miles of limited access highways in the United States that would be integrated into the interstate system. By 1990 the interstate system had grown to 43,414 miles. During this time, mileage in metropolitan areas grew from 164 to 20,439.

The Federal Aid Highway Act of 1944 marks the beginning of significant federal involvement in the planning of a national system of limited access highways. The 1944 legislation instructed the PRA commissioner to formulate a plan for a national system of interstate highways. It stipulated that the system was to be ". . . so located as to connect by routes as direct as practicable, the principal metropolitan areas, cities, and industrial centers, to serve the national defense, and to connect at suitable border points with routes of continental importance in the Dominion of Canada and the Republic of Mexico . . ." In its report that shaped the 1944 legislation, the National Interegional Highway Committee considered the nationwide distribution of population, manufacturing activity, agricultural production, the location of post-WWII employment, a strategic highway network drawn up by the War Department in 1941, the location of military and naval establishments, and interregional traffic demand (in that order) to inform its recommended interregional highway system plan (National Interregional Highway Committee 1944). Furthermore the 1944 highway act does not mention anywhere that these highways should be designed to serve local commuting (Dept. of Transportation, page 277). States were asked to submit proposals for their portion of the interstate highway system in response to the recommended national plan from the Interregional Highway Committee. Over the following three years, each state highway department negotiated with the Public Roads Administration over its portion of the comprehensive national plan. In 1947, roads commissioner MacDonald approved final proposals from the states for 37,324 miles of roadway to be built to federal interstate standards. This plan represents most of the system we see built today, some of it not to be finished until the 1980s. A map of this 1947 plan is presented in Figure 1[4].

Highways in the 1947 plan received minimal federal funding before the Federal Aid Highway and Highway Revenue Acts of 1956. The 1956 Interstate Highway Act expanded the mileage from the 1947 plan to a 41,000 mile interstate system and committed the federal government to pay 90 percent of the cost of construction. A reporting mechanism was put in place such that the federal government was given a record by the states of completion dates of various levels of construction for federally-funded highways. It is these data that form the basis of the empirical analysis done here. Of special importance for the analysis below is that the 41,000 mile system approved by Congress amounted to an itemized list of highways to be built. States requested money each year based on cost of construction and funds were allocated at the discretion of the Federal Highway Administration. Critical to this anlaysis is the 90-10 federal-state cost sharing formula. With such a strong commitment by the federal government to build the interstate system, it becomes hard to argue that some of it was not built because of the lack of state funds. Indeed, by 1999 virtually the entire 1947 plan was built, with the addition of 9,092 miles of which

[4]The 1944 report outlined a recommended plan of 33,920 miles of interregional highways. The majority of these highways survived to the 1947 plan.

3,477 were funded exclusively at the local level (FHWA, 2001). Appendix C discusses in more detail the funding and taxonomy of limited access highways.

The primary highway measure used in this paper is "rays". For the purposes of this analysis, a "center city ray" is defined as a segment of road that connects the central business district of the largest center city of an MSA (as defined by its population in 1950) with the region outside the center city. If a highway passes through the center city, it counts as two rays whereas if a highway terminates in or near the center city it counts as only one. Center city rays may include 2-digit and 3-digit interstate highways as well as limited access non-interstate highways[5]. Table 2 shows the evolution of highway construction over time and the distribution of rays by MSA population. Panel A section 1 includes all center city rays from interstate highways while section 2 shows the distribution of non-interstate rays. Panel A demonstrates that most construction of urban interstates occured during the 1950s and 1960s, with very little occuring in the 1980s. There is considerable heterogeneity in the specific location of highways. While each MSA ended up with at least as many interstate highway rays as were assigned in the 1947 plan, a significant fraction of these rays do not pass near enough to the central business district to be counted as "center city rays"[6]. The large majority of center city rays are interstate highways. Only 67 of 458 center city rays constructed between 1950 and 1990 are not part of the interstate system.

Table 2 Panel B shows the distribution of center city rays built between 1950 and 1990 by MSA population in 1950. While larger metropolitan areas received more highways, even some of the smallest metropolitan areas received up to 4 center city rays and one large metropolitan area (San Francisco) received only one center city ray between 1950 and 1990. Furthermore, while the 1947 plan gives more highways to larger MSAs in general, there still remains considerable variation at the top. Indeed only one of the seven MSAs with at least six center city rays had more than 1 million people in 1950[7]. Partly because the 1947 plan was designed to connect

[5] I only observe the stock of non-interstate limited access highways in 1990, not the flow over time. I assume that none existed in 1950.

[6] In 61 of 240 cases, the number of observed center city interstate rays in 1990 is less than the number assigned in the 1947 plan. However, only 16 cities fall into this category using a more liberal definition in which center city rays can pass up to 4 miles from the CBD instead of just 1 mile.

[7] In order of 1950 population, these MSAs are Orange County CA, San Antonio, Dallas, Atlanta, Houston,

metropolitan areas, there is considerable variation in highway construction within metropolitan area size, and at least some of this variation can be attributed to geographic location. Eight MSAs with fewer than 100,000 people got at least 3 rays in the plan, all but one of which is located far from a coastline or border[8]. Details about how the sample of MSAs was constructed and the precise rules for assigning center city rays are discussed in more detail in Section 4 below.

While we know a lot about the the data generation process for interstate highways at the state level, it is less clear how states determined which interstate highways to build first and where to build extra highways. Indeed this is a key potential source of endogeneity. If states built highways first in areas where there was a high demand for suburbanization, we may erroneously attribute growth in suburbanization to highways when the direction of causation would in fact be reversed. Moreover, even if highway construction is exogenous, limited access highways do not fully capture the transportation network available in cities.

The validity of the 1947 plan as an instrument depends on the fact that the portion of the system in the plan was designed to facilitate trade and national defense, not to facilitate metropolitan area development. Further, it requires the availability of data on control variables that are relevant to determining suburbanization and are correlated with the plan. Appendix Table 2 presents data showing that states constructed the urban sections of their planned federally funded highway system earlier than sections in rural areas. This unbalanced construction timing is evidence that commuting demand was a criterion states used in determining their highway construction priorities. A time-varying instrument must take into account this endogeneity in construction timing. As such, in panel regressions I instrument for the stock of highways with the (potentially fractional) number of rays that would have existed in each year had state governments allocated federally funded highway construction uniformly across space.

Demographic data from 1940 and 1950 provide support for the claim that the 1947 plan is exogenous to suburbanization. A regression of the change in center city rays between 1950

Kansas City and Chicago.

[8] In order of 1950 population, these are Pocatello, Cheyenne, Billings, Sioux Falls, Daytona Beach, Bloomington IL, Hagerstown and Fargo.

and 1990 on the change in log center city population between 1940 and 1950 yields a highly positive coefficient of 1.24 (se=0.67). However, the same regression using planned rays as the independent variable yields a coefficient that is not significantly different from 0 of 0.06 (se=0.63). If 1940 MSA population is included instead in each of these regressions, the coefficient on 1940 population is large and significantly different from 0 for both total center city rays and planned rays. Non-white population and high school graduation rates in 1950 cannot predict either observed highway construction or planned rays. These results give some indication that the federal government planned more highway construction in big cities as they existed in 1940, not to serve fast growing cities or cities that may have had pressures for racial or social segregation. However, cities receiving fewer rays in the plan than would serve their population growth found other ways to pay for needed highways. It also indicates the importance holding population constant in an evaluation of the effect of rays on suburbanization.

3 Theoretical Foundations

To fix ideas about how we may expect new highway infrastructure to affect suburbanization, I adapt a version of the standard monocentric city model to allow for heterogeneity in commuting speeds. In this model's most simple form, all workers must commute to the center to work and locate based on the tradeoff between lost wages due to travel time and their preference for space. The endogenously determined land rent function distributes identical individuals over the available land such that in equilibrium, everyone's utility is equal and population density is decreasing in commuting time. While there is mixed evidence on the value of this model for explaining the spatial distribution of the population by income (Glaeser et al., 2000 and Wheaton, 1977), it provides some useful intuition about the forces at play in determining the spatial distribution of a homogenous population[9].

The implications of extending this model to allow for heterogenous travel speeds have not

[9] Hamilton and Roell (1982) argue that the monocentric model is also unsatisfactory at predicting the equilibrium distribution of commuting times.

been extensively explored. Some past work (as in Leroy and Sonstelie, 1983) has introduced heterogeneity in commuting speed through different travel modes. While allowing mode choice is clearly a relevant approach for a few big cities, in only 6 MSAs did at least 20 percent of the population commute by public transportation in 1960 and by 1990 this had dropped to just one (New York). Moreover, most previous versions of this model have symmetric or one-dimensional space. By including transportation corridors along which travel speed is greater, the version presented here introduces heterogeneity in commuting times such that in equilibrium there exists heterogeneity in residential density at a given radius from the city center. This model is similar in many ways to that formulated by Anas and Moses (1979). The goal in developing this version of the model is to create a tractable theoretical basis that informs the empirical work to follow. Calibration of the model yields effects of new highways that are consistent with the empirical results presented in Section 6.

Each metropolitan area is treated as its own general equilibrium system in which there is a continuum of N individuals, each of whom commutes to the center and earns an exogenously given wage w per unit time. The distance from the central business district to the border between the center city and the suburbs, denoted r_c, is exogenously determined. Households have direct preferences over a consumption good z and land s. I denote the compensated demand functions as $\widetilde{z}(R, u)$ and $\widetilde{s}(R, u)$, where R is the price of land and the price of the consumption good is normalized to 1. Individuals face a budget constraint and a time constraint. Travel at speed $\frac{1}{b}$ is possible along any ray from the origin and along any line perpendicular to a highway. Highways are modelled as rays emanating from the city's core along which the travel speed is $\frac{1}{b\gamma}$. Rays are distributed evenly such that they serve the maximum number of people possible. M denotes the number of rays in the city. I index space in polar coordinates (r, ϕ), where ϕ is the angle to the nearest highway ray. Given this commuting technology, the minimum time it takes to travel from the center $(0, 0)$ to (r, ϕ) is $L(r, \phi) = \min[br, br\widetilde{L}(\phi)]$, where $\widetilde{L}(\phi) = \gamma\cos(\phi) + \sin(\phi)$[10].

[10] Inspection of maps reveals that most city streets travel along straight lines. I use the technology $\widetilde{L}(\phi) = \gamma\cos\phi + \sin\phi$ because it yields the most conservative effects of a new ray in the simulations while retaining travel along straight lines only. Anas and Moses (1979) use the technology $\widetilde{L}(\phi) = \gamma + \phi$ in which travel along any ray through the center or around any circle centered at the CBD is possible at speed $\frac{1}{b}$. Appendix A.3 explores a

Optimizing individuals use the highway for part of their commutes if $\phi < \widetilde{\phi}$ where $\widetilde{\phi}$ solves $\widetilde{L}(\phi) = 1$. Define $\overline{\phi} = \min[\widetilde{\phi}, \frac{\pi}{M}]$. If $\widetilde{\phi} > \frac{\pi}{M}$, everybody uses the highway for part of her commute. If $\gamma = 0.5$ there exist people who do not use a highway for any part of their commutes for $M \leq 5$. I set the pecuniary cost of commuting to 0[11]. Each ray affects the commuting time in the wedge bounded by angle $\overline{\phi}$ on either side of it. In the remaining land, determined by the angle $2\pi - 2M\overline{\phi}$, commuting time is not affected by the rays. Metropolitan areas are large enough to accommodate the mass of N individuals with the urban fringe $r_f^M(\phi)$ endogenously determined by the equilibrium rent function and the market rental rate for rural land. Denote $\overline{r}_f^M = r_f^M(\phi)$ for the region $\phi \geq \widetilde{\phi}$ (if it exists). The bid-rent function for space is denoted $\psi[L(r,\phi), u] = \max_s \left\{ \frac{w[1-L(r,\phi)]-Z(s,u)}{s} \right\}$ and is equal to the market land rent at (r, ϕ). Because everyone is identical, this economy is in equilibrium when utility is the same for everyone and no individual feasibly can be made better off by moving. Fujita's (1989) detailed proof of existence of the equilibrium applies with the replacement of distance to the center with travel time.

This model retains the primary standard results of the classic monocentric city model, except that the uniform linear correspondance between travel time and distance to the center is broken. In this version of the model, land rent is decreasing and convex in travel time from the city center but not necessarily distance. The size of the metropolitan area is determined jointly by the demand function for space, a condition stating everyone has a place to live and an equation that equalizes rent at the edge of the populated area to rural land rent:

$$\psi(b\overline{r}_f^M, u^M) = \max_s \left\{ \frac{w[1 - b\overline{r}_f^M] - Z(s, u^M)}{s} \right\} = R_a \tag{1}$$

Solving equation 1, we have $\overline{r}_f^M = q(u^M)$. Substitution of the demand function and the rear-

third technology in which travel along any straight line in the city at speed $\frac{1}{b}$ is allowed. Qualitative theoretical results of the model are insensitive to the choice of these three commuting technologies. Quantitative results are insensitive to the choice of this technology or the Anas/Moses technology.

[11] As long as pecuniary travel cost is an increasing linear function of $L(r, \phi)$, its exclusion does not affect the qualitative urban form implied by this model. Provided the wage is high enough that pecuniary travel cost is a small fraction of income, it will not matter quantitatively either.

ranged fringe rent function into the market clearing condition for space yields:

$$\begin{aligned} N &= 2M\int_0^{\overline{\phi}}\int_0^{\frac{q(u^M)}{\widetilde{L}(\phi)}} \frac{rdrd\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi),u^M),u^M]} \\ &\quad +(2\pi-2M\overline{\phi})\int_0^{q(u^M)} \frac{rdr}{\widetilde{s}[\psi(br,u^M),u^M]} \end{aligned} \tag{2}$$

Equation (2) determines the equilibrium utility level u^M in the city.

A new highway ray represents a decline in commuting time for a sector of the metropolitan area. This decline in commuting time elicits two effects. First, the price of land decreases because more land is accessible for a given commuting time. As a result, agents look to increase land consumption via a price effect and some are thus inevitably pushed further from the center. Second, average net income rises, causing people to consume more land (assuming land is normal) through a wealth effect, also pushing them away from the center. The new highway thus causes the equilibrium utility level in the city to rise. While the average population density in the metropolitan area declines, the sector nearest the urban fringe may have increased population density due to the population movements caused by the new highway. Thus r_c must be sufficiently small if center city population is to decline with each new highway ray[12].

Figures 2 shows an example of simulated equilibrium population density functions for identical metropolitan areas with 0 and 1 rays. Figure 2 highlights how population density and the shape of the metropolitan area change with a new ray. Population density increases around much of the highway yet decreases in areas far from the highway and near the center of the city. The metropolitan fringe at $\phi > \overline{\phi}$ falls with the introduction of the highway as population spreads out to follow the highway. Figure 3 shows how the changing shape of the bid-rent function implies the different city structures in 0, 1 and 2 ray environments. The shape of the population density functions look similar to the bid-rent functions depicted in Figure 3.

[12] Simulated examples with various demand functions reveal that r_c has to be very near the fringe in order center city population to rise with a new highway. I choose a parameterization of the model such that the quantitative implications of a new highway are not highly sensitive to the choice of r_c.

The model also predicts that the center city population rises with the radius of the center city and MSA population N, and that population near the center rises with the inverse base travel speed b and the speed ratio on city streets to highways γ. Population near the center rises with w if the income elasticity of demand for space is less than 1. The relevant analytical implications of the model are collected in the following lemmas.

Lemma 1 *If* $M' = M + 1$ *then in equilibrium*

i) $u^{M'} > u^{M}$

ii) $\overline{r}_f^{M} > \overline{r}_f^{M'}$

iii) $\frac{\overline{r}_f^{M'}}{\gamma} > \overline{r}_f^{M}$

Proof. *See Appendix A.* ■

Lemma 1 states that an additional ray implies i) a higher equilibrium utility level, ii) a shorter distance from the center to the metropolitan area fringe in directions (if they exist) not affected by any highways and iii) that the metropolitan area fringe at each highway is further from the center in the new regime than the fringe not near highways in the old regime.

Lemma 2 *The center city population* N_c *is increasing in center city radius* r_c *and MSA population* N*. Population near the center is decreasing in number of highway rays* M*. Population near the center is increasing in inverse base travel speed* b *and travel speed ratio* γ*.*

Proof. *See Appendix A.* ■

To get a sense of functional form and the magnitudes of population response to highways, I calibrate several examples with different utility functions and parameter values. Using the utility function $U(z, s) = z + \alpha \log s$, Appendix B.1 derives the following expression for center city population[13]:

$$N_c = \frac{R_a}{\alpha} e^{b\overline{r}_f^M} (\frac{wb}{\alpha})^{-2} * \left[\begin{array}{c} 2M \int_0^{\overline{\phi}} \widetilde{L}(\phi)^{-2}(1 - e^{-r_c wb\widetilde{L}(\phi)/\alpha} - r_c \frac{wb}{\alpha} \widetilde{L}(\phi) e^{-r_c wb\widetilde{L}(\phi)/\alpha}) d\phi \\ +(2\pi - 2M\overline{\phi})[1 - e^{-r_c wb/a} - r_c \frac{wb}{\alpha} e^{-r_c wb/a}] \end{array} \right] \quad (3)$$

The analogous expression in the Cobb-Douglas case is reported in Appendix B.2. I focus on the quasilinear utility results because quasilinear utility has an income elasticity of demand for space of 0, thus will exhibit relatively small responses to better transportation infrastructure. Further, the choice of commuting technology $\widetilde{L}(\phi) = \gamma \cos\phi + \sin\phi$ limits the influence of new highways more than any other technology in which travel only along straight lines is possible. For the purpose of numerical simulations, quasilinear utility is also convenient because results are very stable over a wide range of parameter values for α, b, w and N. Because of the choices of utility function and commuting technology, these simulation results represent a near lower bound on the effect we should expect to estimate empirically.

Taking center city population in the 0 ray equilibrium as given, Table 3 traces out the evolution of $\Delta\log(N_c)$ as a function of the number of rays. Each panel displays the evolution of $\Delta\log(N_c)$ under different assumptions about speeds on surface streets and highways. Changing these two speeds while holding the ratio γ constant does not affect results. Results are also identical for reasonable values of N, w and the shape parameter α. Panel A shows that if speed on the highway is double the speed on surface streets, in a 0-ray equilibrium in which half the population lives in the center city, the first ray causes the log center city population to fall by 0.11, with the fall in center city population declining 1-2 percentage points for each additional ray. The percent decline in center city population falls with increases in initial center city share and r_c. Panels B and C show that the magnitude of these marginal effects are a decreasing function of γ. Simulation results using the Anas-Moses (1979) commuting technology in which $\widetilde{L}(\phi) = \gamma + \phi$ give effects for $\Delta\log(N_c)$ within 0.02 smaller in magnitude than those in Table 3.

[13] One slightly counterintuitive feature of this expression for N_c is that N_c is an increasing function of $\overline{r}_f^M$. To understand this, note that $\overline{r}_f^M$ does not represent the average fringe distance of the city but the distance to the portion of the fringe (if it exists) for which $\phi > \overline{\phi}$. Higher M implies a lower $\overline{r}_f^M$.

Analogous results using a Cobb-Douglas utility function show much larger effects for the first few rays because of the higher income elasticity of demand for space. The Cobb-Douglas results are reported in Appendix Table 3.

The analytical and simulation results of the model lead to three primary implications that are evaluated in the empirical work in the remainder of the paper. First, population in metropolitan areas should spread out along new highways in a similar fashion to that seen in Figure 2. Second, center city population should increase with metropolitan area population and the area of the center city. Third, center city population should decline with the number of highway rays[14]. Using quasilinear utility, the profile of $\Delta \log(N_c)$ for each marginal ray is decreasing for the first few rays, while with Cobb-Douglas utility it is approximately linear if 50% of the population lives in the center city in the 0-ray equilibrium. A log-linear regression specification reasonably captures the profile of center city population response to the number of rays, though specifications with more flexible functional forms are also explored in Section 6.

4 Data

I use a variety of data sources for this analysis: highway segment opening dates from the Federal Highway Administration, Geographic Information Systems data on the location of census tracts and interstate highways, city county data book aggregates for MSAs and places, PUMS census microdata, 1982 Economic Census reports on the location of central business districts (CBDs) and 1993 Highway Performance Monitoring System (HPMS) data.

The highway construction data are from the Federal Highway Administration's "PR 511" records. As part of the agreement for providing funds to build and maintain the nation's system of interstate highways, states were required to report on the progress of construction of all interstate highways within their borders. Each record in the data represents a highway segment

[14]Though in theory there are cases in which a center city that spatially encompasses a large fraction of the metropolitan area may actually gain population with a new ray, in none of a large set of simulations with different utility functions and parameter values did center city population grow with the number of rays.

ranging from 0.1 miles to 50.5 miles in length and includes dates when various levels of planning and construction were completed. The data set contains less complete information on portions of the interstate system constructed before the 1956 Federal Aid Highway Act, much of it toll roads, and locally funded Section 103(c)(4)(a) segments. Checks of other sources verify that the data are accurate to when the road first opened to traffic under interstate standards, though in the case of the Section 103(c)(4)(a) segments, this may represent a minor upgrade of an existing road. Only about half of the 3,477 Section 103(c)(4)(a) mileage is observed in the PR-511 data. Based on detailed investigation of these cases, I assign opening dates to segments of Section 103(c)(4)(a) highways that are not observed in the PR-511 data based on reports of "roadfans" who have kept Internet highway histories. The PR-511 data set allows for separate identification of segments funded as part of the 1956 federal highway act, segments authorized and funded later by the federal government, locally funded segments and toll segments.

I combine the PR-511 data with spatial highway data taken from the 1990 Census Tiger line files to create a data set containing the miles of interstate highway in each county in each year between 1950 and 1990. I select "center city rays" based on visual inspection of each potential ray in the context of what is closest to the definition of "ray" in the model. Center city rays must pass within 1 mile of the CBD and serve a significant area of the MSA outside the 1950-definition center city. Highways that split in or near the border of the 1950-definition center city count as multiple center city rays. Though they may exist inside the central city limits, many beltways, short spurs and connectors do not count. Two highways that pass within one mile of the CBD and converge count as only one ray in the direction of convergence. Since interstate naming follows no consistent convention, both 2-digit and 3-digit interstate highways may be considered center city rays[15]. Interstates with two labels (80-90 in Toledo, OH for example) count as one highway. Limited-access expressways that are not part of the interstate system but satisfy all of the listed criteria also count as rays, though only when considering changes in

[15] For example, in Des Moines, Iowa the highway running through the center city is named I-280 while I-35/I-80 circumvents the city. In Peoria (Figure 4) I-74 runs through the city and I-474 circumvents the city.

infrastructure between 1950 and 1990[16]. As a robustness check, I also consider highways that pass within 4 miles of the CBD as an alternate measure. The correlation between the growth in the two measures of rays between 1950 and 1990 is 0.75. The correlation between the growth in interstate center city rays and total center city rays is 0.92[17].

I define MSAs as county agglomerations using the census definition as of April, 2000[18]. If the MSA existed in 1950 then the 1950 central city definitions were used for the whole panel 1950-1990. For MSAs that formed since 1950, I use a constant central city definition based on data available in 1950. I relegate all but the largest central city in each MSA, based on 1950 population, to be part of the suburbs. Data was constructed for some 2000-definition MSAs not defined yet in 1950 because center city data was available. Data for counties and central cities is taken from the 1940-1990 city-county data books and then aggregated appropriately to form MSAs. Since the city county data book only reports data on cities of at least 25,000 inhabitants, some 2000-definition MSAs are excluded for lack of data. Only MSAs for which there exists center city data in both 1950 and 1990 are included in the sample.

One particularly vexing issue is that over half of the center cities in the sample annexed land over time as their populations decentralized. This phenomenon is especially widespread outside the northeast and midwest. It would be difficult to account for this with theory or econometrics given that city size expansion was clearly endogenous to suburbanization. To deal with this, printed census maps from 1950 were used to match digital maps of 1970 and 1980 census tracts to 1950 geography. I then aggregated census tracts based on these visual comparisons such that

[16] I only observe the stock of non-interstate expressways in 1990 so I cannot make use of time-series variation in their construction.

[17] None of the empirical results reported in this paper are highly sensitive to whether center city rays are defined to pass within 1 mile or 4 miles of the CBD or to whether non-interstate rays are included.

[18] County-based MSAs were used for New England. The criteria used by the Office of Management and Budget (OMB) to choose central cities is important since the empirical definition of "suburban" in this analysis is anything outside of the central city. In the context of the theory outlined above, we would like to define central cities based on their status as employment hubs. In practice, the criteria used are pretty well in line with this definition. The OMB classifies places as a central city if they are the largest incorporated place in an MSA of at least 10,000 people, they are any additional place with at least 250,000 residents or 100,000 workers, they are any additional place of 50,000 – 250,000 residents where the number of jobs exceeds the number of employed residents or they are any additional place 10,000 – 50,000 residents that have at least $\frac{1}{3}$rd the population of the largest place and the number of jobs exceeds the number of employed residents.

the aggregate 1970 and 1980 areas matched as close as possible the land area of the 1950 city geography. In order to avoid understating the post-1950 population, the post-1950 central city area was constructed to always exceed the reported 1950 area. Reported conversion factors map 1980 tracts to 1990 tracts. Tracts from 1960 whose centroids fall inside the constructed 1950 geography as approximated with 1980 tracts were aggregated to form the 1960 cross section. 1960 tract centroid coordinates were taken from the Elizabeth Mullen Bogue file. Cities for which 1950 census maps do not exist had their 1950 geography constructed by visual inspection of the tract data.

Peoria, IL is instructive for highlighting some features of how the data were constructed. Figure 4 displays two maps of Peoria. The Peoria MSA is made up of Peoria, Woodford and Tazewell counties. Within the MSA run I-74, I-474, I-39 and I-155. As seen in Figure 1, I74 was part of the 1947 plan while I-39 and I-155 were not. In fact, I-39 is a Section 103(c)(4)(a) highway that was funded by the state of Illinois and integrated into the interstate system in the mid-1980s. I-155 was not built until the 1990s so is not part of the analysis. The right panel displays the census tracts that make up Peoria as of 1980. Inspection of the 1950 census Peoria urbanized area map reveals that in 1950 only census tracts 2-26 were within the city limits. The area of the city increased from 12.9 square miles in 1950 to 40.9 square miles in 1990. For the purposes of this analysis, the "center city" of Peoria is counted only as tracts 2-26 and the population in the remaining area is counted as living in the suburbs. Peoria gets counted as having 2 center city rays and 2 rays in the plan.

5 Changes in the Spatial Distribution of Residences

Before outlining an econometric strategy, I explore how closely the raw data reflect the predictions of the model in Section 3. Despite the highly stylized nature of the model, it accurately captures the observed spatial pattern of residential development in many cities. As an example, Figure 5 shows the development of the Austin, TX MSA between 1950 and 1990. Austin is a convenient case study because it lies between two larger cities (Dallas and San Antonio), it is one of the largest cities to have only 2 rays and it lies in an area largely unimpeded by natural and political boundaries. Interstate 35 opened through Austin in the 1950s. Even as population of the metropolitan area grew rapidly, the downtown area north of the river lost population between 1950 and 1980, after which its population stabilized. Furthermore, nearly all of the new residential development between 1950 and 1990 occured along the north-south highway and not in the east-west direction. The spatial pattern of Austin's residential development is highly consistent with the spatial patterns predicted by the model.

Table 4 presents a more systematic description of the residential structure of metropolitan areas in the data. Each column in Panel A lists census tract-level OLS regression results from estimating Equation (4) using cross-sectional data in 1970 and 1990 and four different samples.

$$\log P_{ij} = a_i + \beta(dis_{ij}^{cbd}) + c(dis_{ij}^{hwy}) + \varepsilon_{ij} \tag{4}$$

P_{ij} denotes the population per square mile in census tract j of MSA i. dis^{cbd} is the distance from the tract centroid to the central business district and dis^{hwy} is the distance to the nearest interstate highway. I calculate the locations of Central Business Districts as the centroid of the census tracts of CBDs reported in the 1982 Economic Censuses Geographic Reference Manual. The functional form in Equation (4) has been used extensively for estimation of urban density functions (Clark 1951, McDonald 1989) and in the absence of highways it is implied by the quasilinear utility example in the theory section[19]. The first-difference version reported in Panel B includes the distance to the CBD and to any highways that existed in 1970 as controls. Estimates of β from the two cross-sections are in line with estimates from earlier studies.

The results in Table 4 demonstrate that in general, population density is higher near highways. Regressions using the 1970 and 1990 cross-sections show that in MSAs with large populations with CBDs at least 20 miles from a coast or border, the population density decreases by 3 to 4

[19] Appendix B.1 shows that quasilinear utility implies that population density at point (r, ϕ) is $\frac{R_a}{\alpha} e^{\frac{w}{\alpha} b\overline{r}_f} e^{-\frac{w}{\alpha} L(r,\phi)}$.

percent for each additional mile from a highway. The magnitude of this estimated gradient is larger when the sample is selected to include only MSAs with greater population and that are further from a coast or border. All coefficients on distance to the nearest highway are statistically significant. Panel B of Table 4 shows that population density increases around new highways by about 1 percent for each mile of reduction in distance. The statistically significant coefficient of 0.02 on distance to CBD in Panel B is evidence that a significant amount of population decentralization occured in areas unaffected by new highway construction. In sum, Table 4 demonstrates that the patterns seen in Austin also manifest themselves in the rest of the data, though to a somewhat lesser extent[20].

Table 5 explores the relationship between population decentralization and highway construction. The model in Section 3 suggests that a suburbanization measure that is likely to be consistent across metropolitan areas with a range of different structures is the change in log center city population. However, simulations of the model hold MSA population constant while in the data there exists considerable heterogeneity in MSA population growth. In the most select sample, population growth ranged from less than minus 50 percent to over 100 percent between 1950 and 1990. In order to account for this heterogeneity in MSA population growth, Table 5 presents means of the log center city population share in 1950 and 1990 as a function of the difference in the number of center city rays.

Table 5 highlights several features of the data that are worth noting. The full sample in Panel A exhibits a decreasing monotonic relationship between the decline in log center city population share and growth of between 2 and 6 center city rays. This relationship becomes stronger as the sample is selected to include only the class of MSAs that is most relevant to the model. The sample in Panel D only includes larger MSAs that are enencumbered by a coast or border. This sample produces a monotonic relationship between 1 and 7 rays. Given that the sample in Panel D is most relevant to the model, it is the primary sample used in the remainder of the empirical analysis. The means presented in Table 5 Panel D imply that the average effect of

[20] The coefficients on dis^{hwy} for regressions including only tracts in the Austin MSA are -.22 in 1970 and -.19 in 1990.

one ray is associated with a decline in log center city population share of approximately 0.07 if 0 rays are included and 0.10 if 0 rays are excluded, numbers which are similar in magnitude to the simulation results using quasilinear utility[21].

The anomaly at 0 rays exists primarily for two reasons. First, cities that received 0 rays are smaller geographically than other cities. When the small size is controlled for in the regressions, the anomaly partly disappears. Second, many cities that received 0 rays could reasonably have been counted as receiving 2 rays. This manifests itself in the fact that the declines in average log center city population shares between 1950 and 1990 in cities with 0 and 2 rays are very similar at 0.76 and 0.77. In order to be as consistent as possible with the model, cities in which all highways pass more than 1 mile from the CBD were assigned 0 center city rays. Regressions using a less restrictive definition in which highways within 4 miles of the CBD may count towards center city rays yield OLS coefficients of -0.09 excluding 0-ray MSAs and -0.10 including 0-ray MSAs.

6 Results

Table 5 shows a pattern of responses of suburbanization to highway expansion that we should expect to persist in the regressions. Commensurate with the theory section and the evidence from Table 5, the primary dependent variable of interest is the log difference in center city population, where the center city is defined by its boundaries in 1950. The primary independent variable of interest is the change between 1950 and 1990 in the number of highway rays emanating from center cities. Log difference in total MSA population also enters as an independent variable. In addition to difference regressions, this section also presents panel estimation results that include MSA fixed effects using data from the intervening years. In some specifications, the number of rays in the 1947 national plan enters as an instrument for the number of center city rays. In the panel estimation, predicted rays using state-level construction rates enters as the instrument.

[21] These average rates of decline are the coeffiicients on Δray in a simple regression of $\Delta \log(\frac{N_c}{N})$ on Δray. Both coefficients are significant at the 5 percent level.

I estimate the effect of a new highway ray on suburbanization using equation (5), where the unit of observation is the MSA and differences are between 1950 and 1990 levels:

$$\Delta \log N_i^c = \delta_0 + \delta_1 \Delta ray_i + \delta_2 r_{ci} + \delta_3 \Delta \widetilde{w}_i + \delta_4 \Delta \log N_i^{MSA} (+\delta_5 \Delta \widetilde{G}_i) + \varepsilon_i \tag{5}$$

In order to account for the potential endogeneity of the income distribution to suburbanization, I use a simulated income distribution based on the 1940 employment distribution by 1-digit industry for each MSA. I take the distribution of skill prices nationally from the census PUMS excluding the states that encompass each MSA in question for each industry of employment and combine them using the reported 1940 employment shares. Only men working full time and full year are used to build the skill prices. Thus the factors that drive the change in the measured income distribution for an MSA are the evolution of skill prices at the national level and the 1940 employment mix in the MSA. $\widetilde{w}_i$ represents the simulated mean log annual income and $\widetilde{G}_i$ represents the Gini coefficient of the simulated income distribution for MSA i. This formulation of the regression equation is approximately a log-differenced form of equation (3).

Table 6 presents regression estimates from various specifications of Equation (5). Panel A reports OLS estimates and Panel B reports IV estimates. Standard errors are clustered by the state in which the center city is located to account for potential state-level unobservables like environmental laws that could affect suburbanization. Coefficients on center city rays in all specifications have the expected negative sign and are usually statistically significant and sizable. As each of the control variables in the model is added to the regression specification, the estimated coefficient on rays increases in the majority of samples. A positive correlation between the area of the center city and Δlog MSA population and the change in number of rays accounts for the larger coefficient on rays when these variables enter as controls.

Table 7 presents the same specifications as Table 6 with a variety of sample selection rules and the inclusion of state fixed effects. The coefficient on highway rays is very consistent across samples, except that the OLS results that include small MSAs have a smaller coefficient in several specifications. When the plan instruments for rays, however, this discrepancy disappears, likely because instrumenting reduces the bias due to highway substitution that occurs in the smaller cities that received fewer rays. The state fixed effects estimates are a bit smaller but still significant when the full array of controls is included[22]. OLS estimates of the coefficient on rays in specification 4 which is implied by the model range from -0.04 to -0.06 and IV estimates range from -0.08 to -0.14. The simulation results from Section 3 imply an effect of about -0.09.

As is predicted by the theory, the coefficients on the square root of center city area and metropolitan area population growth are positive. The estimated coefficients on log simulated income and gini coefficient are unstable and not statistically significant. The panel results discussed below give more precise estimates of these effects. Including the square root of MSA area as an additional control produces small and not statistically significant coefficients on MSA size with little change in the other coefficients. This check indicates that the MSA definitions from 2000 are spatially inclusive enough to include all relevant suburban areas. A quadratic term in the change in the number of rays gives a decreasing and concave function with the linear and quadratic terms jointly significant at the 1 percent level[23].

There are several distinct advantages to evaluating the effect of highways using long differences. The highway data in 1950 and 1990 are more complete than in the intervening years because of the inclusion of both interstate and non-interstate rays. Moreover, the 1950 to 1990 differences provide sufficient time for people to move in response to changes in the transportation infrastructure and thus are more likely to accurately reflect long-run equilibrium responses. Unfortunately, there are some drawbacks to using the long differences. While I try to use selection rules to make the sample more homogenous, metropolitan areas are unique in many ways. Being able to control for metropolitan area structure with fixed effects is thus potentially valuable in

[22] It is not clear whether it is the right approach to include state fixed effects in any specification. In only a few states are there enough similar metropolitan areas from which would come a sensible source of identification.

[23] I also test the possibility that 1950 population is a better predictor of suburbanization than new highways by including 1950 population in the regressions reported in Tables 6 and 7. One problem with this approach is that the number of highways received is a function of population levels, so it could be that including population in the regression would erroneously attribute some suburbanization to 1950 population when actually population is just soaking up some of the variation in rays. The OLS coefficient on rays falls to -0.03 and the IV coefficient falls to -0.11 when log 1950 population is included in the regression, though both remain statistically significant.

allaying concerns about omitted variable bias.

Tables 8 and 9 repeat the regressions from Tables 6 and 7 in levels with MSA fixed effects. Each observation represents an MSA in a census year between 1950 and 1990. Standard errors are clustered by state, allowing for MSA-level serial correlation and cross-sectional intra-state correlation in the error term. Due to limitations in available data, the variable measuring the number of rays in the panel regressions only reflects interstate highways, not other limited access highways. The number of MSAs in the sample is smaller than in the long-difference regressions because center city population is not available for all cities in all years.

Using the stock of center city rays as an explanatory variable presents some difficulties in a panel setting. Given the possibility of adjustment costs causing slow transitions to new equilibria, it is not clear what the appropriate timing of the highway measure is for the intervening years of the panel. If, for example, it takes 20 years for residential location patterns to respond fully to changes in highway infrastructure, panel results without somehow smoothing rays or instrumenting will be significantly attenuated towards 0 because they allow only for adjustment over at most a 10 year period[24]. If it takes time for individuals to adjust to new transportation infrastructure, and this new infrastructure is arriving continuously over time as it was in 1960 and 1970, we can also think of highways as being measured with error. Two different observations for 1970 may represent one city that got its rays in 1969 and the other that got its rays in 1961. Such inconsistent measurement of timing is likely to bias the estimated coefficient towards 0. Furthermore, highways often opened in stages such that in a given year only part of a given ray may have been available for use.

The small coefficients on rays in specifications 3 and 4 in Panel A of Table 8 reflect these measurement problems. To mitigate these measurement problems, I also use a measure of smoothed rays alongside discrete rays. Smoothed rays is the stock of center city rays in 1990 multiplied by the fraction of mileage of center city rays completed in each MSA at each point

[24] While slow convergence rates toward new spatial equilibria are likely, it is not clear what highway construction year should be used. If agents have rational expectations, they should react when announcements of new highways are made. Specification checks show, however, that using the timing of planning instead of completion does not change results much.

in time. Smoothing the center city rays increases the coefficients in the specification implied by the model to about -0.05, about 0.01 smaller in magnitude than the OLS coefficients in Tables 6 and 7. Results using smoothed rays are reported as specifications 5-8 in Tables 8 and 9.

The panel IV results are consistent with results from the long differences whether endogenous center city rays are smoothed or not. By using only the part of the center city rays correlated with the aggregate flow in statewide construction, IV smooths out the center city rays measure used in specifications 1-4. Allowing rays to take on fractional values allows even small suburbanization effects to show up in the coefficient. The fact that the IV results are similar for the two different highway measures supports the claim that measurement error is the likely culprit to explain the small OLS coefficients in specifications 3 and 4.

The coefficient on log MSA population is positive in both the long difference and panel regressions, though it is smaller in the panel regressions. The coefficient on simulated log income is negative, statistically significant and more stable in the panel regressions. A mean-preserving spread in the simulated income distribution is also estimated to decrease the population of the center city. The model predicts that an increase in the wage will result in a new equilibrium with more spatial dispersion of residences only if the income elasticity of demand for space is greater than 1. Glaeser et al. (2000) estimate the income elasticity of demand for space to be less than 1 and propose the existence of heterogeneity in commuting modes as a potential explanation for the fact that the poor tend to live nearer to city centers. Rather than reflecting this elasticity, the negative coefficient on mean simulated income may reflect migration of low skilled people to the suburbs to follow the more rapid suburbanization of employment in low wage industries than in high wage industries. Though it may be endogenous, including the actual log income instead of employment distribution constant log income also produces a negative coefficient and changes the coefficient on rays by less than 0.01.

7 Interpretation and Implications

Taken together, the empirical estimates presented in Tables 6-9 indicate an effect of the marginal highway ray on log center city population of between -0.06 and -0.12. On average, MSAs got 2.5 new center city rays between 1950 and 1990. Calibrations of the model imply that in a metropolitan area with half its population in the center city at 0 rays, the third ray causes a change in log center city population of between -0.05 and -0.11 depending on assumptions about travel speed ratio on city streets versus highways. Below I discuss reasons for the wide range of empirical estimates and several potential sources of bias: the endogeneity of population, highway congestion and employment suburbanization. Aftwerwards, I quantify how much spatial population diffusion within metropolitan areas we can attribute to highway expansion.

The nature of the first-stage relationship between rays in the plan and observed highway construction helps to explain the discrepancies between the long-difference IV estimates, the panel IV estimates and the OLS estimates of the coefficient on rays. There are several reasons for deviations of the observed number of rays from the number of planned rays. Many smaller cities that received rays in the plan apparently had little pent up commuting demand because they allowed planned highways to bypass them, thereby receiving 0 center city rays[25]. Other small cities that received no highways in the plan substituted with locally funded highways or successfully lobbied to get federally funded highways serving them added for the 1956 version of the plan[26]. Many larger cities that got only a few rays in the plan built locally funded highways to supplement federally funded highways from the plan. Cities that received more than 4 rays in the plan often reduced this to fewer center city rays through consolidation of highways far from the center city or having a highway bypass the center city[27]. Thus cities that received few or no rays in the plan have more center city rays on average than were planned and cities that received many rays in the plan ended up with fewer center city rays on average than were planned. As a

[25] Several examples are Pittsfield, MA and Fort Wayne, IN.

[26] Examples include Cedar Rapids, IA and Lubbock, TX.

[27] A common way of doing this is to have all of the planned rays go to a beltway and have only a few continue on to the CBD. Indianapolis is an example of a city that ended up with fewer center city rays than the number it received in the plan.

result, the plan is best at predicting the number of actual rays for those cities receiving between 2 and 5 rays in the plan, but a poor predictor of actual rays for those cities that received 0, 1 and more than 5 rays in the plan.

The IV results from the long difference regressions consistently show larger effects of highways than the IV results from the panel regressions. The discrepancy between the two sets of IV estimates can largely be attributed to the fact that including MSA fixed effects better ameliorates the fact that the plan does not predict highway construction well in the few MSAs that received 5-7 rays in the plan. Figure 6 shows graphs of the actual rays constructed and the predicted rays from the first stage as a function of the rays in the plan. The graph on the left with results from the long differences shows that after 5 rays in the plan, the average number of rays actually constructed between 1950 and 1990 is flat or decreasing while the predicted rays are still increasing. Indeed the coefficient on rays if the first stage regression is restricted to 5-7 rays in the plan is not significantly different from 0. The two graphs on the right show that while the first stage from the panel regressions also does not fit too well in this region, the fit is better. Appendix Table 6 presents results when the sample is restricted to those MSAs that received only 0-4 rays. It shows very similar effects for the IV results from the panel using discrete rays and the long differences. Restricting the sample to MSAs receiving between 0-4 rays in the plan reduces the long difference IV estimate by 0.05 while the estimated effect of rays from the panel, which have a better fit in the first stage, is reduced by only 0.01[28].

The fact that center city rays do not fully capture relevant changes in metropolitan area transportation infrastructure accounts for much of the discrepancy between the IV and OLS estimates. Suburban highways that can be used for commuting to the CBD in the absence of

[28] The rays measure used may also contribute to some of the discrepancy. Because of data limitations, the panel estimates are derived using a measure of rays that only includes interstate highways, not other limited access highways. A correlation of 0.94 between the two measures of rays implies that measurement differences are a minor reason. This is largely because states have a cost incentive to get locally funded limited access highways integrated into the interstate system (and observed over the full panel) through Section 103(c)(4)(a) of the 1956 legislation. In 1990, 14 percent of interstate highway mileage in MSAs was not federally funded compared to only 10 percent outside of MSAs, indicating the existence of some commuting demand response by local governments in the data.

center city rays are more numerous in metropolitan areas that received fewer center city rays. The correlation between the number of center city rays and non-center city rays is -0.22. Adding a measure of suburban rays to the regression equation reduces the IV-OLS gap to only 0.02 in the long differences and to 0.03 in the smoothed panel. Specification 2 in Appendix Table 6 reports these regression results. We might expect the gap to remain larger in the panel regressions because the difficulty in accurately representing the timing of construction is likely to bias the OLS estimates downward[29][30].

One way to interpret the small coefficient on discrete rays in the panel regressions is that there are adjustment costs that slow the transition to a new spatial equilibrium. I evaluate the speed of convergence to new equilibria by examining results using 1950-1970 differences. Appendix Table 4 reports the same set of regressions reported in Tables 6 using 1950-1970 differences. The resulting coefficient on highway rays is somewhat smaller but still significant. OLS using the specification implied by the model produces a coefficient of -0.04 and IV produces a coefficient of -0.07. These estimates indicate that while at least half of the estimated response to rays can be attributed to the 1950-1970 portion of the differences, a significant fraction of the adjustment happened after 1970.

To this point, I have maintained the assumption that MSA population is exogenous. Considering a system of cities, however, requires endogenizing N. An extended version of the model would suggest that holding the infrastructure in all other cities constant, more rays would attract new migrants to a city because they would cause the equilibrium utility level to increase[31]. Thus the effect of a ray on center city population holding N constant should be larger in magnitude than the effect if N is allowed to vary due to migration. That is, accounting for endogenous

[29] The trouble with including non-center city rays as a control is that it may be endogenous for the same reason center city rays are endogenous. With only the plan as an instrument it is difficult to instrument for both center city and suburban rays simultaneously.

[30] Another way of reducing the discrepancy is to limit the sample to only include MSAs that are less likely to deviate from their number of planned rays. Among the 75 large centrally located MSAs that received between 2 and 4 rays in the plan, the IV-OLS gap is less than 0.04 in the long differences and the panel using smoothed rays.

[31] If amenities change over time or are complementary to land, they would represent another reason population is endogenous. For example, Glaeser and Kohlhase (2003) suggest that the southwest may have become more livable as air conditioning has become more affordable.

MSA population should increase the magnitude of the estimated effect of highway rays on center city population. Appendix Table 7 reports results from IV regressions treating population as endogenous. I instrument for population growth between 1950 and 1990 with population growth between 1940 and 1950 and for the level of MSA population with its 10 year lag. Results from the regressions in Appendix Table 7 produce coefficients on rays that are within 0.01 of the results in which population is treated as exogenous. When instrumenting for population, the magnitude of the coefficient on rays increases by about 0.01 in the long difference regressions and decreases by about 0.01 in the panel regressions. Full first stage results are reported in Appendix Table 5.

The model presented in Section 3 also assumes that the transport infrastructure is not congestible. One simple way of extending the analysis to include congestion, similar to that employed by Anas and Moses (1979), is to make γ an increasing function of the population affected by a highway: $\gamma = f(\int_0^{\overline{\phi}} \int_0^{\frac{\overline{r}_f^M}{\widetilde{L}(\phi)}} \frac{r dr d\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi), u^M), u^M]})$, $f' \geq 0$[32]. Denote γ_M to be the equilibrium value of γ given M rays. Congestion represents another force pushing population density up near the center of the city in response to an increase in N because $\frac{dN_c}{d\gamma} > 0$ and $\frac{df}{dN} > 0$. Similarly, this formulation of congestion implies that *ceteris paribus,* more rays lead to a weak decline in the equilibrium value of γ because they induce some highway users to move from using other rays, thereby reducing the population around each ray. Thus holding the number of lanes constant, the effect of the first ray on center city population is smaller than it would be without congestion. The effect of the second ray is larger than it would be if γ were fixed at γ_1 because the next ray causes γ to fall to γ_2. The parameterization of the function f and the profiles of the price and wealth effects of demand for space as a function of γ determine whether the response of the center city population to the second ray in a world with congestion is less or greater than in a world without congestion.

[32] Vickrey (1969) proposes a more complicated formulation which in the context of this model would manifest itself as a "flow congestion" term in the travel time function: $L(r, \phi) = \min[br, br(\gamma \cos \phi + \sin \phi) + \lambda \int_0^{r \cos \phi} \left(\frac{N(v)}{t(v)}\right)^k dv]$ where $N(v)$ is the number of commuters using the highway between v and the edge of the MSA and t is the throughput of the highway.

I evaluate the potential importance of congestion by simulating the model allowing γ to be determined by the equilibrium population using the highway. I take the formula for speed on congested highways from the Texas Transportation Institute's 2004 Mobility Report, assuming that each new highway is 4 lanes in each direction and that 2 individuals commute together in each vehicle[33]. The simulation results with congestion are sensitive to the population of the metropolitan area. With this formulation of the congestion function and transportation infrastructure, congestion starts to reduce travel speeds when the metropolitan area reaches about 500,000 people. A metropolitan area of 1 million inhabitants with half its population in the center city in the 0 ray equilibrium sees center city population drop by 3 percent for the first ray, 4 percent for the second, third and fourth rays and 5 percent for the fifth ray. After 8 rays, the spatial distribution of the population looks the same as in the uncongested case because there is enough transportation infrastructure to bring γ back to its uncongested value.

Local transportation authorities have the option of mitigating potential highway congestion by building highways that have greater capacity in areas with greater traffic volumes. Indeed, limited empirical evidence suggests that over the relevant period, most local authorities are able to respond to demand with appropriate road capacity and that commuting time lost to congestion is likely to be small. Highway Performance Monitoring System (HPMS) Data from the Federal Highway Administration shows that local authorities build wider highways in sections nearer to center cities where travel demand is greater. In 76 of 103 MSAs with urbanized areas of at least 200,000 people, sampled sections of interstate highways inside the urbanized areas had more lanes on average than sections outside the urbanized areas (with 11 more having the same number of lanes). Moreover, calculations done by the Texas Transportation Institute using the HPMS data confirm that while congestion travel delays have climbed significantly since 1982, most of this increase occured after 1992 (Schrank and Lomax, 2004). According to the TTI 1994 Mobility Report, the average ratio of freeflow to rush hour speed in the 40 cities in its sample that were at least 20 miles from a border or coast in 1992 is 1.12. Of these, only 5 cities had

[33] Given that about half the population commutes to work outside the home, the 2 person per car assumption allows the model to be more consistent with the data.

uncongested traffic speeds at least 20 percent higher than rush hour traffic speeds[34].

Data from the Texas Transportation Institute's Mobility Report allows for estimation of the effect of a marginal ray on congestion. The formulation of congestion described above implies the following estimation equation.

$$\Delta\gamma_i = \frac{\partial f}{\partial \ln N}\Delta \ln N_i + \frac{\Delta f}{\Delta M}\Delta M_i + \frac{\partial f}{\partial w}\Delta\widetilde{w}_i + \varepsilon_i \tag{6}$$

Results from estimating Equation (6) using the TTI congestion data on a sample of MSAs that had center city rays in 1960 gives very small negative estimated effects, whether instrumenting for the change in rays with the plan or not. The estimated coefficient on change in log population is positive as expected. Though better data is needed to fully address the question, these results support the claim that the portion of the effect of highways on suburbanization due to changes in congestion is likely to be small.

A final potential criticism of this methodological approach is that the location of employment has been treated as exogenous. It is well known that employment has been decentralizing along with population (Ihlandfeldt, 1997). In 1950, 20 million of 40 million MSA jobs were in center cities while by 1990 only 27 million of 87 million jobs remained in the center city. However, as seen in Table 1, 49 million of 102 million MSA residents lived in center cities in 1950 compared to 58 million of 182 million in 1990. Clearly a monocentric city model requires some innovation endogenizing production location to generate the observed pattern of employment dispersion. One approach is to use spatial production or information externalities coupled with commuting cost as the basis of a model in which firms have an incentive to cluster at the center and in one or more non-central rings (Lucas & Rossi, 2002). Henderson and Mitra (1996) consider a model of employer location in which a profit-maximizing developer decides the location at which to establish an employment center outside the central business district based on the ability to capture the associated land rent increases. They show using simulation that a wide range of

[34]The 2004 Mobility Report presents congestion calculations for 85 urbanized areas. The average ratio of uncongested to rush hour travel speeds in the whole sample is 1.15 in 1992 including 21 urbanized areas with a ratio of at least 1.2. Los Angeles had by far the highest ratio at 1.76.

different potential spatial equilibriua exist including no suburban employment and significant employment at the fringe depending on primary city production capacity and population. The pattern of static equilibria do not change in a predictable way as the city grows in population or as production externalities change. Glaeser & Kahn (2004) extend their model and show that a decline in transportation cost has an ambiguous effect on employment density[35]. Even if we had a model with convincing predictions about how employment location responds to improvements in transportation infrastructure, detailed geographic data on employment location is not readily available over a long panel.

The existence of employment suburbanization complicates the interpretation of the coefficient on highway rays. It is possible that people have moved to the suburbs not directly because transportation costs have fallen. Instead firms may have relocated their employment centers in response to changes in the transportation infrastructure and people have followed the jobs. As the distribution of industries and occupations has moved away from manufacturing and towards services, and with a more highly developed transportation network, the production returns associated with being centrally located may have declined. While the estimates presented here should be considered a total effect, they hold the distribution of employment at the 1940 industry mix for each MSA. Thus movements in the spatial distribution of jobs not explained by highways is reflected in the simulated income control variable. Without more detailed historical data on the spatial distribution of employment it will be difficult to separate out the extent to which transportation improvements cause jobs to lead people or vice-versa.

Taken together, the long-difference and panel results give an effect of one new highway ray on the change in log constant center-city population of between -0.09 and -0.12. Log population in large central constant-area center cities fell on average by 0.30 between 1950 and 1990. If each city received one exogenously assigned highway (2 rays), estimates thus indicate that the decline in population would have been cut in half. Empirically, cities received 2.5 rays on average between 1950 and 1990, though not all of these were randomly assigned. Table 10

[35] Hamilton and Roell (1982) note that if employment only agglomorates at the center and production takes no space, allowing employment outside the center does not change the spatial structure of a monocentric city.

explores several counterfactual situations for highway construction and compares them with the observed evolution of center city population over time using the same samples as in Table 1. The second and fourth rows of each panel show the counterfactual evolution of aggregate center city population had the interstate highway system not been built. The third and fifth rows show the counterfactual 1990 aggregate center city population assuming no highways of any kind had been built. The "low" counterfactual assumes a coefficient on rays in the second stage of -0.09 and the "high" counterfactual assumes a coefficient of -0.12. These counterfactuals allow MSA characteristics to evolve over time. The only adjustment is to add extra population that would not have been lost had highways not been built to observed center city populations.

The counterfactual evolution of aggregate constant area center city population is constructed as follows. The predicted number of rays from a separate first stage regression for each sample determines the number of "exogenous rays" for each metropolitan area in each year. For example, the regression used to construct exogenous rays in Table 10 Panel D is the same as that reported in Appendix Table 5 Panel B Specification 2 for smoothed rays. To build the time series for total rays I assume that non-interstate rays were built at the same rate as interstate rays in each MSA. I then first-difference the predicted rays from the first stage and multiply the resulting number by 0.09 or 0.12 to derive the log difference in center city population that can be attributed to new exogenous highways during each decade between 1950 and 1990 for each MSA. I subtract the estimated log difference in center city population due to exogenous highway expansion (which is negative) from the observed log difference in center city population during each decade, calculate the counterfactual log levels in 1960-1990 based on the 1950 cross section and exponentiate to put the estimates in terms of population. The numbers reported in Table 10 are the aggregates derived by summing these resulting populations over the MSAs in the given sample.

Panel A of Table 10 shows that had the interstate highway system not been built, the low estimate indicates that aggregate center city population would have increased by 6 percent between 1950 and 1990. The high estimate indicates a counterfactual increase of 14 percent. These aggregate effects are larger than the average effect because cities with a higher population received more rays on average. A 2 to 5 additional percentage point increase in aggregate center city population would have occured had limited access highways that are not part of the interstate system not been built. Aggregate effects are slightly larger for the set of MSAs with greater population shown in Panels B and C. Even in the sample of MSAs that had the fastest decline in aggregate population, virtually all flight from the center cities can be attributed to limited access highway construction.

Patterns over time in the counterfactual evolution of the spatial distribution of the population provide some clues as to the importance of other factors in explaining center city decline. Only in the 1960s did the counterfactual growth rate of aggregate center city population with no highways equal the growth rate of the total U.S. population. In all other decades, counterfactual aggregate population in center cities declined while the U.S. population grew. The decline in counterfactual center city population was, however, significantly less pronounced than the decline in actual aggregate center city population. The biggest declines occured in the 1970s, with contemporaneous highway construction accounting for one-half to two thirds of the aggregate population loss in center cities during this decade. Though some of this may be due to residual responses to pre-1970 highway construction, increases in crime and forced school desegregation during the 1960s and 1970s may account for the fact that even center cities without new highways would have seen such rapid population decline during this period. Further investigation is required to determine what other factors are important in explaining center city decline since 1970.

8 Conclusions

Urban transportation improvements are an important element in explaining post-WWII suburbanization in the United States. I find strong evidence that the decline in the population of center cities in the U.S. between 1950 and 1990 would not have occured had the interstate highway system not been built. In fact, aggregate center city population may have grown by as much as 18 percent had no limited access highways been built. Highway construction is thus an extremely important part of the explanation for center city decline since 1950. A simple model is presented that incorporates spatial heterogeneity in travel speed into a classical monocentric city framework. I use unique data to estimate the effect of new highway rays on suburbanization using a 1947 plan of the interstate highway system as a source of exogenous variation. The magnitude of the empirical estimates is in line with simulation results from the model over a wide range of populations and center city sizes.

Though the analysis done here is a start, there remains much to be learned about the causes of suburbanization. The estimates presented in this paper can explain at most about half of the difference in the number of people living in 1950 definition center cities in 1990 and the number that would have lived there had their population densities grown proportionally with national population. The changing income distribution, changes in the distribution of household size and changes in the spatial distribution of local public goods provision are phenomena that are potentially important yet have not been extensively explored in the context of explaining the declining average population density in metropolitan areas. Another potentially important part of the story that invites future investigation is the changing nature of spatial complementarities in production and their interaction with improvements in urban transportation infrastructure. Theories with cleaner predictions about the interaction between firm location and residential location would aid an empirical investigation into the relative importance of employment and residential decentralization in the evolution of the spatial structure of metropolitan areas.

In order to better inform transportation policy, an analysis evaluating the distribution of welfare effects of new transportation would also be instructive. One criticism of federally-funded transportation improvements oriented toward commuters is that their full cost is not borne by those who use them. The result is pressure for overinvestment in local infrastructure instead of locally administered use and congestion fees. Depending on the relative importance of relocation externalities and value of space, new highways may actually represent a welfare loss for poor inner-city residents, though clearly they represent a welfare gain for those who use them to commute from the suburbs. Formulation of a model that can be used as a basis for estimating these welfare effects is another ripe area for future research. Implications of such a welfare analysis would be valuable in informing future urban transportation policy, particularly in developing countries.

A Derivations

A.1 Proof of Lemma 1:

If M′= M + 1 then in equilibrium

i) $u^{M'} > u^M$:

Compare a city with 0 rays and 1 ray. Equation (2) implies that

$$\begin{aligned} 0 &= 2\int_0^{\overline{\phi}} \int_0^{\frac{q(u^1)}{\widetilde{L}(\phi)}} \frac{rdrd\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi), u^1), u^1]} \\ &+(2\pi - 2\overline{\phi}) \int_0^{q(u^1)} \frac{rdr}{\widetilde{s}[\psi(br, u^1), u^1]} - 2\pi \int_0^{q(u^0)} \frac{rdr}{\widetilde{s}[\psi(br, u^0), u^0]} \end{aligned} \tag{7}$$

Suppose that $u^0 > u^1$. I prove by contradiction that utility cannot be decreasing in M. Using Equation (1), the Implicit Function Theorem and the Envelope Theorem, $\frac{d\overline{r}_f}{du} = -\frac{-\frac{\partial z(s,u)}{\partial u}}{-wb} < 0$ so

$q(u^1) > q(u^0)$. Using the fact that space is a normal good, $\widetilde{s}[\psi(L(r,\phi), u^1), u^1] < \widetilde{s}[\psi(L(r,\phi), u^0), u^0]$. These two conditions imply that

$$2\pi \left[\int_0^{q(u^1)} \frac{rdr}{\widetilde{s}[\psi(br, u^1), u^1]} - \int_0^{q(u^0)} \frac{rdr}{\widetilde{s}[\psi(br, u^0), u^0]} \right] > 0 \tag{8}$$

and applying Equation (8) to (7) we have

$$\int_0^{\overline{\phi}} \int_0^{\frac{q(u^1)}{\widetilde{L}(\phi)}} \frac{rdrd\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi), u^1), u^1]} < \overline{\phi} \int_0^{q(u^1)} \frac{rdr}{\widetilde{s}[\psi(br, u^1), u^1]} \tag{9}$$

But

$$\overline{\phi}\int_{0}^{q(u^1)}\frac{rdr}{\widetilde{s}[\psi(br,u^1),u^1]} = \int_{0}^{\overline{\phi}}\int_{0}^{q(u^1)}\frac{rdrd\phi}{\widetilde{s}[\psi(br,u^1),u^1]}$$

$$< \int_{0}^{\overline{\phi}}\int_{0}^{\frac{q(u^1)}{\widetilde{L}(\phi)}}\frac{rdrd\phi}{\widetilde{s}[\psi(br,u^1),u^1]}$$

$$< \int_{0}^{\overline{\phi}}\int_{0}^{\frac{q(u^1)}{\widetilde{L}(\phi)}}\frac{rdrd\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi),u^1),u^1]}$$

which contradicts (9). Thus, it must be that $u^1 > u^0$. An analogous argument follows for all $M > 0$.

ii) $\overline{r}_f^M > \overline{r}_f^{M'}$:

To understand how equilibrium land use changes with M, we must first understand how the equilibrium land rent function changes with M. We can express land rent in terms of the bid-rent function:

$$\psi(L(r,\phi),u) = \max_{s}\left\{\frac{w[1-L(r,\phi)]-Z(s,u)}{s}\right\} \tag{10}$$

Using the envelope theorem, $\frac{\partial\psi}{\partial u} < 0$. Thus given result i, areas of the city with no change in travel times see land rents fall with M. Therefore, since R_a does not change, fringe distance in these same areas also falls with M.

iii) $\frac{\overline{r}_f^{M'}}{\gamma} > \overline{r}_f^M$:

Once again, consider the case of moving from a regime with 0 rays to a regime with 1 ray. Result i states that utility rises with M and ii) shows that equilibrium land rent falls with M for $\phi > \overline{\phi}$. Thus since space is a normal good, $\widetilde{s}[\psi(L(r,\phi),u^1),u^1] > \widetilde{s}[\psi(L(r,\phi),u^0),u^0]$ in the region $\phi > \overline{\phi}$. Also note from result ii that that $\psi(0,u^1) < \psi(0,u^0)$.

To examine the $\phi < \overline{\phi}$ region, it is instructive to think about the shape of the bid-rent function for land in the 0-ray equilibrium compared to that in the 1-ray equilbrium at $\phi \geq \overline{\phi}$ and $\phi = 0$.

The derivative of the rent function as a function of r is:

$$\psi_r = -\frac{w \min[b, b\widetilde{L}(\phi)]}{\widetilde{s}[\psi(L(r,\phi),u),u]} \tag{11}$$

The rent function is thus less steep in the region $\phi < \overline{\phi}$ than in the remainder of the metropolitan area. Further, the rent function at all points is less steep in the 1-ray equilibrium than the 0-ray equilibrium. Define $r^*(\phi)$ to solve $\psi(rb\widetilde{L}(\phi), u^1) = \psi(rb, u^0)$ for the region $\psi(rb, u^0) > R_a$. Given the normality of land and the fact that the fringe distance is the furthest from the center at $\phi = 0$, it must also be true that for $r \leq r^*(\phi)$, $s^1(r,\phi) > s^0(r,\phi)$. Using the market clearing condition for space and the result that $\overline{r}_f^1 < \overline{r}_f^0$:

$$\begin{aligned} & N - (2\pi - 2\overline{\phi}) \int_0^{\overline{r}_f^0} \frac{rdr}{\widetilde{s}[\psi(br,u^0),u^0]} - 2\int_0^{\overline{\phi}} \int_0^{r^*(\phi)} \frac{rdrd\phi}{\widetilde{s}[\psi(br,u^0),u^0]} \\ > \; & N - (2\pi - 2\overline{\phi}) \int_0^{\overline{r}_f^1} \frac{rdr}{\widetilde{s}[\psi(br,u^1),u^1]} - 2\int_0^{\overline{\phi}} \int_0^{r^*(\phi)} \frac{rdrd\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi),u^1),u^1]} \end{aligned}$$

or

$$2\int_0^{\overline{\phi}} \int_{r^*(\phi)}^{\frac{\overline{r}_f^1}{\widetilde{L}(\phi)}} \frac{rdrd\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi),u^1),u^1]} > 2\int_0^{\overline{\phi}} \int_{r^*(\phi)}^{\overline{r}_f^0} \frac{rdrd\phi}{\widetilde{s}[\psi(br,u^0),u^0]}$$

That is, there remain more people to be housed in the region $r \in [r^*(\phi), \infty)$ X $\phi \in (0, \overline{\phi})$ in the 1-ray equilibrium than the 0-ray equilibrium. $r^*(\phi)$ must exist for some ϕ, otherwise not everybody could be housed in the 1-ray equilibrium. By definition of r^* and the fact that $\psi_r(b\gamma r, u^1) > \psi_r(br, u^0)$, rent must be greater in the 1-ray equilibrium than the 0-ray equilibrium in the region $r > r^*(\phi)$. Because R_a is the same in both equilibria, the extent of the city at $\phi = 0$ must be greater in the 1-ray equilibrium than the 0-ray equilibrium. This argument is depicted graphically in Figure 3. The same argument follows for all $M > 0$.

A.2 Proof of Lemma 2:

$\frac{dN_c}{dr_c} > 0$: The following expression for N_c shows that it is increasing in r_c.

$$N_c = 2M \int_0^{\overline{\phi}} \int_0^{r_c} \frac{r dr d\phi}{\widetilde{s}[\psi(br\widetilde{L}(\phi), u^M), u^M]} + (2\pi - 2M\overline{\phi}) \int_0^{r_c} \frac{r dr}{\widetilde{s}[\psi(br, u^M), u^M]} \quad (12)$$

$\frac{dN_c}{dN} > 0$: $\frac{dN_c}{dN} = \frac{\partial N_c}{\partial \widetilde{s}}[\frac{\partial \widetilde{s}}{\partial R}\frac{\partial R}{\partial u^M} + \frac{\partial \widetilde{s}}{\partial u^M}]\frac{\partial u^M}{\partial N}$ Using equation (2) and noting from the proof of Lemma 1 that $q'(u^M) < 0$, $\frac{\partial u^M}{\partial N} < 0$. So $\frac{dN_c}{dN} = (-)[(-)(-) + (+)](-) > 0$. When population of the city increases, population density throughout the metropolitan area increases and the fringe distance also increases because the rental price of land is bid up everywhere.

Population near the center is decreasing in M: This can most easily be seen by noting that $\psi_u < 0$. Since u is increasing in M (Lemma 1), rent at the center falls and thus population density also falls at radius 0 through a price effect and a wealth effect. By the same argument, population density falls in all parts of the metropolitan area for which the new ray(s) do not affect the same commuting time to the center. In the region affected by new rays, there is some subset of this region near the center in which rent falls, and thus density falls. Since at all angles from the center population density falls at some radius, population density falls in the entire region near the center of the city for an increase in rays.

It is most straightforward to evaluate the comparative statics for changes in b, γ and w in terms of the slope of the bid-rent function. If the slope of the bid-rent function gets steeper, that is $\psi_{rx} \leq 0$ at all angles ϕ, then an increase in the parameter x will push people toward the center, *ceteris paribus*. Each derivation uses $\psi_r = -\frac{w \min[b, b\widetilde{L}(\phi)]}{s}$.

$\psi_{rb} = -\frac{w \min[1, \widetilde{L}(\phi)]}{s} + \frac{1}{s^2}\frac{\partial \widehat{s}}{\partial I}(-w \min[1, \widetilde{L}(\phi)]) < 0$

$\psi_{r\gamma} = -\frac{w \min[0, \frac{d\widetilde{L}(\phi)}{d\gamma}]}{s} + \frac{1}{s^2}\frac{\partial \widehat{s}}{\partial I}(-w \min[0, \frac{d\widetilde{L}(\phi)}{d\gamma}]) \leq 0$

Also note this result: $\psi_{rw} = -\frac{L_r}{s} + \frac{wL_r}{s^2}\frac{\partial s}{\partial I}(1 - L(r, \phi)) = \frac{L_r}{s}[\frac{\partial \widehat{s}}{\partial I}\frac{w(1-L)}{s} - 1] < 0$ if $\frac{\partial \ln(\widehat{s})}{\partial \ln(I)} < 1$

A.3 An Alternate Commuting Technology:

This section shows that the assumption of travel speed at $\frac{1}{b\gamma}$ along the highway and $\frac{1}{b}$ along any other straight line in the metropolitan area implies a commuting time function of $L(r,\phi) = \min[br, br(\gamma\cos\phi + \sqrt{1-\gamma^2}\sin\phi)]$.

Those that commute partially via the highway must choose a point $(x,0)$ at which to enter the highway. Using the law of cosines and ignoring b, the optimal choice of x is the result of the minimization problem:

$$\min_x[\gamma x + \sqrt{r^2 + x^2 - 2xr\cos\phi}]$$

The first-order condition implies the quadratic equation in x:

$$(1-\gamma^2)x^2 + 2r\cos\phi(\gamma^2 - 1)x + r^2\cos^2\phi - \gamma^2 r^2 = 0$$

The quadratic formula implies

$$x^* = r\frac{(1-\gamma^2)\cos\phi \pm \sqrt{\cos^2\phi(\gamma^2-1)^2 - (1-\gamma^2)(\cos^2\phi - \gamma^2)}}{1-\gamma^2}$$

Simplifying the expression under the square root and using the fact that $x^* < r\cos\phi$, this becomes

$$\begin{aligned} x^* &= r\frac{(1-\gamma^2)\cos\phi \pm \gamma\sin\phi\sqrt{1-\gamma^2}}{1-\gamma^2} \\ &= r(\cos\phi - \frac{\gamma}{\sqrt{1-\gamma^2}}\sin\phi) \end{aligned}$$

Using the commuting function and the solution for x,

$$\begin{aligned} L(r,\phi) &= \min[br, bx^*\gamma + b\sqrt{x^{*2} + r^2 - 2x^* r\cos\phi}] \\ &= \min[br, br(\gamma\cos\phi + \sqrt{1-\gamma^2}\sin\phi)] \end{aligned}$$

I choose not to use this commuting technology because it implies $\overline{\phi}$ is much larger than in the other two technologies discussed in the paper. Therefore, simulations using this technology produce larger effects of rays on suburbanization than either of the other technologies.

B Derivations of Cases for Simulations

Below the expressions used to carry out the simulations are derived using the bid-rent function method. It is equivalent to solve them by using the first order conditions from utility maximization.

B.1 Quasilinear Example

This is a variant of the example worked out in Glaeser and Kahn (2003). Using $-\frac{\partial Z}{\partial s} = \psi(L(r,\phi),u)$,

$$\frac{\alpha}{s} = \frac{w[1-L(r,\phi)] - u + \alpha \log s}{s}$$

Solving for s yields

$$s = e^{\frac{u}{\alpha}+1} e^{-\frac{w}{\alpha}} e^{\frac{w}{\alpha}L(r,\phi)} \tag{13}$$

At the urban fringe, we have $R_a = \psi(b\overline{r}_f, u^*)$ giving us

$$e^{\frac{u}{\alpha}+1} = \frac{\alpha}{R_a} e^{\frac{w}{\alpha}(1-b\overline{r}_f))} \tag{14}$$

where $\overline{r}_f$ is the fringe at $\phi > \overline{\phi}$. This expression justifies that since everyone must have the same utility, equalizing utility at the fringe implies $r_f(\phi) = \frac{\overline{r}_f}{\widetilde{L}(\phi)}$.

Combining the expressions for utility and demand for space yields:

$$s^*(r,\phi) = \frac{\alpha}{R_a} e^{-\frac{w}{\alpha}b\overline{r}_f} e^{\frac{w}{\alpha}L(r,\phi)} \tag{15}$$

Using the land market clearing condition yields an equation that determines $\overline{r}_f^M$:

$$N = \frac{R_a}{\alpha} e^{\frac{w}{\alpha}b\overline{r}_f^M} \left(\frac{wb}{\alpha}\right)^{-2} \left[\begin{array}{c} 2M \int_0^{\overline{\phi}} \int_0^{\frac{\overline{r}_f^M}{\widetilde{L}(\phi)}} r e^{-\frac{w}{\alpha} r b \widetilde{L}(\phi)} dr d\phi \\ +(2\pi - 2M\overline{\phi})[1 - e^{-\overline{r}_f^M wb/a} - \overline{r}_f^M \frac{wb}{\alpha} e^{-\overline{r}_f^M wb/a}] \end{array} \right] \tag{16}$$

In the simulations, the integral with respect to ϕ was solved numerically. The expression in the text for N_c is the same as that listed above for N, except the upper limit of integration with respect to r is r_c.

B.2 Cobb-Douglas Example

This is a variant of the example worked out in Chapter 3 of Fujita (1989). Using $-\frac{\partial Z}{\partial s} = \psi(L(r,\phi), u)$,

$$-e^{\frac{u}{\alpha}}(-\frac{\beta}{\alpha})s^{-\frac{\beta}{\alpha}-1} = \frac{w[1-L(r,\phi)] - e^{\frac{u}{\alpha}}s^{\frac{-\beta}{\alpha}}}{s}$$

Solving for s yields

$$s^*(r,\phi,u) = e^{u/\beta}\alpha^{-\alpha/\beta}w^{-\alpha/\beta}(1-L(r,\phi))^{-\alpha/\beta} \tag{17}$$

At the urban fringe, we have $R_a = \psi(\overline{r}_f, u^*)$ giving us

$$e^{\frac{u}{\beta}} = \frac{\beta}{R_a}w^{1/\beta}\alpha^{\alpha/\beta}(1-\overline{r}_f b)^{1/\beta} \tag{18}$$

where $\overline{r}_f$ is the fringe at $\phi > \overline{\phi}$. This expression justifies that since everyone must have the same utility, equalizing utility at the fringe implies $r_f = \frac{\overline{r}_f}{\widetilde{L}(\phi)}$.

Combining the expressions for utility and demand for space yields:

$$s^*(r,\phi) = \frac{\beta}{R_A}(1-\overline{r_f}b)^{1/\beta}w(1-L(r,\phi))^{-\alpha/\beta} \tag{19}$$

Using the land market clearing condition yields an equation that determines $\overline{r}_f^M$:

$$N = (1-\overline{r}_f^M b)^{-\frac{1}{\beta}}\frac{R_a}{w}\frac{1}{1+\beta}\begin{bmatrix} 2M\int_0^{\overline{\phi}}\int_0^{\frac{\overline{r}_f^M}{\widetilde{L}(\phi)}} r[1-rb\widetilde{L}(\phi)]^{\frac{\alpha}{\beta}}drd\phi \\ +(2\pi-2M\overline{\phi})[(1-b\overline{r}_f^M)^{\frac{\alpha}{\beta}}((\overline{r}_f^M)^2 - \frac{\alpha\overline{r}_f^M}{b} - \frac{\beta}{b^2}) + \frac{\beta}{b^2}] \end{bmatrix} \tag{20}$$

In the simulations, the integral with respect to ϕ was solved numerically. The expression for N_c is the same as that listed above for N, except the upper limit of integration with respect to r is

r_c:

$$N_c = (1 - L(\overline{r}_f))^{-\frac{1}{\beta}} \frac{R_a}{w} \frac{1}{1+\beta} * \left[\begin{array}{c} 2M \int_0^{\overline{\phi}} (1 - br_c \widetilde{L}(\phi))^{\frac{\alpha}{\beta}} (r_c^2 - \frac{\alpha r_c}{b\widetilde{L}(\phi)} \\ - \frac{\beta}{b^2 \widetilde{L}(\phi)^2}) + \frac{\beta}{b^2 \widetilde{L}(\phi)^2} d\phi \\ +(2\pi - 2M\overline{\phi})[(1 - br_c)^{\frac{\alpha}{\beta}} (r_c^2 - \frac{\alpha r_c}{b} - \frac{\beta}{b^2}) + \frac{\beta}{b^2}] \end{array} \right] \quad (21)$$

Appendix Table 3 lists simulation results using this utility function for a city of 1 million.

C The History of Interstate Highway Classification and Funding

Prior to 1944 no federal money was available specifically for limited access highways. The 1944 Federal Aid Highway Act appropriated $125 million for the first time specifically for urban highways. Federal construction guidelines at this time were not up to interstate standards and only a subset of the resulting highways were upgraded later and integrated into the interstate system. Only Detroit, New York and a few other cities had plans ready for urban highways in 1944, hence all of the resulting construction was concentrated in just a few cities (Seely 1987).

The 1947 plan only included highways connecting metropolitan areas and did not consider local commuting. Many communities were unhappy that the planned highways would not meet their commuting needs. Therefore, as the 1947 plan was being negotiated, an understanding was reached between the states and the BPR that a plan for a system of local interstates (mostly signed with 3 digits) would be determined afterwards. The BPR published a book of maps in 1955 detailing its plan for local interstates in each city, a plan that was no doubt highly influenced by the demand for suburbanization (Bureau of Public Roads, 1955). This plan is commonly known as the "Yellow Book". The planned highways from the Yellow Book persisted into the 1956 interstate highway plan.

Between 1944 and 1953, Congress appropriated approximately $500 million per year to states for all highway construction. Funding was allocated based $\frac{1}{3}$rd on population and $\frac{2}{3}$rds on state area and existing road mileage under a system in which the federal government and the states would split the construction cost evenly and the federal government would pay $\frac{2}{3}$rds of the right of way acquisition costs. Though this represented a significant new federal funding commitment for highways, very little funding went towards interstate construction. Not until 1952 was any federal money earmarked for interstate construction, and only $25 million was budgeted in this year. The 1954 highway act earmarked $175 million solely for interstate construction based $\frac{1}{2}$ on land area and $\frac{1}{2}$ on population with 60-40 federal-state construction cost sharing. Though this was relatively little money it was the 1954 act that would form the basis for the federal government's long-lasting support for interstate highway construction. The 1956 highway legislation raised the amount of money available, expanded the planned system by about 3,000 miles, and shifted more of the cost burden towards the federal government. The apportionment formula followed the same 50 percent land area 50 percent population rule established in the 1954 act, but allocated considerably more money - about $2 billion per year. The 50-50 apportionment formula for allocating funds was only maintained between 1957 and 1959, after which states requested money each year based on cost of construction and funds were allocated at the discretion of the Federal Highway Administration. The federal government assumed 90 percent of the cost of construction starting in 1957 with the remaining 10 percent left to the states.

In 1968, 1,700 additional miles were authorized by Congress, and again in 1973 300 additional miles were authorized. These are known as "Howard-Cramer" miles. In addition, Section 103(c)(4)(a) of the 1956 federal highway legislation stipulates that if state governments update roadways to interstate standards and they form a logical part of the system, they will be eligible to be included in the system. Between 1956 and 1990, the federal government spent a total of $129 billion on the interstate highway system. Starting in the 1980s Congress approved additional mileage as parts of other legislation. All segments of the system not in the 1947 and 1956 plans are identifiable in the data and are a small fraction of the total mileage. Interstate construction in MSAs exhibits a similar pattern over time as construction nationwide, though metropolitan area construction is slightly weighted towards the 1950s and 1960s. Interstate mileage in MSAs that existed in 1950 reached 1,000 by 1956, picked up considerably in the 1960s and early 1970s, and then tailed off in the 1980s to about 20,500 miles. This represents about one-half of aggregate interstate mileage nationwide. Appendix Table 2 details the evolution of aggregate interstate mileage inside and outside of MSAs.

References

[1] A. Alesina, R. Baqir, and C. Hoxby. Political jurisdictions in heterogeneous communities. *Journal of Political Economy* **112**(2), 348–396 (2004).

[2] W. Alonso. "Location and Land Use". Harvard University Press, Cambridge (1964).

[3] A. Anas and L. N. Moses. Mode choice, transport structure and urban land use. *Journal of Urban Economics* **6**(2), 228–246 (1979).

[4] N. Baum-Snow and M. E. Kahn. The effects of new public projects to expand urban rail transit. *Journal of Public Economics* **77**(2), 241–263 (2000).

[5] M. G. Boarnet and A. F. Haughout. Do highways matter? evidence and policy implications of highways' influence on metropolitan development (2000). Brookings Institution Center on Urban and Metropolitan Policy Dicussion Paper.

[6] C. Clark. Urban population densities. *Journal of the Royal Statistical Society* **114**, 490–496 (1951).

[7] N. I. H. Committee. "Interregional Highways: Report of The National Interregional Highway Committee Outlining and Recommending a National System of Interregional Highways". Federal Works Agency, Washington, DC (1944).

[8] D. Epple and H. Sieg. Estimating equilibrium models of local jurisdictions. *Journal of Political Economy* **107**(4), 645–681 (1999).

[9] R. Fernandez and R. Rogerson. Income distribution, communities, and the quality of public education. *Quarterly Journal of Economics* **111**(1), 135–164 (1996).

[10] M. Fujita. "Urban Economic Theory". Cambridge University Press, Cambridge (1989).

[11] E. Glaeser and M. Kahn. Sprawl and urban growth. In J.-F. Thisse and J. V. Henderson, editors, "Handbook of Urban and Regional Economics", ch. 56. Elsevier Science, Amsterdam, Netherlands (2004).

[12] E. L. Glaeser, M. E. Kahn, and J. Rappaport. Why do the poor live in cities? (2000). NBER Working Paper #7636, April.

[13] E. L. Glaeser and J. Kohlhase. Cities, regions and the decline of transport costs (2003). Harvard Institute of Economic Research Discussion Paper No. 2014.

[14] B. Hamilton and A. Roell. Wasteful commuting. *Journal of Political Economy* **90**(5), 1035–1053 (1982).

[15] V. J. Henderson and A. Mitra. The new urban landscape: Developers and edge cities. *Regional Science and Urban Economics* **26**, 613–643 (1996).

[16] K. R. Ihlanfeldt. Information on the spatial distribution of job opportunities within metropolitan areas. *Journal of Urban Economics* **41**(2), 218–42 (1997).

[17] S. F. Leroy and J. Sonstelie. Paradise lost and regained: Transportation innovation, income, and residential location. *Journal of Urban Economics* **13**(1), 67–89 (1983).

[18] R. E. J. Lucas and E. Rossi-Hansbert. On the internal structure of cities. *Econometrica* **70**(4), 1445–1476 (2002).

[19] J. F. McDonald. Econometric studies of urban population density: A survey. *Journal of Urban Economics* pp. 361–385 (1989).

[20] P. Mieszkowski and E. S. Mills. The causes of metropolitan suburbanization. *Journal of Economic Perspectives* **7**(3), 135–147 (1993).

[21] E. S. Mills. An aggregative model of resource allocation in a metropolitan area. *The American Economic Review* **57**(2), 197–210 (1967).

[22] R. Muth. "Cities and Housing". University of Chicago Press, Chicago (1968).

[23] T. J. Nechyba. Local property and state income taxes: The role of interjurisdictional competition and collusion. *Journal of Political Economy* **105**(2), 351–384 (1997).

[24] B. of Public Roads. "General Location of National System of Interstate Highways, Including All Additional Routes at Urban Areas Designated in September, 1955". U.S.

Government Printing Office, Washington, DC (1955).

[25] M. Rose. "Interstate Express Highway Politics 1939-1989". The University of Tennessee Press, Knoxville, TN (1990).

[26] D. Schrank and T. Lomax. The 2004 urban mobility report (2004). Texas Transportation Institute.

[27] B. E. Seely. "Building the American Highway System: Engineers as Policy Makers". Temple University Press, Philadelphia, PA (1987).

[28] C. M. Tiebout. A pure theory of local expenditures. *Journal of Political Economy* **64**(5), 416–424 (1956).

[29] F. H. A. U.S. Department of Transportation. "America's Highways 1776-1976". U.S. Government Printing Office, Washington, DC (1976).

[30] F. H. A. U.S. Department of Transportation. "Route Log and Finder List". U.S. Government Printing Office, Washington, DC (2001).

[31] W. S. Vickrey. Congestion theory and transport investment. *American Economic Review* **59**(2), 251–260 (1969).

[32] W. Wheaton. Income and urban residence: An analysis of consumer demand for location. *American Economic Review* **67**(4), 620–632 (1977).

Figure 1
The Projected System of Interstate Highways in 1947

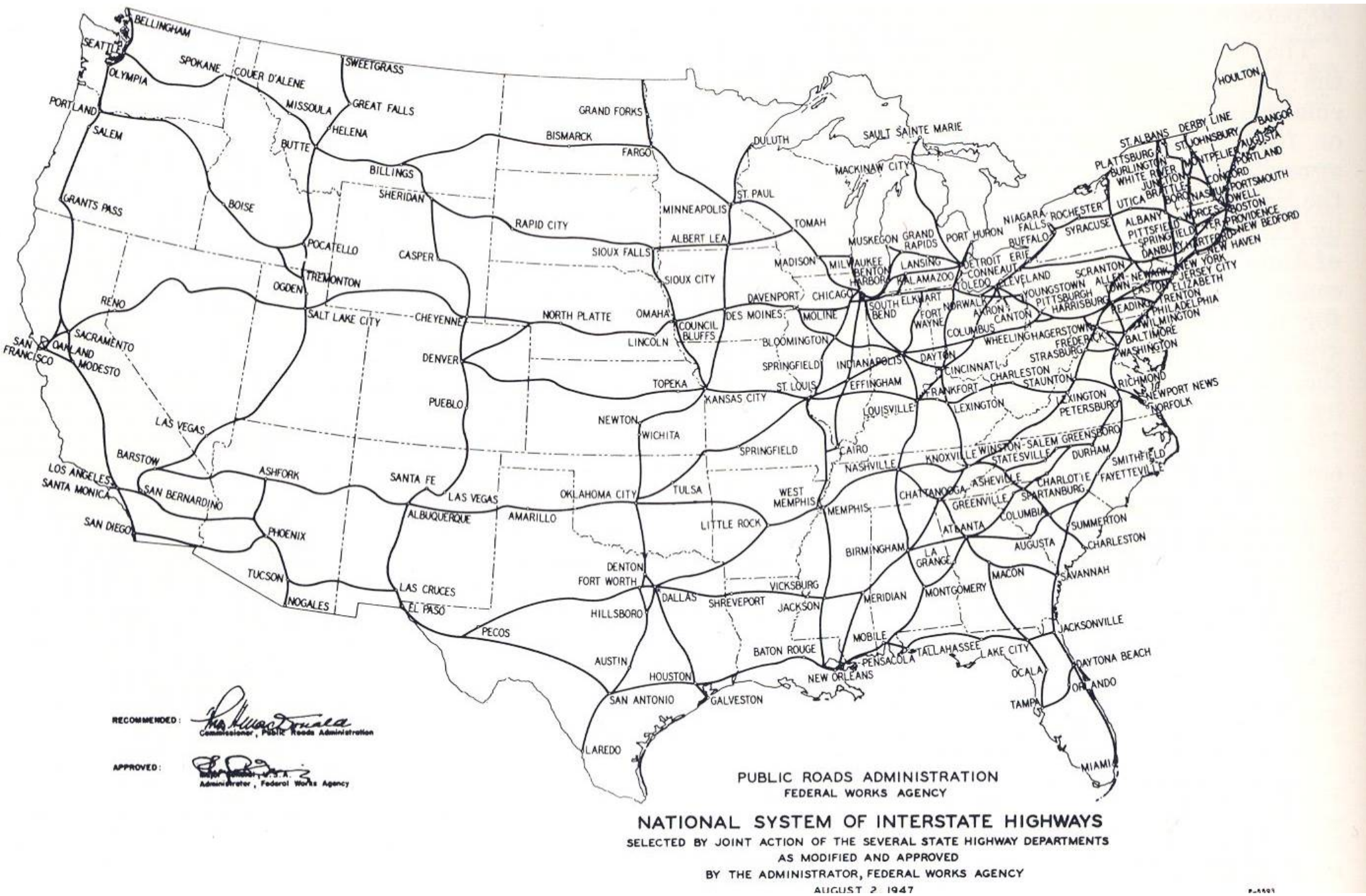
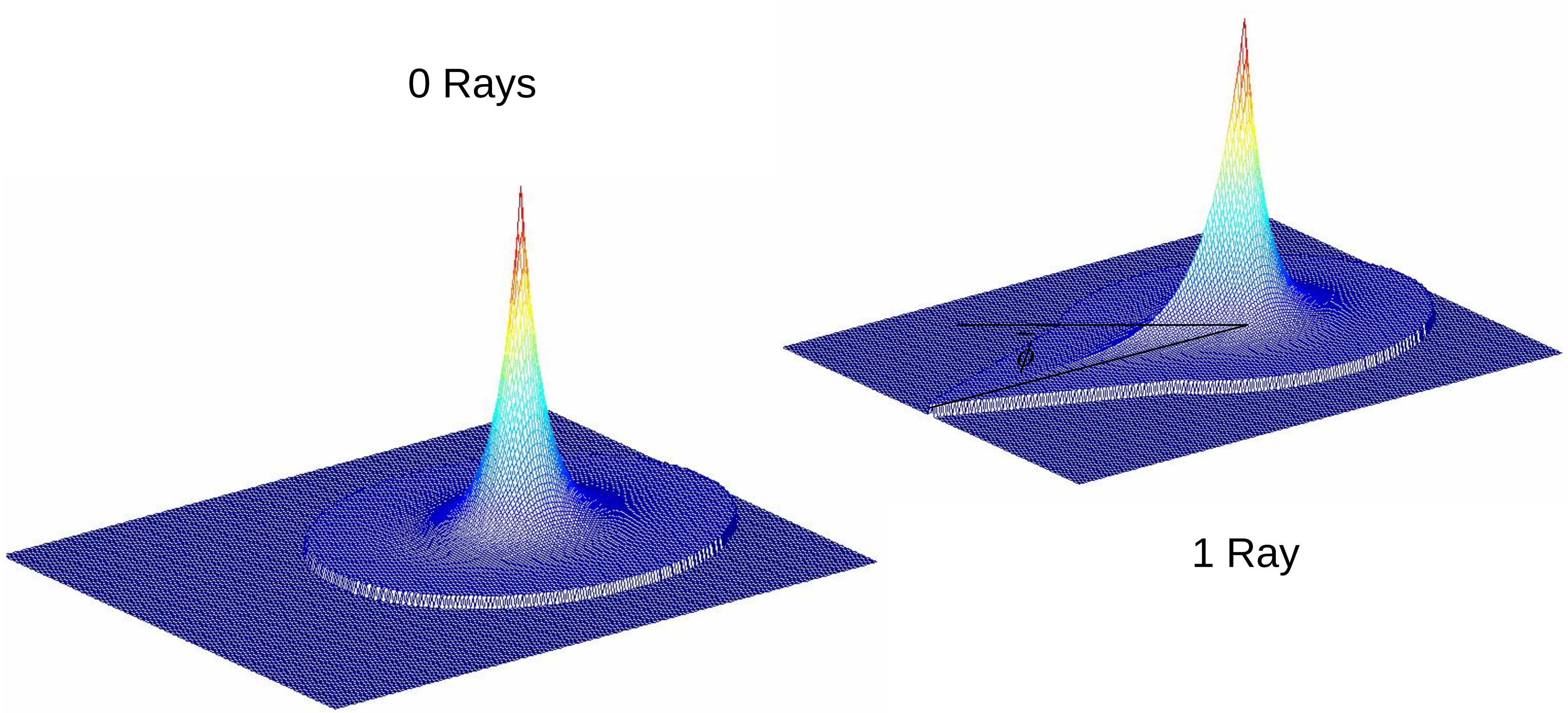


Figure 2
Population Density Functions



Notes: Based on a simulated economy with 1 million identical individuals with the utility function U=z+0.3log(s), γ=0.5, w=100, R_a=1 and b=.004. This implies $\bar{r}_f^0 = 11.40$ and $\bar{r}_f^1 = 11.12$.

Figure 3

Graphical Depiction of Rent Functions in 0, 1 and 2 Ray Equilibria

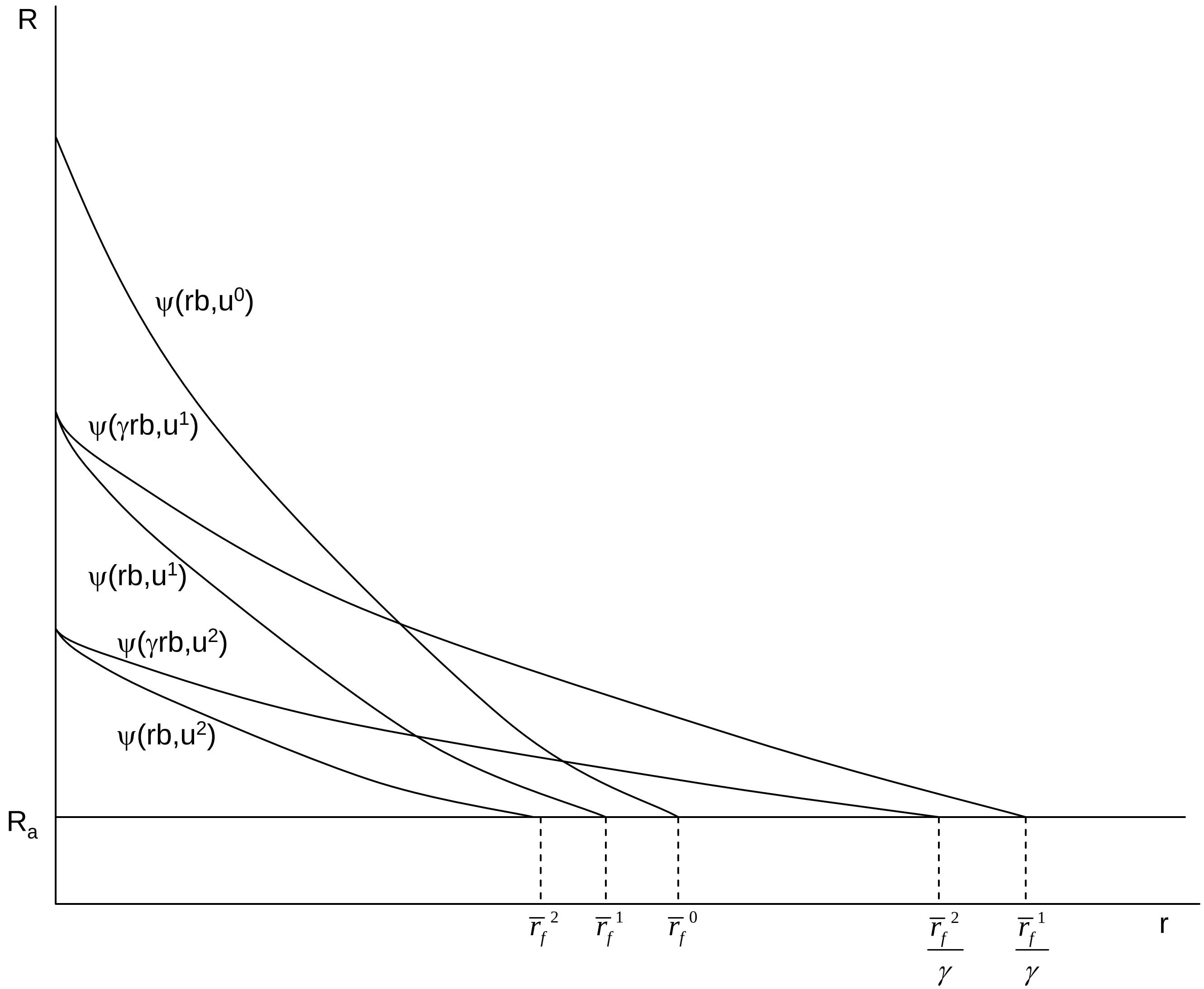


Figure 4
An Example MSA
Peoria, IL

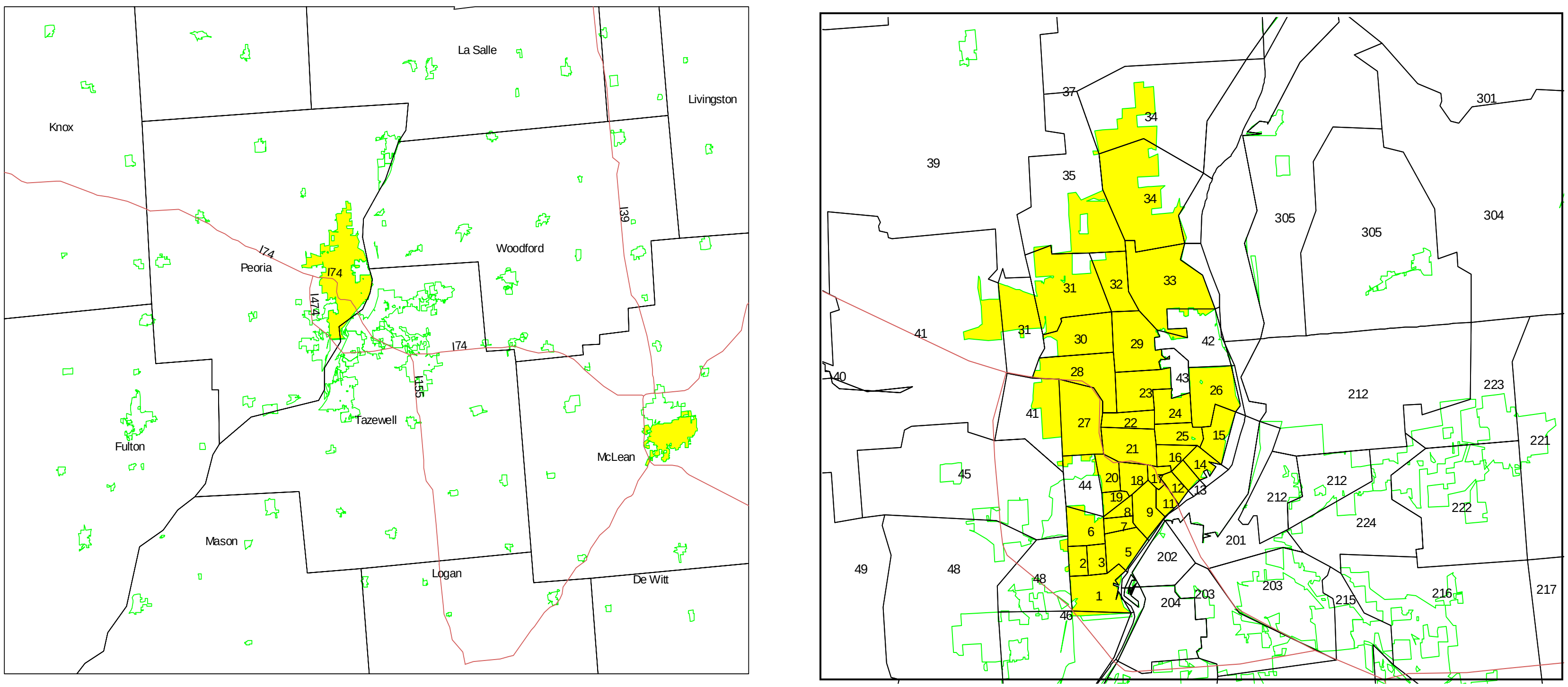


Figure 5
Development Patterns in Austin, TX

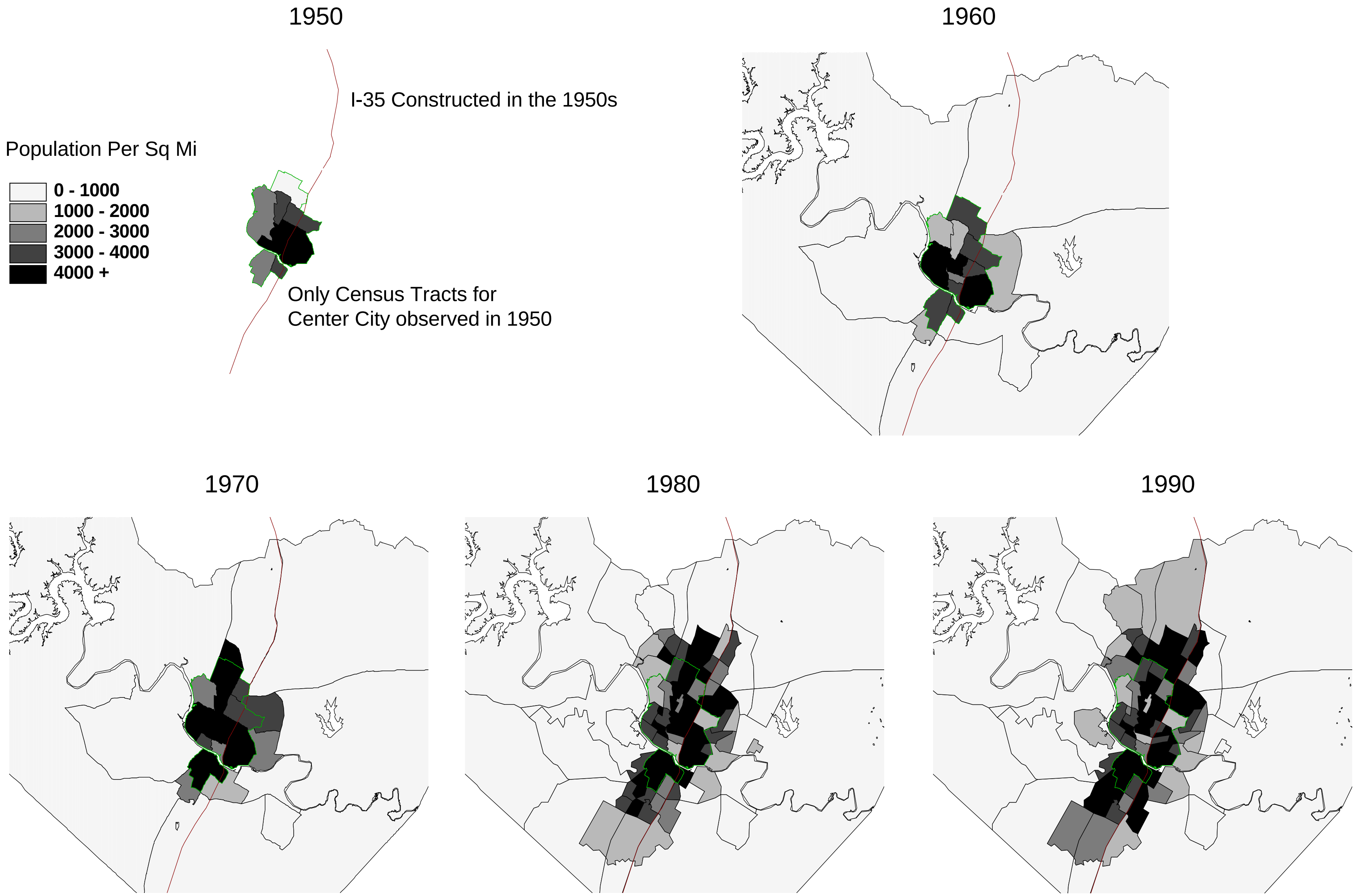


Figure 6
First Stage Results

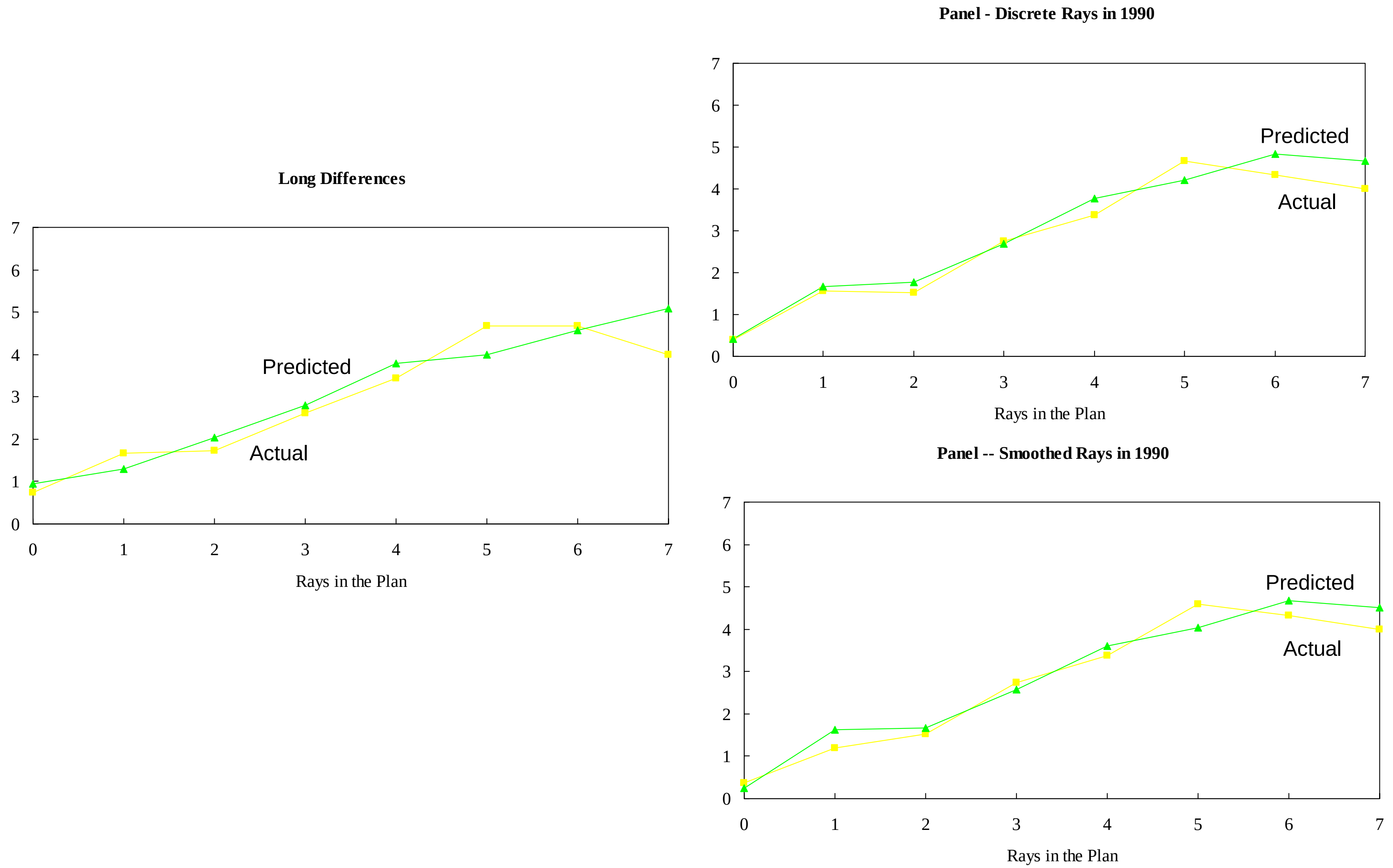


Table 1: Aggregate Trends in Suburbanization 1950-1990

	1950	1960	1970	1980	1990	% Chg 50-90
Panel A: All MSAs in Data						
MSA Population	102,084,899	128,159,438	149,351,539	163,451,119	181,594,984	0.78
Total CC Population	48,557,119	53,612,893	57,384,368	55,856,121	58,433,238	0.20
Constant Area CC Population	48,557,119	46,499,835	45,981,811	41,561,514	40,851,551	-0.16
N for Cons. Area CC Pop	240	184	221	239	240	
Panel B: MSAs in 1950						
MSA Population	93,871,209	117,079,019	135,378,447	146,250,163	161,358,068	0.72
Total CC Population	45,392,211	49,420,900	52,295,467	50,231,751	52,080,405	0.15
Constant Area CC Population	45,392,211	44,681,478	43,267,097	38,495,675	37,745,474	-0.17
N for Cons. Area CC Pop	151	140	151	151	151	
Panel C: MSAs With 1950 Population At least 100,000 and Center City Population at Least 50,000						
MSA Population	92,856,033	115,828,842	134,044,686	144,786,609	159,827,023	0.72
Total CC Population	44,663,375	48,489,912	51,297,083	49,179,465	50,973,591	0.14
Constant Area CC Population	44,663,375	44,244,297	42,601,702	37,867,639	37,136,928	-0.17
N for Cons. Area CC Pop	139	132	139	139	139	
Panel D: MSAs With 1950 Pop > 100,000 and CC Pop > 50,000 and CC > 20 Miles from Border/Coast						
MSA Population	39,158,432	48,877,441	57,034,661	64,981,266	73,505,147	0.88
Total CC Population	16,841,779	19,726,370	22,101,290	22,092,098	23,220,841	0.38
Constant Area CC Population	16,841,779	16,490,819	15,382,022	13,349,161	12,491,324	-0.26
N for Cons. Area CC Pop	100	94	100	100	100	
Total US Population	150,697,361	178,464,253	202,143,934	225,179,263	247,051,601	0.64

Notes: 1950 geography is used for constant area center city population. Census tract data were not available to build constant area center city populations for some small cities in 1960 and 1970. These cities are assigned a population of 0 for the purpose of constructing the aggregate center city populations. Data for Newburgh, NY MSA is not available in 1980 and is omitted from Panel A. Reported total US population excludes Alaska and Hawaii.

Table 2: Facts About Highway Construction

Panel A: Distribution of Interstate Rays Over Time

	I: Unique Interstate Rays in Center Cities						II: Non-Interstate
	1950	1960	1970	1980	1990	50-90	Rays 50-90
0	233	164	99	91	81	81	193
1	4	11	19	21	29	30	34
2	3	46	66	68	70	72	8
3	0	7	23	24	24	25	3
4	0	9	22	24	23	21	2
5	0	2	9	9	11	9	0
6	0	1	1	1	1	1	0
7	0	0	1	1	1	1	0

Panel B: Distribution of Rays By 1950 MSA Population

	I: Total CC Rays Built between 1950 and 1990					II: Rays in the 1947 Plan				
	<100k	100k-250k	250k-500k	500k-1m	>1m	<100k	100k-250k	250k-500k	500k-1m	>1m
0	43	24	1	0	0	39	29	4	0	0
1	7	20	5	0	1	1	2	3	2	1
2	20	23	15	6	1	27	34	19	4	2
3	4	6	10	3	5	5	7	9	6	4
4	1	3	9	9	6	3	5	10	5	6
5	0	0	6	2	3	0	0	0	5	4
6	0	1	0	4	0	0	0	1	2	0
7	0	0	0	1	1	0	0	0	1	0

Notes: Each entry is a number of MSAs from the set of 240 MSAs for which we observe demographic characteristics in 1950 and 1990. Populations refer to 1950 levels for the MSA. The variable in Section I of Panel B is the primary explanatory variable used throughout this analysis. Total center city rays may include both 2-digit and 3-digit interstates, as well as other expressways. Potential rays are selected for inclusion if they were not bypasses, spurs or beltways and connect the CBD and 1950-definition center city to the suburbs. Center city rays must pass within 1 mile of the central business district to be counted.

Table 3: Simulation Results -- Quasilinear Utility
Δ Log Center City Population for a Marginal Ray

Panel A: 30 mph on Surface Streets, 60 mph on Highways

Fraction in CC	Number of Rays							
with 0 Rays	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
0.10	-0.15	-0.12	-0.11	-0.09	-0.08	-0.07	-0.06	-0.05
0.25	-0.13	-0.11	-0.10	-0.08	-0.07	-0.06	-0.05	-0.04
0.50	-0.11	-0.09	-0.08	-0.07	-0.06	-0.05	-0.04	-0.03
0.75	-0.08	-0.07	-0.05	-0.05	-0.04	-0.03	-0.03	-0.02

Panel B: 25 mph on Surface Streets, 60 mph on Highways

Fraction in CC	Number of Rays							
with 0 Rays	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
0.10	-0.23	-0.18	-0.15	-0.12	-0.10	-0.08	-0.06	-0.05
0.25	-0.21	-0.16	-0.13	-0.11	-0.09	-0.07	-0.06	-0.05
0.50	-0.18	-0.14	-0.11	-0.08	-0.07	-0.06	-0.05	-0.04
0.75	-0.14	-0.10	-0.08	-0.06	-0.05	-0.04	-0.03	-0.03

Panel B: 35 mph on Surface Streets, 60 mph on Highways

Fraction in CC	Number of Rays							
with 0 Rays	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
0.10	-0.09	-0.08	-0.07	-0.07	-0.06	-0.06	-0.05	-0.04
0.25	-0.08	-0.07	-0.06	-0.06	-0.05	-0.05	-0.04	-0.04
0.50	-0.07	-0.06	-0.05	-0.05	-0.04	-0.04	-0.03	-0.03
0.75	-0.05	-0.04	-0.04	-0.03	-0.03	-0.03	-0.02	-0.02

Notes: The utility function used is U = z+.3ln(s). Holding gamma constant, reported results do not change for all reasonable travel speeds on surface streets. Gamma gives the ratio of surface street travel speed to highway travel speed. Results are invariant to reasonable wage levels and metropolitan area populations. Magnitudes are within .01 for other reasonable coefficients on ln(s).

Table 4: Urban Form in the Data

Panel A: 1970 and 1990 Cross-Sections

Sample		Log Population Density 1970	Log Population Density 1990
All MSAs	**Distance to Nearest**	-0.010	-0.024
	Highway	(0.002)**	(0.002)**
	Distance to Nearest	-0.141	-0.121
(41756 tracts, 235 MSAs)	**CBD**	(0.001)**	(0.001)**
MSAs of at	**Distance to Nearest**	-0.018	-0.027
Least 150	**Highway**	(0.002)**	(0.002)**
Thousand in 1970	**Distance to Nearest**	-0.113	-0.096
(39167 tracts, 159 MSAs)	**CBD**	(0.001)**	(0.001)**
CBD At Least	**Distance to Nearest**	-0.021	-0.028
20 Miles from	**Highway**	(0.003)**	(0.003)**
Coast or Border	**Distance to Nearest**	-0.165	-0.147
(20679 tracts, 175 MSAs)	**CBD**	(0.002)**	(0.002)**
MSAs of At Least	**Distance to Nearest**	-0.033	-0.036
150 Thousand	**Highway**	(0.003)**	(0.002)**
in 1970 w/ Inland CBD	**Distance to Nearest**	-0.126	-0.112
(18354 tracts, 106 MSAs)	**CBD**	(0.002)**	(0.001)**

Panel B: Evolution Between 1970 and 1990

Sample		∆Log Population Density
All MSAs	**∆Distance to Nearest**	-0.014
	Highway	(0.002)**
	Distance to Nearest	0.019
(41756 tracts, 235 MSAs)	**CBD**	(0.000)**
MSAs of at	**∆Distance to Nearest**	-0.018
Least 150	**Highway**	(0.002)**
Thousand in 1970	**Distance to Nearest**	0.017
(39167 tracts, 159 MSAs)	**CBD**	(0.000)**
CBD At Least	**∆Distance to Nearest**	-0.013
20 Miles from	**Highway**	(0.002)**
Coast or Border	**Distance to Nearest**	0.020
(20679 tracts, 175 MSAs)	**CBD**	(0.001)**
MSAs of At Least	**∆Distance to Nearest**	-0.011
150 Thousand	**Highway**	(0.003)**
in 1970 w/ Inland CBD	**Distance to Nearest**	0.018
(18354 tracts, 106 MSAs)	**CBD**	(0.001)**

Notes: All regressions include MSA fixed effects. Regressions in Panel B include the distance to the nearest highway in 1970. Estimated coefficients on distance to nearest highway in 1970 are between -0.02 and 0.00. Regressions using the distance to planned highways as an instrument for the distance to observed highways yield similar results. Sample sizes differ from other tables because of lack of 1970 census tract data in some MSAs.

Table 5: Suburbanization by Highways Over Time
Log Fraction of MSA in the Center City

Panel A: All MSAs

	Change in Number of Center City Rays							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1950	-0.79	-0.80	-0.85	-0.94	-0.80	-0.74	-0.84	-0.45
	0.33	0.45	0.45	0.43	0.37	0.14	0.48	0.02
1990	-1.54	-1.57	-1.60	-1.86	-1.68	-1.78	-2.01	-1.35
	0.45	0.62	0.58	0.63	0.56	0.39	0.65	0.42
Change	-0.75	-0.77	-0.75	-0.92	-0.88	-1.04	-1.17	-0.90
	(0.56)	(0.77)	(0.73)	(0.76)	(0.67)	(0.41)	(0.81)	(0.42)
Δ Fraction	-0.24	-0.24	-0.23	-0.24	-0.26	-0.30	-0.31	-0.37
N	68	33	65	28	28	11	5	2

Panel B: MSAs That Existed in 1950

	Change in Number of Center City Rays							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1950	-0.73	-0.77	-0.78	-0.91	-0.81	-0.74	-0.66	-0.45
	0.39	0.47	0.43	0.41	0.37	0.14	0.31	0.02
1990	-1.45	-1.46	-1.56	-1.81	-1.67	-1.78	-1.85	-1.35
	0.54	0.59	0.56	0.63	0.57	0.39	0.62	0.42
Change	-0.72	-0.69	-0.78	-0.90	-0.86	-1.04	-1.19	-0.90
	(0.67)	(0.75)	(0.71)	(0.75)	(0.68)	(0.41)	(0.69)	(0.42)
Δ Fraction	-0.25	-0.24	-0.25	-0.24	-0.26	-0.30	-0.36	-0.37
N	21	24	38	24	27	11	4	2

Panel C: MSAs With 1950 MSA Population > 100,000 and 1950 CC Population > 50,000

	Change in Number of Center City Rays							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1950	-0.86	-0.83	-0.81	-0.96	-0.81	-0.74	-0.66	-0.45
	0.35	0.47	0.43	0.39	0.37	0.14	0.31	0.02
1990	-1.60	-1.54	-1.60	-1.88	-1.67	-1.78	-1.85	-1.35
	0.51	0.57	0.55	0.61	0.57	0.39	0.62	0.42
Change	-0.74	-0.71	-0.79	-0.92	-0.86	-1.04	-1.19	-0.90
	(0.62)	(0.74)	(0.70)	(0.72)	(0.68)	(0.41)	(0.69)	(0.42)
Δ Fraction	-0.22	-0.23	-0.25	-0.23	-0.26	-0.30	-0.36	-0.37
N	16	21	36	22	27	11	4	2

Panel D: MSAs with 1950 MSA Pop > 100,000 and 1950 CC Pop > 50,000 and > 20 Miles from Coast or International Border

	Change in Number of Center City Rays							
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1950	-0.89	-0.89	-0.85	-0.97	-0.88	-0.74	-0.66	-0.46
	0.34	0.55	0.47	0.28	0.42	0.15	0.31	
1990	-1.65	-1.54	-1.62	-1.87	-1.82	-1.78	-1.85	-1.65
	0.50	0.58	0.60	0.58	0.58	0.41	0.62	
Change	-0.76	-0.65	-0.77	-0.90	-0.94	-1.04	-1.19	-1.19
	(0.60)	(0.80)	(0.76)	(0.64)	(0.72)	(0.44)	(0.69)	
Δ Fraction	-0.22	-0.22	-0.23	-0.22	-0.26	-0.30	-0.36	-0.44
N	15	13	27	13	17	10	4	1

Notes: Entries are the average log fraction of MSA population living in the center city as defined by its 1950 borders. Standard Deviations are in parentheses. Δ Fraction is the difference between the average 1990 and 1950 fractions for the group.

Table 6: Difference Regressions 1950-1990
Center City > 20 Miles from Border/Coast, 1950 MSA Pop >100,000, 1950 CC Pop > 50,000

Panel A: OLS

	Change in Log Population in Constant-Area Center Cities				
	1	**2**	**3**	**4**	**5**
Change in Number of	-0.000	-0.040	-0.045	-0.062	-0.063
Highway Rays Thru CC	(0.018)	(0.019)*	(0.017)*	(0.017)**	(0.016)**
Square Root of of		0.054	0.062	0.052	0.053
1950 CC Area		(0.017)**	(0.014)**	(0.014)**	(0.013)**
Change in Simulated			0.985	0.048	-12.349
Log Income			(0.447)*	(0.450)	(8.395)
Change in Log of MSA				0.325	0.242
Population				(0.086)**	(0.094)*
Change in Gini Coeff					-46.089
of Simulated Income					(31.420)
Constant	-0.302	-0.478	-1.169	-0.618	9.553
	(0.050)**	(0.074)**	(0.290)**	(0.291)*	(6.915)
Obs	100	100	100	100	100
R-squared	0.00	0.11	0.16	0.34	0.36

Panel B: Instrument For Rays With Rays in the 1947 Plan

	Change in Log Population in Constant-Area Center Cities				
	1	**2**	**3**	**4**	**5**
Change in Number of	-0.014	-0.101	-0.114	-0.142	-0.132
Highway Rays Thru CC	(0.026)	(0.030)**	(0.029)**	(0.038)**	(0.030)**
Square Root of of		0.088	0.101	0.093	0.089
1950 CC Area		(0.018)**	(0.019)**	(0.020)**	(0.017)**
Change in Simulated			1.138	0.027	-13.223
Log Income			(0.533)*	(0.526)	(9.864)
Change in Log of MSA				0.391	0.293
Population				(0.100)**	(0.100)**
Change in Gini Coeff					-49.274
of Simulated Income					(36.868)
Constant	-0.269	-0.494	-1.293	-0.645	10.233
	(0.072)**	(0.080)**	(0.346)**	(0.350)	(8.120)
Obs	-0.269	-0.494	20.330	10.233	10.494
R-squared	(0.072)**	(0.080)**	(7.315)**	(8.120)	(7.889)

Notes: Standard errors are in parentheses. ** indicates significant at the 1% level, * indicates significant at 5% level. For summary statistics see Appendix Table 1. First stage results for Specification 4 are in Appendix Table 5. Standard errors are clustered by state of the MSA center city.

Table 7: Coefficients from Difference Regressions 1950-1990

		Without State Fixed Effects					With State Fixed Effects				
		1	2	3	4	5	1	2	3	4	5
All 2000-	**A**	0.004	-0.012	-0.007	-0.047	-0.047	-0.009	-0.015	-0.010	-0.036	-0.035
Definition		(0.021)	(0.023)	(0.023)	(0.012)**	(0.012)**	(0.012)	(0.012)	(0.011)	(0.015)*	(0.016)*
MSAs	**B**	-0.032	-0.087	-0.076	-0.129	-0.127	-0.024	-0.047	-0.046	-0.091	-0.090
		(0.015)*	(0.024)**	(0.022)**	(0.028)**	(0.027)**	(0.014)	(0.017)**	(0.017)**	(0.026)**	(0.026)**
All MSAs	**A**	0.003	-0.032	-0.036	-0.062	-0.058	-0.003	-0.025	-0.024	-0.041	-0.040
That Existed		(0.015)	(0.014)*	(0.013)**	(0.012)**	(0.013)**	(0.012)	(0.013)	(0.013)	(0.016)*	(0.016)*
in 1950	**B**	-0.030	-0.100	-0.105	-0.123	-0.115	-0.006	-0.043	-0.048	-0.086	-0.081
		(0.019)	(0.029)**	(0.030)**	(0.029)**	(0.027)**	(0.016)	(0.018)*	(0.018)*	(0.027)**	(0.024)**
All MSAs	**A**	0.005	-0.032	-0.036	-0.059	-0.055	-0.005	-0.029	-0.028	-0.042	-0.041
With Pop>100,000		(0.016)	(0.015)*	(0.014)*	(0.014)**	(0.014)**	(0.015)	(0.015)	(0.015)	(0.017)*	(0.017)*
and CC	**B**	-0.030	-0.103	-0.108	-0.120	-0.111	-0.009	-0.049	-0.052	-0.083	-0.079
Pop>50,000 in 1950		(0.022)	(0.032)**	(0.032)**	(0.030)**	(0.027)**	(0.018)	(0.019)*	(0.019)**	(0.027)**	(0.027)**
All MSAs	**A**	-0.000	-0.040	-0.045	-0.062	-0.063	-0.013	-0.039	-0.032	-0.037	-0.037
With Pop>100,000		(0.018)	(0.019)*	(0.017)*	(0.017)**	(0.016)**	(0.022)	(0.024)	(0.023)	(0.022)	(0.021)
and CC Pop>50,000 in 1950	**B**	-0.014	-0.101	-0.114	-0.142	-0.132	-0.012	-0.059	-0.059	-0.102	-0.094
and > 20 Miles from Coast/Border		(0.026)	(0.030)**	(0.029)**	(0.038)**	(0.030)**	(0.021)	(0.034)	(0.030)	(0.042)*	(0.040)*

Notes: Each entry in this table represents the coefficient on 2-digit highway rays from a different regression with controls listed in Table 5. Sample sizes are 240 for block 1, 151 for block 2, 139 for block 3 and 100 for block 4. First stage results (for block 4) are reported in Appendix Table 5.

Table 8: Panel Regressions 1950-1990

Panel A: OLS

	Log Center City Population					
	3	**4**	**5**	**6**	**7**	**8**
Number of Highway	-0.018	-0.014				
Rays Thru CC	(0.011)	(0.011)				
(1990 CC Rays)X(Fraction			-0.081	-0.039	-0.050	-0.047
of CC Rays Completed at t)			(0.014)**	(0.014)**	(0.011)**	(0.011)**
Log Simulated	-0.447	-0.351		-0.255	-0.388	-0.300
Income	(0.080)**	(0.067)**		(0.068)**	(0.080)**	(0.066)**
Log MSA	0.167	0.147			0.228	0.208
Population	(0.082)*	(0.078)			(0.083)**	(0.080)*
Simulated Gini		-2.460				-2.183
Coefficient		(0.716)**				(0.742)**
Constant	3.752	3.579	-2.356	1.308	3.136	2.963
	(0.752)**	(0.658)**	(0.000)**	(0.667)	(0.765)**	(0.660)**
MSA Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Groups	94	94	94	94	94	94

Panel B: Instrument For Rays and MSA Population

	Log Center City Population					
	3	**4**	**5**	**6**	**7**	**8**
Number of Highway	-0.123	-0.120				
Rays Thru CC	(0.025)**	(0.025)**				
(1990 CC Rays)X(Fraction			-0.101	-0.071	-0.088	-0.086
of CC Rays Completed at t)			(0.018)**	(0.016)**	(0.015)**	(0.015)**
Log Simulated	-0.158	-0.104		-0.148	-0.306	-0.231
Income	(0.116)	(0.096)		(0.073)*	(0.086)**	(0.071)**
Log MSA	0.234	0.223			0.282	0.266
Population	(0.091)*	(0.089)*			(0.088)**	(0.086)**
Simulated Gini		-1.396				-1.836
Coefficient		(1.033)				(0.836)*
Constant	0.624	0.578	-2.637	-1.636	2.312	2.154
	(1.069)	(0.984)	(0.000)**	(0.741)*	(0.821)**	(0.723)**
MSA Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes
Groups	94	94	94	94	94	94

Notes: Standard errors are in parentheses. ** indicates significant at the 1% level, * indicates significant at 5% level. Standard errors are clustered by state. For summary statistics see Appendix Table 1. Each group has 5 observations, one for each year 1950 to 1990. First stage results for Specifications 3 and 7 are in Appendix Table 5

Table 9: Coefficients from Panel Regressions 1950-1990

		Log Center City Population							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
All 2000-	**A**	-0.057	-0.021	-0.028	-0.016	-0.067	-0.039	-0.053	-0.044
Definition		(0.014)**	(0.010)*	(0.009)**	(0.010)	(0.015)**	(0.012)**	(0.010)**	(0.011)**
MSAs	**B**	-0.102	-0.109	-0.129	-0.125	-0.090	-0.080	-0.095	-0.089
		(0.017)**	(0.020)**	(0.021)**	(0.025)**	(0.017)**	(0.015)**	(0.014)**	(0.016)**
All MSAs	**A**	-0.065	-0.012	-0.016	-0.010	-0.075	-0.034	-0.045	-0.041
That Existed		(0.012)**	(0.010)	(0.008)	(0.009)	(0.014)**	(0.012)**	(0.009)**	(0.010)**
in 1950	**B**	-0.109	-0.110	-0.125	-0.123	-0.096	-0.074	-0.086	-0.083
		(0.016)**	(0.023)**	(0.024)**	(0.026)**	(0.016)**	(0.014)**	(0.013)**	(0.014)**
All MSAs	**A**	-0.065	-0.009	-0.013	-0.008	-0.075	-0.033	-0.043	-0.039
With Pop>100,000		(0.012)**	(0.010)	(0.009)	(0.009)	(0.014)**	(0.013)*	(0.009)**	(0.010)**
and CC	**B**	-0.109	-0.120	-0.133	-0.131	-0.097	-0.077	-0.087	-0.084
Pop>50,000 in 1950		(0.016)**	(0.025)**	(0.027)**	(0.028)**	(0.015)**	(0.014)**	(0.013)**	(0.014)**
All MSAs	**A**	-0.070	-0.014	-0.018	-0.014	-0.081	-0.039	-0.050	-0.047
With Pop>100,000		(0.013)**	(0.013)	(0.011)	(0.011)	(0.014)**	(0.014)**	(0.011)**	(0.011)**
and CC Pop>50,000 in 1950	**B**	-0.113	-0.103	-0.123	-0.120	-0.101	-0.071	-0.088	-0.086
and > 20 Miles from Coast/Border		(0.018)**	(0.024)**	(0.025)**	(0.025)**	(0.018)**	(0.016)**	(0.015)**	(0.015)**

Notes: Each entry in this table represents the coefficient from a different regression. The number of MSAs in the sample are 179 for block 1, 140 for block 2, 132 for block 3, and 94 for block 4. First stage results (for block 4) are in Appendix Table 5.

Table 10: Predicted Trends in Suburbanization 1950-1990 Without Highways

	1950	1960	1970	1980	1990	% Chg 50-90
Panel A: All MSAs in Data						
Constant Area CC Population	48,557,117	46,499,835	45,981,811	41,561,514	40,851,551	-0.16
Forecast CC Pop Less All Interstates, Low	48,557,117	48,245,886	54,333,929	51,610,934	51,346,918	0.06
Forecast CC Pop Less All Rays, Low	48,557,117	48,545,172	55,114,895	52,594,076	52,514,337	0.08
Forecast CC Pop Less All Interstates, High	48,557,117	48,867,236	57,524,429	55,594,398	55,537,754	0.14
Forecast CC Pop Less All Rays, High	48,557,117	49,281,354	58,646,122	57,031,593	57,249,540	0.18
Panel B: MSAs in 1950						
Constant Area CC Population	45,392,211	44,681,478	43,267,097	38,495,675	37,745,474	-0.17
Forecast CC Pop Less All Interstates, Low	45,392,209	46,838,368	52,212,751	49,063,038	48,822,632	0.08
Forecast CC Pop Less All Rays, Low	45,392,209	47,232,777	53,134,954	50,167,152	50,124,705	0.10
Forecast CC Pop Less All Interstates, High	45,392,209	47,605,405	55,660,995	53,297,104	53,300,806	0.17
Forecast CC Pop Less All Rays, High	45,392,209	48,149,777	56,990,975	54,922,265	55,227,365	0.22
Panel C: MSAs With 1950 Population At least 100,000 and Center City Population at Least 50,000						
Constant Area CC Population	44,663,375	44,244,297	42,601,702	37,867,639	37,136,928	-0.17
Forecast CC Pop Less All Interstates, Low	44,663,373	46,419,115	51,544,830	48,424,480	48,210,453	0.08
Forecast CC Pop Less All Rays, Low	44,663,373	46,815,423	52,477,468	49,538,756	49,521,804	0.11
Forecast CC Pop Less All Interstates, High	44,663,373	47,193,083	54,995,485	52,659,261	52,693,117	0.18
Forecast CC Pop Less All Rays, High	44,663,373	47,739,982	56,340,986	54,300,551	54,635,181	0.22
Panel D: MSAs With 1950 Pop > 100,000 and CC Pop > 50,000 and CC > 20 Miles from Border/Coast						
Constant Area CC Population	16,841,779	16,490,819	15,382,022	13,349,161	12,491,324	-0.26
Forecast CC Pop Less All Interstates, Low	16,841,779	17,165,780	18,384,028	16,918,793	16,084,506	-0.04
Forecast CC Pop Less All Rays, Low	16,841,779	17,349,896	18,754,234	17,395,693	16,631,388	-0.01
Forecast CC Pop Less All Interstates, High	16,841,779	17,406,985	19,542,262	18,356,944	17,548,591	0.04
Forecast CC Pop Less All Rays, High	16,841,779	17,660,977	20,077,071	19,061,988	18,363,564	0.09

Notes: Center city population represents population using the 1950 geography. "Low" estimates assume that each randomly assigned ray causes a decrease in 0.09 in log center city population and "high" estimates assume a decrease of 0.12. "Randomly assigned" rays are determined by taking predicted values from a separate first stage regression for each panel. Observations for which center city data is not available contribute 0 to the aggregates.

Appendix Table 1: Summary Statistics

Variable	1950	1990	1990-1950	Min	Max
Fraction of Population Living Inside Constant Area CC	0.45	0.21	-0.25	-0.51	-0.03
	(0.16)	(0.11)	(0.11)		
Fraction of Population Living Inside of CC	0.45	0.36	-0.09	-0.42	0.33
	(0.16)	(0.19)	(0.13)		
Log Population of Center City (1950 Area, millions)	-2.05	-2.36	-0.30	-0.81	0.70
	(0.69)	(0.71)	(0.26)		
Log Population of Center City (Political Boundary, millions)	-2.05	-1.83	0.22	-0.81	2.22
	(0.69)	(0.84)	(0.55)		
Log MSA Population (millions)	-1.19	-0.65	0.54	-0.21	1.95
	(0.68)	(0.82)	(0.40)		
Total Number of Rays Through CC	0.06	2.61	2.55	0	7
	(0.31)	(1.78)	(1.75)		
Number of Interstate Rays Through CC	0.06	2.25	2.19	0	6
	(0.31)	(1.63)	(1.60)		
Number of Planned Rays	2.60	2.60	-	0	7
	(1.56)	(1.56)			
Square Root of Center City Area	5.08	5.08	-	2.05	12.65
	(2.00)	(2.00)			
Square Root of MSA Area	45.65	45.65	-	15.03	165.14
	(19.39)	(19.39)			
Simulated Mean Log Income Using 1940 Employment Distribution	9.59	10.26	0.67	0.58	0.89
	(0.12)	(0.06)	(0.07)		
Gini Coefficient of Simulated Income Distribution	0.33	0.37	0.04	-0.02	0.07
	(0.03)	(0.01)	(0.02)		
Median Log Household Income	9.98	10.57	0.60	0.27	0.99
	(0.16)	(0.13)	(0.15)		

Notes: The sample size is 100 and consists of the same MSAs used in the regressions in Table 6. Standard deviations are in parentheses. Min and max refer to the 50-90 difference unless the variable does not change over time.

Appendix Table 2: Interstate Highway Construction

Stock of Interstate Highways (miles)

	Nationwide			240 MSAs Only			Fraction of	Fraction of Fed
Year	**2-Digit**	**3-Digit**	**Fed Fund**	**2-Digit**	**3-Digit**	**Fed Fund**	**Tot in MSA**	**Fund in MSA**
50	328	13	155	155	9	74	0.48	0.48
51	372	29	194	193	12	101	0.51	0.52
52	429	34	256	244	12	152	0.55	0.59
53	540	49	380	292	26	212	0.54	0.56
54	806	70	576	438	36	312	0.54	0.54
55	1,385	123	814	793	85	418	0.58	0.51
56	1,924	154	1,070	1,145	116	573	0.61	0.54
57	2,986	252	1,571	1,875	177	920	0.63	0.59
58	3,573	295	1,963	2,303	205	1,149	0.65	0.59
59	4,908	411	2,988	3,125	302	1,740	0.64	0.58
60	6,083	456	4,191	3,784	346	2,433	0.63	0.58
61	7,796	584	6,009	4,639	453	3,372	0.61	0.56
62	9,521	709	7,822	5,442	575	4,274	0.59	0.55
63	11,572	841	9,965	6,364	696	5,285	0.57	0.53
64	13,635	1,080	12,195	7,223	886	6,311	0.55	0.52
65	16,382	1,257	14,955	8,422	1,042	7,590	0.54	0.51
66	19,401	1,451	18,098	9,704	1,208	8,980	0.52	0.50
67	21,378	1,594	20,185	10,375	1,336	9,752	0.51	0.48
68	23,481	1,711	22,389	11,156	1,427	10,609	0.50	0.47
69	25,394	1,913	24,449	11,957	1,611	11,552	0.50	0.47
70	27,302	2,110	26,515	12,622	1,777	12,352	0.49	0.47
71	29,075	2,220	28,384	13,257	1,886	13,082	0.48	0.46
72	30,352	2,379	29,780	13,658	2,038	13,602	0.48	0.46
73	31,651	2,509	31,170	14,152	2,150	14,172	0.48	0.45
74	32,965	2,640	32,488	14,689	2,280	14,772	0.48	0.45
75	33,938	2,752	33,485	14,993	2,385	15,157	0.47	0.45
76	34,838	2,835	34,441	15,266	2,468	15,499	0.47	0.45
77	35,604	2,958	35,253	15,557	2,559	15,845	0.47	0.45
78	36,198	3,107	35,847	15,756	2,678	16,070	0.47	0.45
79	36,661	3,167	36,345	15,903	2,738	16,254	0.47	0.45
80	37,014	3,295	36,802	15,975	2,830	16,395	0.47	0.45
81	37,364	3,358	37,193	16,093	2,893	16,554	0.47	0.45
82	37,762	3,437	37,643	16,248	2,970	16,759	0.47	0.45
83	37,916	3,479	37,789	16,302	3,010	16,813	0.47	0.44
84	38,048	3,586	37,939	16,340	3,108	16,880	0.47	0.44
85	38,238	3,744	38,143	16,443	3,219	17,018	0.47	0.45
86	38,481	3,827	38,379	16,534	3,283	17,131	0.47	0.45
87	38,658	3,888	38,565	16,622	3,333	17,227	0.47	0.45
88	38,910	3,985	38,775	16,726	3,414	17,330	0.47	0.45
89	39,155	4,039	38,957	16,822	3,462	17,387	0.47	0.45
90	39,295	4,119	39,139	16,903	3,536	17,507	0.47	0.45
91	39,381	4,170	39,189	16,918	3,579	17,535	0.47	0.45
92	39,547	4,210	39,228	16,938	3,610	17,551	0.47	0.45
93	39,758	4,382	39,319	17,014	3,779	17,632	0.47	0.45

Appendix Table 3: Simulation Results -- Cobb-Douglas Utility
Δ Log Center City Population for a Marginal Ray

Panel A: 30 mph on Surface Streets, 60 mph on Highways

Fraction in CC	Number of Rays							
with 0 Rays	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
0.10	-0.36	-0.38	-0.45	-0.60	-0.92	-0.08	-0.06	-0.05
0.25	-0.32	-0.33	-0.36	-0.42	-0.48	-0.07	-0.06	-0.05
0.50	-0.27	-0.26	-0.26	-0.27	-0.27	-0.07	-0.05	-0.05
0.75	-0.22	-0.20	-0.19	-0.18	-0.17	-0.06	-0.05	-0.04

Panel A: 25 mph on Surface Streets, 60 mph on Highways

Fraction in CC	Number of Rays							
with 0 Rays	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
0.10	-0.49	-0.52	-0.65	-1.13	-0.15	-0.09	-0.07	-0.06
0.25	-0.45	-0.45	-0.49	-0.64	-0.12	-0.08	-0.07	-0.06
0.50	-0.38	-0.35	-0.35	-0.37	-0.10	-0.08	-0.06	-0.05
0.75	-0.32	-0.28	-0.25	-0.23	-0.09	-0.07	-0.06	-0.05

Panel A: 35 mph on Surface Streets, 60 mph on Highways

Fraction in CC	Number of Rays							
with 0 Rays	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8
0.10	-0.25	-0.27	-0.30	-0.36	-0.48	-0.78	-0.17	-0.05
0.25	-0.22	-0.23	-0.25	-0.28	-0.33	-0.41	-0.10	-0.04
0.50	-0.18	-0.18	-0.19	-0.19	-0.21	-0.22	-0.07	-0.04
0.75	-0.15	-0.14	-0.14	-0.13	-0.13	-0.13	-0.05	-0.03

Notes: The utility function used is U = .7ln(z)+.3ln(s). The time endowment is 10 hours per day. The wage is set to 100 per day. Metropolitan area population is set to 1 million. Results are at most 0.02 smaller for a metropolitan area population of 100,000 and within 0.01 for a metropolitan area population of 10 million.

Appendix Table 4: Difference Regressions 1950-1970
Center City > 20 Miles from Border/Coast,
1950 MSA Pop >100,000, 1950 CC Pop > 50,000

Panel A: No Instrument for Highway Rays

	Change in Log Population in Constant-Area Center Cities				
	1	2	3	4	5
Change in Number of	0.004	-0.037	-0.038	-0.041	-0.041
Highway Rays Thru CC	(0.012)	(0.011)**	(0.011)**	(0.011)**	(0.011)**
Square Root of of		0.052	0.055	0.048	0.046
1950 CC Area		(0.007)**	(0.006)**	(0.008)**	(0.008)**
Change in Simulated			0.621	0.244	2.870
Log Income			(0.234)*	(0.297)	(1.445)
Change in Log of MSA				0.277	0.234
Population				(0.090)**	(0.091)*
Change in Gini Coeff					13.200
of Simulated Income					(7.162)
Constant	-0.112	-0.295	-0.687	-0.510	-2.375
	(0.030)**	(0.025)**	(0.148)**	(0.169)**	(1.022)*
Obs	100	100	100	100	100
R-squared	0.00	0.21	0.25	0.34	0.36

Panel B: Instrument With 1947 Interstate Highway Plan

	Change in Log Population in Constant-Area Center Cities				
	1	2	3	4	5
Change in Number of	-0.003	-0.057	-0.061	-0.068	-0.067
Highway Rays Thru CC	(0.015)	(0.016)**	(0.016)**	(0.015)**	(0.016)**
Square Root of of		0.063	0.067	0.061	0.060
1950 CC Area		(0.007)**	(0.007)**	(0.008)**	(0.008)**
Change in Simulated			0.652	0.264	2.776
Log Income			(0.238)**	(0.319)	(1.540)
Change in Log of MSA				0.289	0.248
Population				(0.094)**	(0.097)*
Change in Gini Coeff					12.626
of Simulated Income					(7.573)
Constant	-0.097	-0.308	-0.721	-0.542	-2.326
	(0.036)*	(0.024)**	(0.149)**	(0.181)**	(1.085)*
Obs	100	100	100	100	100
R-squared	0.00	0.19	0.22	0.31	0.32

Notes: Standard errors are in parentheses. ** indicates significant at the 1% level, * indicates significant at 5% level. These regressions are exactly the same as those in Table 6 except that only interstate highways are used to define center city rays and the final year is 1970 instead of 1990.

Appendix Table 5: First Stage Results

Center City > 20 Miles from Border/Coast, 1950 MSA Pop > 100,000, 1950 CC Pop > 50,000

Panel A: Long Difference

	Change in CC Rays				Pop Growth 50-90			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Rays in	0.667	0.404	0.654	0.416			0.050	0.047
the Plan	(0.091)**	(0.095)**	(0.089)**	(0.095)**			(0.017)**	(0.019)*
Δ Log Pop			2.337	1.310	2.146	1.823	2.113	1.871
40-50			(1.007)*	(0.996)	(0.199)**	(0.202)**	(0.192)**	(0.197)**
Constant	0.817	-1.489	0.375	-0.982	0.107	-1.099	-0.017	-1.045
	(0.276)**	(1.414)	(0.331)	(1.460)	(0.049)*	(0.296)**	(0.063)	(0.289)**
Controls	No	Yes	No	Yes	No	Yes	No	Yes
Obs	100	100	100	100	100	100	100	100
R-squared	0.35	0.50	0.39	0.51	0.54	0.61	0.58	0.64

Panel B: Full Panel

	CC Rays				Smoothed CC Rays				Log MSA Pop			
	1	**2**	**3**	**4**	**1**	**2**	**3**	**4**	**1**	**2**	**3**	**4**
Smoothed Rays	0.804	0.508	0.617	0.502	0.796	0.701	0.677	0.689			-0.019	-0.001
in Plan	(0.032)**	(0.046)**	(0.037)**	(0.046)**	(0.025)**	(0.035)**	(0.030)**	(0.035)**			(0.005)**	(0.004)
Lagged Log			0.663	0.111			0.421	0.678	0.992	0.812	1.015	0.814
Population			(0.077)**	(0.221)			(0.062)**	(0.170)**	(0.008)**	(0.020)**	(0.010)**	(0.021)**
Constant	0.354	-11.133	1.273	-10.388	0.115	0.795	0.699	2.373	0.145	-0.005	0.196	-0.038
	(0.068)**	(2.688)**	(0.125)**	(2.794)**	(0.053)*	(2.085)	(0.100)**	(2.150)	(0.010)**	(0.242)	(0.016)**	(0.267)
Controls	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Groups	94	94	94	94	94	94	94	94	94	94	94	94
R-squared	0.57	0.84	0.63	0.84	0.68	0.88	0.71	0.88	0.97	0.99	0.97	0.99

Notes: Specification 2 for rays is the first stage for the results reported in Panel B of Tables 6 and 8.

Appendix Table 6: Evaluating Causes of IV-OLS Discrepancy

Center City > 20 Miles from Border/Coast, 1950 MSA Pop > 100,000, 1950 CC Pop > 50,000

Panel A: Long Difference

	ΔLog Population in Constant-Area Center Cities			
	A: OLS		B: IV	
	1	2	1	2
Change in Number of	-0.043	-0.070	-0.088	-0.090
Highway Rays Thru CC	(0.018)*	(0.018)**	(0.059)	(0.027)**
Square Root of of	0.051	0.056	0.071	0.066
1950 CC Area	(0.016)**	(0.014)**	(0.027)*	(0.015)**
Change in Simulated	0.066	0.065	0.052	0.077
Income	(0.429)	(0.434)	(0.456)	(0.442)
ΔLog MSA Population	0.298	0.299	0.336	0.304
	(0.088)**	(0.089)**	(0.105)**	(0.089)**
Non-Center City		-0.025		-0.027
Rays		(0.019)		(0.018)
Constant	-0.636	-0.593	-0.642	-0.609
	(0.277)*	(0.295)	(0.303)*	(0.302)
Obs	90	100	90	100
R-squared	0.33	0.35	0.27	0.34

Panel B: Full Panel

	Log Population in Constant-Area Center Cities							
	A: OLS				B: IV			
	1a	1b	2a	2b	1a	1b	2a	2b
Center City Rays	-0.009		-0.020		-0.109		-0.103	
	(0.011)		(0.012)		(0.041)*		(0.020)**	
Smoothed Center		-0.036		-0.049		-0.076		-0.081
City Rays		(0.011)**		(0.012)**		(0.020)**		(0.015)**
Simulated	-0.450	-0.405	-0.383	-0.344	-0.215	-0.331	-0.135	-0.280
Income	(0.083)**	(0.085)**	(0.083)**	(0.083)**	(0.148)	(0.098)**	(0.110)	(0.087)**
Log MSA Population	0.167	0.210	0.177	0.234	0.233	0.264	0.233	0.279
	(0.080)*	(0.083)*	(0.079)*	(0.082)**	(0.090)*	(0.089)**	(0.086)*	(0.087)**
Non-Center City			-0.024	-0.019			-0.031	-0.017
Rays			(0.012)	(0.012)			(0.013)*	(0.012)
Constant	3.315	2.933	2.728	2.415	1.198	2.306	0.463	1.858
	(0.863)**	(0.882)**	(0.851)**	(0.847)**	(1.446)	(0.995)*	(1.096)	(0.888)*
Obs	84	84	94	94	84	84	94	94

Notes: Specification 1 includes only MSAs from the primary sample that received between 0 and 4 rays in the plan. Specification 2 includes all MSAs in the primary sample and a control for the number of non-center city rays. Specification 2 of the long differences includes only interstate rays.

Appendix Table 7: Instrumenting for Population
Coefficients on ΔRays or Rays

		1	2	3	4	5	6	7	8
All 2000-	**Long Diff**	-0.032	-0.087	-0.076	-0.131	-0.130			
Definition		(0.015)*	(0.024)**	(0.022)**	(0.028)**	(0.026)**			
MSAs	**Panel**	-0.102	-0.109	-0.127	-0.123	-0.090	-0.080	-0.094	-0.088
		(0.017)**	(0.020)**	(0.023)**	(0.026)**	(0.017)**	(0.015)**	(0.015)**	(0.017)**
All MSAs	**Long Diff**	-0.030	-0.100	-0.105	-0.126	-0.121			
That Existed		(0.019)	(0.029)**	(0.030)**	(0.028)**	(0.027)**			
in 1950	**Panel**	-0.109	-0.110	-0.123	-0.120	-0.096	-0.074	-0.084	-0.081
		(0.016)**	(0.023)**	(0.025)**	(0.027)**	(0.016)**	(0.014)**	(0.014)**	(0.015)**
All MSAs	**Long Diff**	-0.030	-0.103	-0.108	-0.122	-0.121			
With Pop>100,000		(0.022)	(0.032)**	(0.032)**	(0.029)**	(0.028)**			
and CC	**Panel**	-0.109	-0.120	-0.131	-0.129	-0.097	-0.077	-0.086	-0.084
Pop>50,000 in 1950		(0.016)**	(0.025)**	(0.027)**	(0.029)**	(0.015)**	(0.014)**	(0.014)**	(0.015)**
All MSAs	**Long Diff**	-0.014	-0.101	-0.114	-0.150	-0.142			
With Pop>100,000		(0.026)	(0.030)**	(0.029)**	(0.043)**	(0.038)**			
and CC Pop>50,000 in 1950	**Panel**	-0.113	-0.103	-0.117	-0.115	-0.101	-0.071	-0.084	-0.082
and > 20 Miles from Coast/Border		(0.018)**	(0.024)**	(0.026)**	(0.026)**	(0.018)**	(0.016)**	(0.016)**	(0.016)**

Notes: Each entry in this table represents the coefficient on 2-digit highway rays from a different regression with controls listed in Tables 6 and 8. Sample sizes are 240 for block 1, 151 for block 2, 139 for block 3 and 100 for block 4. First stage results (for block 4) are reported in Appendix Table 5.