Urban Transport Expansions, Employment Decentralization, and the Spatial Scope of Agglomeration Economies*

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Abstract

Using planned portions of the U.S. highway system as a source of exogenous variation, this paper demonstrates that each new radial highway displaced 16% of central city working residents but only 6% of jobs to the suburbs in the 1960-2000 period. In the context of a calibrated model of urban structure, the implied elasticity of central city TFP to central city employment relative to suburban employment is 0.02-0.05, meaning that a large fraction of overall agglomeration economies operate at spatial scales below the metropolitan area level. Finance, insurance and real estate exhibits the strongest such localized agglomeration spillovers and wholesale/retail trade the weakest. Each highway causes central city income net of commuting costs to increase by up to 3.6% and housing cost to decline by up to 3.0%. Factor reallocation toward land in housing production generates the plurality of population decentralization with new highways.

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1 Introduction

A large literature, including Ellison & Glaeser (1997), Rosenthal & Strange (2003), Duranton & Overman (2005), Arzhagi & Henderson (2008), Ellison, Glaeser & Kerr (2010) and Billings & Johnson (2016), uses observed spatial distributions of firms and employment to draw conclusions about the implied strength of agglomeration spillovers at very local spatial scales. Related papers use plausibly exogenous sources of variation in firm location incentives to recover information about agglomeration economies in specific settings such as the siting of new large industrial plants (Greenstone et al., 2010) and the rise and fall of the Berlin Wall (Ahlfeldt et. al, 2015). A different literature, including Baum-Snow (2007), Duranton & Turner (2012) and Allen & Arkolakis (2014), examines how transport infrastructure influences the spatial distribution of population within and between cities and evaluates the social rate of return to interregional highways.

This paper uses estimated treatment effects of radial urban highways on the allocations of jobs and resident workers between central cities and suburbs of U.S. metropolitan areas to recover estimates of parameters that govern productivity spillovers that operate below metro area spatial scales and of components of the welfare consequences of new highways in the context of a quantitative model. Highway treatment effects are recovered using planned portions of the highway system as a source of exogenous variation, as in Baum-Snow (2007), coupled with newly organized information from 1960 and 2000 on spatial distributions of employment and resident worker locations by industry within metropolitan areas. The model is specified with a geography that facilitates the use of estimated treatment effects and standard calibrated housing demand and production function parameters as inputs. The welfare analysis incorporates the potential for new highways to influence agglomeration spillovers both within and between cities and their surrounding suburbs because of the exogenous shifts to firm and residential location incentives that come with reduced commuting costs.

Estimates indicate that while each radial highway displaced 16 percent of central city working residents to suburbs, only 6 percent of jobs were displaced. This statistically significant difference amounts to greater residential than employment decentralization in absolute terms for each new highway, even with the initial higher concentration of employment in central cities. Greater effects of highways on residential than job location are also found in each broad industry category. Among large private sector industries, wholesale & retail trade exhibits the highest employment location response to new highways while finance, insurance and real estate (FIRE) exhibits the lowest. The smaller amount of variation in estimates across industries for workers' residential locations than employment locations is an indication of variation in the strength of local agglomeration economies across industries.

Relative magnitudes of agglomeration spillovers within versus between metropolitan area subregions are quantified using estimated treatment effects of highways on employment location and calibrated cost and expenditure share parameters. Results indicate that the elasticity of central city total factor productivity (TFP) with respect to central city employment is at least 0.02 to 0.05 greater than the elasticity of central city TFP with respect to suburban employment, *ceteris* *paribus*. This calculation follows directly from firms' spatial indifference condition, which says that the strength of localized agglomeration economies must compensate for wage and land rental cost differences across locations, as mediated by cost shares. As commuting costs fall, central city wage and rent premiums over the suburbs also fall, thereby requiring the central city TFP premium to fall as well. Calibrated changes in relative TFP implied by changes in relative costs are compared to estimated employment location responses to back out the relative productivity effects of employment within versus across metropolitan sub-regions. As in Roback (1982) and Albouy (2016), these quantitative conclusions only depend on spatial indifference conditions and do not require imposing land market clearing or considering residential location choices. Central to the analysis is that metropolitan area population is held constant. This allows for maintaining focus on productivity impacts of spatial reorganization of a fixed population due to new highways without having to consider population growth effects simultaneously.

The estimated range of relative agglomeration spillovers indicate that most or all of the overall metropolitan area level elasticity of TFP with respect to population is driven by sub-metropolitan area scale interactions. Combes & Gobillon (2015) summarize consensus estimates of 0.04-0.07 for elasticities of TFP with respect to metropolitan area population. Consistent with evidence in Baum-Snow & Pavan (2012), estimates in this paper call into question the possibility that mechanisms for agglomeration economies that operate at metropolitan area spatial scales, like labor market pooling, are its important drivers. While in principle calibration of the model can also deliver quantitative estimates of absolute levels of agglomeration spillovers in the central city and suburbs, in addition to their relative levels, doing so requires imposing additional structure on the model. Agglomeration parameter levels would be identified mostly off of structural assumptions rather than primarily off of variation in firm location choices that are induced by exogenous commuting cost reductions. As such, it seems more sensible to reference the literature, which uses more appropriate models and sources of identifying variation, for estimates of these metropolitan area scale agglomeration parameters.

Calibrations of the full model reveal that each radial highway generates real income increases of up to 3.6 percent and housing cost declines of up to 3.0 percent for central city residents, while central city land rents decline by 4.3 to 12.8 percent with each radial highway. About half of the real income increases occur because new highways open up additional urban space for productive use, increasing land-labor ratios, while most of the remainder comes because of direct productivity effects of reduced intra-urban travel times. Finally, despite the importance of local agglomeration spillovers for influencing firm location choices, such spillovers explain only a small part of residential location responses to new highways. About half of the decentralization caused by each highway ray comes through reallocation toward land in housing production.

To summarize, this paper moves the literature forward in three directions. First, it provides the first estimates of the causal effects of highways on the spatial organization of economic activity by industry within metropolitan areas, examining employment and residential location responses simultaneously. Second, it is the first to employ exogenous shocks to the environment in a large set of cities to facilitate recovery of productivity spillovers that operate at sub-metropolitan area spatial scales. Third, as a complement to Duranton & Turner (2012) who calculate welfare effects of new highways associated with metropolitan area population changes, this is the first paper to quantify the welfare benefits of new highways that accrue through various mechanisms in the context of an environment in which population and employment is constrained to only move within an urban area.

2 Data and Descriptive Evidence

2.1 Data on Worker and Job Location

Primary outcomes of interest are constructed using journey to work tabulations from the 1960 and 2000 censuses and 1960 census tract data coupled with digitized maps of 1960 geography central cities and metropolitan areas. Commuting flows by industry within and between central cities, 1960 definition standard metropolitan statistical area (SMSA) remainders and other regions for each of the 100 largest SMSAs nationwide are reported in the journey to work supplement of the 1960 Census of Population. I aggregate this information into counts of workers and working residents for central cities and SMSA remainders. Unfortunately, the 1960 census does not in most cases report data in a way that makes it possible to break out such information for different central cities. Therefore, all central cities in SMSAs with multiple central cities are necessarily treated as one spatial unit. For the 78 fully tracted large SMSAs in 1960, I also construct counts of residents by location and commuting flows to the primary central city.[1]

For 2000, the Census Transportation Planning Package (CTPP) reports counts of workers and working residents by industry for various small geographic units. It also reports the total count of commuters between all pairs of these microgeographic units nationwide.[2] This analysis maintains the 1960 definition central city and SMSA geographies over time. In order to do this, digital maps of 1960 central cities and SMSAs were created so that year 2000 census units could be spatially allocated.[3] Year 2000 microgeographic units of tabulation, typically traffic analysis zones, but census block groups or census tracts in some states, were allocated to 1960 geographies and analogous counts were calculated through spatial aggregation.

As an illustration of the issues that sometimes arose in building this data set, Figure 1 shows the Davenport-Rock Island-Moline IA-IL SMSA with its central city geographies in 1960 and 2000. Traffic analysis zones, for which 2000 data are reported, are bounded by thin lines. Each of the three 1960 SMSA central cities expanded geographically over time. The 1960 tracted region of the SMSA includes only the central cities. Also note that the extent of the SMSA geography

[1] The 1960 census does report some commuting flow information for the 89 SMSAs with populations between 100,000 and 250,000. Unfortunately, the total number of SMSA workers cannot be determined for these smaller SMSAs, nor is place of work broken out by industry.

[2] The 2000 CTPP does not report commuting flows by industry of employment.

[3] This creation of constant spatial units is a crucial feature of the data since more than half of central city jurisdictions more than doubled in area between 1960 and 2000.

is somewhat constrained. For this reason, I find it important to make use of information about commutes into and out of each SMSA for the analysis, as is described in more detail below.

2.2 Decentralization of Working Residents, Employment and Commutes

Baum-Snow (2007a) documents that population decentralization out of central cities occurred in almost all U.S. metropolitan areas between 1950 and 1990. Figure 2 shows that similar patterns hold for working residents. Panel A shows cumulative distribution functions of aggregate working residential population in 1960 and 2000 by distance to SMSA central business districts (CBDs). The change in log aggregate working residents is depicted on the same graph (right axis). I restrict this analysis to the 78 large SMSAs that were fully tracted in 1960. In order to make SMSAs of different shapes and sizes comparable, I index location such that 0 is the CBD and 1 is the furthest census tract in the SMSA's primary central city. Suburban jurisdictions tracts that are closer to the CBD than the furthest central city tract receive index values of less than 1. In Panel A we see that working residents live in much more dispersed locations in 2000 than in 1960 and that the working residential population of areas just outside of CBDs actually declined in the interim period. In Panel B, I break out residential location into primary central cities and suburbs. It shows that even within each geography, working residents became more decentralized during the study period.[4] Figure A1 depicts similar patterns for residents working in each major 1-digit industry.

Table 1 gives an overview of the extent of decentralization of working residents and jobs that occurred between 1960 and 2000. For the 100 metropolitan areas of over 250,000 in 1960, it shows aggregate counts of workers in central cities and 1960-definition SMSAs. The final row gives the count of people who either work or live in SMSAs and is calculated from commuting data. Table 1 indicates large shifts in the locations of both employment and residences between 1960 and 2000. The fractions of SMSA jobs and working residents in central cities each fell by about 25 percentage points over this period. It is interesting to note that the relative extent of centralization of jobs and workers remained almost constant over time. Both decentralized at rapid rates with jobs more clustered in central cities than residences in both years.

The fact that employment locations remain more centralized than residential locations is *prima facie* evidence that local agglomeration spillovers existed in both 1960 and 2000. Without this force, firms would seek to lower their costs by locating closer to workers in areas with lower rents. However, it is notable that job centralization declined as much as it did despite the declines in commuting costs that occurred during the study period. Indeed, land use models with endogenous employment location typically indicate that sufficiently low commuting costs support the monocentric equilibrium, in which firms all cluster in one location to take advantage of their mutual agglomeration spillovers. In this environment, firms do not face as much of a burden in compensating workers for longer commutes. That is, evidence in Table 1 indicates that giving up very local agglomeration spillovers are not deal breakers impeding employment decentralization.

[4] While it would be instructive to examine a similar figure showing changes in the full spatial distribution of jobs over time, no such data readily exists for 1960.

Table 2 examines the extent to which industries differ in their patterns of decentralization. From left to right, one digit industries (the finest detail for which 1960 data is available) are listed in order of 1960 SMSA employment shares.[5] Rows 5 through 8 of Table 2 report overall trends in SMSA working residents and employment by industry between 1960 and 2000. They show that manufacturing and retail/wholesale trade were declining industries while services and finance, insurance and real estate were growing. More relevant to the current analysis is the comparison across industries of relative decentralization rates of jobs and workers' residential locations. Comparisons of numbers in Rows 2 and 4 reveal less variation in the changes in central city fraction of working residents than jobs across industries. Perhaps this is not surprising, as workers in each industry have experienced the same set of incentives (apart from potential differential changes in job access) to suburbanize. However, differences between results in Row 4 from Row 2 provides some evidence about the differences across industries in the ease of decentralization.

As is discussed in Baum-Snow (2010), the primary process through which decentralization of firms and workers occurred was by the modal commute shifting from being entirely within central cities to being entirely within suburban regions. Figure 3 presents plots of the average fraction commuting to primary central cities in 1960 and 2000 as functions of residential location in the same 78 SMSAs used to construct Figure 2 using the same location index. Whether examined for SMSAs overall (Panel A) or with primary central cities broken out separately from suburbs (Panel B), we see secular declines in the fraction of working residents commuting to central cities at all residential locations. Figure A2 shows that very similar changes in commuting patterns also hold for six individual large metropolitan areas.

Table 3 quantifies the associated changes in commuting patterns for the full sample of 100 large SMSAs. It shows that while 43 percent of SMSA workers or jobs involved commutes within central cities in 1960, this share fell to just 16 percent by 2000. Over the same period, the fraction living and working in the suburban ring rose from 28 percent to 42 percent of the total. The only types of commutes with declining shares of the total were those within central cities and those from suburbs to central cities. This evidence is consistent with declines in the types of agglomeration forces that keep firms in central cities. At 7 percent in 2000 and 6 percent in 1960, reverse commutes have had a small stable market share. The empirical work will conclude that shifts in commuting costs are unrelated to shifts in patterns of reverse commutes across SMSAs. Therefore, reverse commutes are not emphasized in the model in Section 6.

The final two columns of Table 3 give average one-way commuting times by type of commute in 2000. Unfortunately such data are not available in 1960 as the commute time question did not appear until the 1980 census. Results show that the longest commutes other than those involving crossing SMSA boundaries are traditional suburb-central city commutes, at 25 to 46 percent longer (depending on weighting procedure) than within central city commutes, which took 27 minutes for the average worker and 19 minutes when averaged across SMSAs. Within suburban ring commute

[5] Because of inconsistencies across census years in the classification of different types of services, I am forced to combine all services into one broad industry category in order to make valid comparisons between 1960 and 2000.

times are notably similar to within central city commute times, though workers presumably enjoy a rent discount which ends up capitalized into lower wages. This commuting time data will be used in Section 6 to help recover parameters in the model.

2.3 Highway Data

Counts of radial limited access highways serving primary central cities' central business districts in 1950, 1960 and 2000 is the primary treatment variable used.[6] As in Baum-Snow (2007a), Michaels (2008), Baum-Snow (2010) and Duranton & Turner (2012), there is an econometric concern that highways were not allocated randomly to metropolitan areas. Instead, highway construction certainly responded to increases in commuting demand precipitated by metropolitan area population and economic growth. In addition, Duranton & Turner (2012) provide evidence that the federal government bankrolled additional highways beyond those in pre-1956 plans for economically struggling regions to achieve fiscal redistribution and to stimulate their local economies.

To address such potential endogeneity concerns, I instrument for the number of radial highways constructed prior to 2000 with the number in a 1947 plan of the interstate highway system. As is discussed in more detail in Baum-Snow (2007a), this plan was developed by the federal Bureau of Public Roads based on observed levels of intercity traffic and defense needs to promote intercity trade and national defense. This highway plan was explicitly not developed to facilitate commuting (U.S. Department of Transportation, 1977, p. 277). While the 1960 geography central city area and radius are significantly positively correlated with the number of planned highways, neither SMSA population growth prior to 1950 nor the 1940 share of SMSA employment in any 1-digit industry significantly predicts the number of planned highways. Regressions of planned rays on this set of shares or 1940-1950 SMSA population growth yield p-values of greater than 0.2 for all coefficients. The coefficient on 1950 SMSA population in such a regression is positive with a p-value of 0.179 while that for central city radius is just 0.007. More important central cities were larger in area and got allocated more planned highways as a result; other potential indicators of cities' importance for a national network are highly enough correlated with this measure that they do not independently matter. Virtually the entire planned system (and more) was constructed because the federal government provided 90 percent matching funding to an initial 10 percent covered by individual states. Since the federal funding stream did not begin until 1956, it is logical that prior outcomes are not correlated with planned rays.

This compendium of evidence supports the contention that the plan is a valid instrument for highway construction of the subsequently built interstate system conditional on a measure of central city size and SMSA fixed effects. Inclusion of central city radius in regressions throughout this analysis controls for the fact that more important cities, which are also larger, received more planned highways.[7] Table A1 presents summary statistics about the highway and demographic data

[6] Additional counts of other types of highways were also recorded but are not extensively used due to difficulties in isolating exogenous variation in them.

[7] Robustness checks on a subset of the sample and outcomes presented below using central city geographies that are artificially constructed to be the same size in all SMSAs reveals no independent effect of politically defined central

used in this analysis. It shows that sampled metropolitan areas received an average of 2.7 radial highways between 1950 and 2000, with 2.0 of these built after 1960. The mean number of planned highways is 2.9. Because of the high cost of building highways to serve central business districts, cities with may planned highways often consolidate them into fewer central arteries serving the downtown core.[8]

There is some question as to the appropriate starting year for measuring highways. With interstate highway construction begun at a rapid rate after the passage of federal legislation in 1956, many cities had planned, partially completed or just opened segments in 1960. It is unlikely that SMSA spatial equilibria would have come close to fully responding to this new transport infrastructure in such a short time. Indeed, evidence in Baum-Snow (2007a) indicates that about two-thirds of the long run response of urban form to the highway system occurs within 20 years. Therefore, the main analysis in this paper uses the number of new radial highways serving central cities constructed between 1950 and 2000.

Results in Table 4 show that this decision on how to count highways is if anything conservative. Table 4 presents first stage results of the effects of planned radial highways on the number actually built. Panel A shows results using 1950 as a base while Panel B presents results using 1960 as a base. Included control variables in Column 3, which is the baseline specification throughout the paper, can be justified by a typical land use model as in Lucas & Rossi-Hansberg (2002) or a more spatially aggregated version of such a model, as in that developed in Section 5 below. The choice of control variables does not influence first stage coefficients on planned rays. With 1950 as the base year, coefficients on planned rays are between 0.47 and 0.53. Coefficients of interest are smaller by 0.13 to 0.17 when 1960 is instead the base year. Additional inclusion of 1950 log SMSA population, 1940-1950 SMSA population growth and 1940 1-digit industry shares do not significantly change coefficients on planned rays, nor are coefficients on any of these variables statistically significant (not reported). Because planned rays coefficients are smaller for 1960-2000 than for 1950-2000, second stage estimates are always larger if 1960 is used as the base year. Given the potential concern that the timing of highway construction may be endogenous to commuting demand, with the highways with the largest treatment effects built first, results in the remainder of the paper use 1950 to 2000 radial highway construction as the endogenous variable of interest, even though outcomes of interest are measured as of 1960 and 2000.

One other piece of evidence in Table 4 is relevant for helping to justify the empirical strategy laid out in the following section. Inclusion of growth in the number of people who live or work in the SMSA does not affect the coefficient on the instrument. As is discussed in more detail below, this variable is included in the first stage in order to hold SMSA scale constant throughout the analysis. In practice, inclusion of this control variable brings up potential endogeneity concerns.

city size on outcomes of interest, as should be expected.

[8] I also tried using the number of radial highways of various classes of priority serving each city in a 1922 federal war department plan of the national highway system, the "Pershing Map", as instruments. This plan was put together with less regard for intercity trade than the 1947 plan used to construct the instrument. Unfortunately, instruments derived from the Pershing Map are insufficiently strong to be useful for this analysis.

However, conditioning on this variable has no effect on results because it is not correlated with the instrument. A regression of 1960-2000 SMSA population or employment growth in 1947 planned radial highways and central city radius yields a small insignificant coefficient of 0.014 (se=0.029). This very small correlation between the instrument and SMSA growth means that true coefficients of interest can be estimated with very tight bounds, as is further explored in the following section.

3 Empirical Strategy

The primary empirical goal of this paper is to recover average treatment effects of radial highways on the decentralization of central city working residents and jobs in broad industry categories. Because SMSA employment by industry may endogenously respond to the highway treatment, as in Duranton & Turner (2012) and Duranton, Morrow & Turner (2013), it is important to explicitly hold SMSA employment by industry constant. Rather than using log central city employment or working residents by industry as dependent variables, it is tempting to conceptualize a neighborhood choice model with Extreme Value Type I shocks, which would deliver log central city shares as dependent variables of interest. Any estimated effects of roads would then reflect some combination of impacts on decentralization and growth. Controlling for SMSA employment by industry on the right hand side instead facilitates empirically isolating the effects of roads on the allocation of employment and resident workers between central cities and suburbs. The focus of this section is to show how this is achieved in a practical way, while taking into account the potential endogeneity of SMSA employment mix and scale to the highway treatment. As is discussed in the prior section, the potential endogeneity of Δhwy is addressed by instrumenting with the number of radial highways in the 1947 national plan.

The objective is to estimate coefficients in the following equations. In these equations, ρ_{1k} and r_{1k} describe causal effects of highways on the allocations of employment emp_{ki}^{CC} and working population pop_{ki}^{CC} in industry k and SMSA i between central cities and suburbs. Key here is to hold SMSA employment or working population in industry k constant.

$$\Delta \ln emp_{ki}^{CC} = \rho_{0k} + \rho_{1k}\Delta hwy_i + \rho_{2k}\Delta \ln emp_{ki}^{SMSA} + \sum_{j\neq k} \rho_{2k}^{j} \Delta \ln emp_{ji}^{SMSA} + X_i \varrho_k + \upsilon_{ki} \quad (1)$$

$$\Delta \ln pop_{ki}^{CC} = r_{0k} + r_{1k}\Delta hwy_i + r_{2k}\Delta \ln pop_{ki}^{SMSA} + \sum_{j\neq k} r_{2k}^{j} \Delta \ln pop_{ji}^{SMSA} + X_i R_k + u_{ki} \quad (2)$$

One challenge with recovering consistent estimates of parameters of interest ρ_{1k} and r_{1k} is the fact that highways may not only cause decentralization, but they may also cause the industry mix to change. That is, $\Delta \ln emp_{ki}^{SMSA}$ and $\Delta \ln pop_{ki}^{SMSA}$ may be endogenous, or correlated with the error term, even after instrumenting for Δhwy_i with planned highways from 1947. This occurs because $\Delta \ln emp_{ki}^{SMSA}$ and $\Delta \ln pop_{ki}^{SMSA}$ may themselves respond to the instrument, thereby violating the standard exclusion restriction required for IV to provide consistent estimates. There are of course additional identification concerns in Equations (1) and (2). These are discussed below in the context of equations whose parameters are actually estimated. A final potential difficulty is that there may be cross-industry effects. That is, for example, the total number of SMSA workers in services may influence where manufacturing firms locate. I provide some indirect evidence below that such cross-industry effects, as captured by ρ_{2k}^{j} and r_{2k}^{j}, are small.

To get around inclusion of industry-specific SMSA employment as predictors for identifying parameters of interest ρ_{1k} and r_{1k}, I proceed in two steps. The first step generates estimates of the effects of highways on the mix of SMSA employment across industries. The results of this step are interesting in their own right, but are not the focus of this analysis. Similar estimates have been explored in existing research with more detailed and appropriate data, as in Duranton, Morrow & Turner (2013). The second step is to recover the reduced form effects of highways on central city employment and working residents by industry taking as given only the evolution of total metropolitan area employment between 1960 and 2000. Combining estimates from these two steps yields effects of highways on this set of outcomes holding the evolution of total SMSA employment by industry fixed. In practice, these two steps can be carried out simultaneously using GMM or 3SLS.

In step one of the empirical analysis, I consider regressions of the form:

$$\Delta \ln emp_{ki}^{SMSA} = \alpha_{0k} + \alpha_{1k}\Delta hwy_i + \alpha_{2k}\Delta \ln popemp_i^{SMSA} + X_i\beta_k + \varepsilon_{ki} \qquad (3)$$

$$\Delta \ln pop_{ki}^{SMSA} = a_{0k} + a_{1k}\Delta hwy_i + a_{2k}\Delta \ln popemp_i^{SMSA} + X_i B_k + e_{ki} \qquad (4)$$

Rather than using either SMSA employment or working population as controls, I instead control for $\Delta \ln popemp^{SMSA}$, which is the change in the log of the number of people who either work or reside (or both) in SMSA i. This allows any differences in coefficient estimates between (3) and (4) to be uniquely attributable to the different outcomes. The control for $\Delta \ln popemp^{SMSA}$ is necessary for the coefficients α_{1k} and a_{1k} to capture the effects of highways on SMSA industry composition rather than simply the level of employment in each industry. The reduced form causal effects of highways absent this control variable would partially reflect the effect on total SMSA population or employment, overstating the effect of highways holding SMSA scale constant. X_i is a vector of additional control variables conditional on which the planned rays instrument is exogenous.

Several identification concerns arise in estimating Equations (3) and (4). First is the endogeneity of $\Delta \ln hwy$, which is addressed by instrumenting with the number of radial highways in the 1947 national plan. Second is the potential endogeneity of $\Delta \ln popemp^{SMSA}$. If highways are an amenity, this object should respond positively to the number of highways, whether planned or built. On the other hand, direct inclusion of $\Delta \ln popemp^{SMSA}$ may introduce a correlation with the error term since shocks to one sector of employment mechanically affect aggregate employment in all sectors. In practice, results in the next section indicate that the bias from excluding this control is small since it does not respond much to highways.

If highways cause SMSA population growth, it can be shown that excluding $\Delta \ln popemp_i^{SMSA}$ from (3) and (4) leads to transport coefficients that are positively biased, whereas including this variable yields transport coefficients that are negatively biased. The econometrics of these biases is seen in the following simplified environment. Consistent with (3) and (4), suppose that the underlying structural equations for SMSA jobs in each industry are

$$\Delta \ln emp_{ki}^{SMSA} = \alpha_{0k} + \alpha_{1k}\Delta hwy_i + \alpha_{2k}\Delta \ln popemp_i^{SMSA} + \varepsilon_{ki}.$$

Here, Δhwy_i is instrumented with hwy_i^{47}, which is uncorrelated with ε_{ki}. An analogous vector of equations describe the data generating process for SMSA working residents in each industry. The probability limit of the IV estimate of α_{1k} excluding $\Delta ln(popemp_i^{SMSA})$ from the regression equals

$$\alpha_{1k} + \alpha_{2k}\frac{Cov(hwy^{47}, \Delta \ln popemp^{SMSA})}{Cov(\Delta hwy, hwy^{47})}.$$

The probability limit of the IV estimate of α_{1k} including this variable in the regression, as written above, is

$$\alpha_{1k} - \frac{Cov(hwy^{47}, \Delta \ln popemp^{SMSA})Cov(\Delta \ln popemp^{SMSA}, \varepsilon_k)}{D > 0^9}.$$

That is, given that $Cov(hwy^{47}, \ln popemp^{SMSA}) > 0$, as is true in the data and is also found by Duranton & Turner (2012), and $Cov(\ln popemp^{SMSA}, \varepsilon_k) > 0$, as is true if unobservables driving variation in $\ln emp_k^{SMSA}$ also influence the total SMSA employment, excluding versus including the control for metropolitan area scale bookends true highway rays coefficients in (3) and (4). As an alternative, one can instrument for $\Delta \ln popemp^{SMSA}$ in addition to Δhwy. Similar to Glaeser & Gyourko (2005) and Saiz (2010), I use average January temperature and annual precipitation as instruments in a robustness check, as these amenities are stronger relative consumer demand shifters for living in SMSAs in 2000 than they were in 1960 because of improvements in climatization and building technologies.[10]

An additional issue is to consider which variables belong in additional controls X. There are two justifications for including variables in this control set. First, from an econometric perspective, any variable correlated with the number of planned highways that may cause the SMSA industry mix to change must be included for an IV estimator to yield consistent estimates of a_1 and α_1. Second, in the estimation equations specified below that describes changes in the allocation of workers and jobs between central cities and suburbs, there are theoretical justifications to include any exogenous variables that appear in a typical closed city land use model. Strictly speaking, given an ideal instrument for highways that is unconditionally random, we would not need to include any such variables. However, central city size is both model-relevant and correlated with planned rays, and thus must be included as a control variable in regressions. Larger area central cities received more planned highways and (all else equal) had less loss of population and jobs to the suburbs.

It should be noted that with ideal data in a world perfectly described by land use models,

[10] An alternative commonly used instrument for the growth in total metropolitan area employment or population is Bartik (1991) style industry shift-shares. Such instruments are less suitable for this analysis since historical industry shares are likely to be mechanically correlated with unexplained components of 1960-2000 industry specific employment changes.

Equations (3) and (4) would be identical. That is, conceptually we typically define metropolitan areas as commuting zones that are fully self-contained. In practice, as seen in Table 3, 8 percent of SMSA workers or residents either lived or worked outside their SMSA in 1960, rising to 22 percent by 2000. Use of data on all people who live or work in each SMSA is thus important, so that the analysis is not artificially constrained by SMSA geographies. Results reported in the next section will reveal that SMSA counts of jobs and working residents are sufficiently similar such that we cannot statistically distinguish between estimates of α_{1k} and a_{1k}.

Armed with estimates of a_{1k} and α_{1k}, the next step is to specify equations that allow for recovery the impacts of highways on urban decentralization by industry holding the SMSA industry composition constant. In order to avoid including endogenous variables, I specify these equations as the following "reduced forms" in which the prediction variables are exactly the same as in Equations (3) and (4) and the outcomes are for 1960 definition central cities. Indeed, substitution of (3) and (4) into (1) and (2) yields a pair of equations that resemble (5) and (6).

$$\Delta \ln emp_{ki}^{CC} = \omega_{0k} + \omega_{1k}\Delta hwy_i + \omega_{2k}\Delta \ln popemp_i^{SMSA} + X_i D_k + \varpi_{ki} \tag{5}$$
$$\Delta \ln pop_{ki}^{CC} = w_{0k} + w_{1k}\Delta hwy_i + w_{2k}\Delta \ln popemp_i^{SMSA} + X_i \delta_k + v_{ki} \tag{6}$$

In estimating parameters of these equations, once again rays in the 1947 plan serve as an instrument for Δhwy and similar justifications hold for inclusion of additional control variables X. Arguments for negative biases of ω_{1k} and w_{1k} when including $\Delta \ln popemp^{SMSA}$ in the regressions and positive biases of these coefficients when excluding $\Delta \ln popemp^{SMSA}$ from these regressions hold as for (3) and (4). In particular, since unobservables driving variation in outcomes are also likely to influence $\Delta \ln popemp^{SMSA}$ in the same direction, $\Delta \ln popemp^{SMSA}$ is likely to be positively correlated with the error terms. Weather variables again serve as instruments for $\Delta \ln popemp^{SMSA}$ in robustness checks.

Solving out from the reduced forms, the causal effects of each highway on the decentralization of jobs or working resident population by industry are given by the following expressions respectively:

$$\rho_{1k} = \omega_{1k} - \frac{\omega_{2k}}{\alpha_{2k}}\alpha_{1k} + \sum_{j \neq k}(\frac{\alpha_{1k}}{\alpha_{2k}}\alpha_{2j} - \alpha_{1j})\rho_{2k}^{j} \tag{7}$$
$$r_{1k} = w_{1k} - \frac{w_{2k}}{a_{2k}}a_{1k} + \sum_{j \neq k}(\frac{a_{1k}}{a_{2k}}a_{2j} - a_{1j})r_{2k}^{j} \tag{8}$$

These expressions capture the intuition that the structural effect of a highway on decentralization within a given industry is the direct effect on central city industry employment or working population with one adjustment for the effect on industry composition, whose size depends on highways' influence on the importance of the industry in the economy, and an additional adjustment for cross-industry effects. Note that while ρ_{2k}^{j} and r_{2k}^{j} are not identified, they are expected to be between -1 and 1. Therefore, the terms capturing cross-industry effects can be bounded. Moreover, the cross-industry adjustment is expected to be smaller than the own-industry adjustment, which is shown in the following section to be negligible except in manufacturing.

The following section discusses estimates of the four sets of elements used to build the ultimate parameters of interest. Parameters can be recovered using linear IV equation by equation or GMM or 3SLS on the systems of five equations given by (3), (4) (5), (6) and a "first stage" highways equation estimated separately for each industry k.

4 Estimated Treatment Effects

4.1 Effects of Highways on SMSA Employment and Industry Mix

Table 5 reports regression results of Equations (3) and (4) in which planned highways enters as an instrument for the total number of radial highways. Results in the first column reveal no evidence of a significant effect of highways on total SMSA population or employment, though the point estimate for total employment is slightly positive.[11] The remaining columns of Table 5 show that manufacturing is the only industry with a statistically significant response of SMSA employment to new transport infrastructure. Each radial highway is estimated to cause about 11 percent of the manufacturing jobs and 14 percent of working residents to depart an SMSA, either to rural areas or abroad.

While most rays coefficients in Panel B are not statistically different from those in Panel A, highways are estimated to cause greater declines in SMSA working residents than employment in each industry. Gaps between rays coefficients in Panel A and B range from 0.03 to 0.09 across industries. In addition to its effect on manufacturing, each highway is estimated to cause the number of SMSA residents working in retail or wholesale trade to significantly decline by 5 percent and residents working in public administration to significantly decline by 9 percent. Estimates for other industries are not statistically significant. The consistent discrepancy between highways coefficients in Panels A and B reflects the residential decentralization out of 1960 definition SMSAs caused by new highways.

Estimates in Table 5 are robust to various alternative specifications. As predicted by the bounding argument given above, excluding $\Delta \ln popemp^{SMSA}$ from industry-specific regressions always increases rays coefficients, with a maximum increase of 0.04 (for manufacturing employment and working residents only) and in no cases changes statistical significance of estimates. Instrumenting for $\Delta \ln popemp^{SMSA}$ with weather variables changes rays coefficients reported in Table 5 by at most 0.01, though the joint first stage F-statistic falls from 16.75 to 5.30. No rays coefficient changes by more than 0.02 or is significantly affected by inclusion of a control for 1950 log SMSA population except for total employment, which increases by 0.03 and military employment, which

[11] This result is in contrast to evidence in Baum-Snow (2007a) and Duranton & Turner (2012) that more highways led to metro area population increases. There are two reasons for this discrepancy. First, this paper uses more constrained metropolitan area geographies and much of the urban growth caused by highways manifested itself as sprawl into outlying areas. Second, samples in the other two papers include many metropolitan areas that were smaller than 250,000 in 1960. Point estimates for a subset of these smaller metropolitan areas also imply positive population growth effects of highways within 1960 SMSA geographies.

increases by 0.05. Additional inclusion of 1940 1-digit industry shares typically additionally increases coefficients, though not significantly for any outcome. OLS regressions analogous to those in Table 5 yield similar and statistically indistinguishable results for all outcomes except the number of resident workers in manufacturing. In industries for which they differ at all, OLS estimates are slightly less negative than IV estimates, indicating that endogenously constructed highways had smaller influences on the SMSA industry mix than their exogenous counterparts.

4.2 Effects of Highways on Decentralization by Industry

Table 6 reports estimated effects of radial highways on central city employment by industry in Panel A and working population by industry in Panel B. Because most highways coefficients in Table 5 are near 0, highways coefficients in Table 6 for all industries except manufacturing are very close to treatment effects of one radial highway on the allocation of that industry's jobs or resident workers between the central city and the suburbs holding the SMSA industry mix constant.

Before exploring heterogeneity in effects across industries, it is instructive to examine results in the first column, for all workers. Baum-Snow (2007a) estimates highway treatment effects analogous to that reported in Panel B Column 1, but for full population rather than just workers. This estimate, that each ray causes 16 percent of the working population of central cities to move to the suburbs, heavily overlaps with the confidence interval of the analogous Baum-Snow (2007a) estimate of -0.12. It should be noted that this estimate applies to only about half of people used in Baum-Snow (2007a). The effect of each ray on the total number of jobs, reported in column 1 of Panel A, is much smaller in absolute value at -0.06. This difference of 0.10 is statistically significant and this gap far exceeds that which would be needed for a highway to move the same number of workers and jobs to the suburbs. The fact that the allocation of jobs between central cities and suburbs does not respond as much (in percentage or numerical terms) to new transport infrastructure as the allocation of working residents is expected. New highways allow for population decentralization while at the same time lowering input costs to firms conditional on their locations. Firms face a trade-off between decentralizing (and further lowering input costs) or maintaining some level of clustering to take advantage of agglomeration spillovers that operate at sub-market spatial scales. The fact that the coefficient for all employment in Panel A is less negative than that in Panel B for all working residents reflects this additional force pushing for firm centralization.

This same logic carries through when considering employment and working population in individual industries. In each industry, estimated effects of highways on the decentralization of jobs is smaller than the estimated effects of highways on the decentralization of workers. There is also quite a bit of heterogeneity in estimated rays coefficients across industries. Given that resident workers' location decision calculus is influenced by the same amount regardless of the industry in which they work conditional on the spatial distribution of employment locations, it is natural to interpret these coefficient differences as at least partly reflecting differences across industries in agglomeration spillovers. Results in Table 7 will revisit these effects with appropriate adjustments for the SMSA industry mix.

As with the SMSA level regressions in Table 5, results in Table 6 are robust to a host of alternative specifications. Consistent with the bounding argument above, exclusion of $\Delta \ln popemp^{SMSA}$ from (5) and (6) increases the rays coefficient for all outcomes except the residential locations of military workers, but only by up to 0.03. Use of weather variables as instruments for $\Delta \ln popemp^{SMSA}$ affects coefficients of interest by less than 0.03 in all cases, except for military employment coefficients which change by 0.03. Inclusion of 1950 log SMSA population and 1940 employment shares in no case significantly change rays coefficients in Table 6.

Analogous OLS rays coefficients reported in Table A2 are, with the exception of agricultural and military employment, greater than their IV counterparts for all outcomes considered. As is discussed in Baum-Snow (2007a), this discrepancy in part reflects the fact that suburban highway infrastructure likely matters for decentralization in addition to central city rays. In this case, IV and OLS bound true treatment effects since conditional on central city radius, the partial correlation between central city and suburban ray construction is negative whereas the plan predicts positive suburban ray construction. In addition, Duranton & Turner (2012) provide evidence that struggling metropolitan areas were more likely to receive "endogenous" highways not predicted by the 1947 plan as a form of local economic development. Being less dynamic places growing at slower rates, these metropolitan areas had fewer resources to build out and decentralize. Moreover, endogenous highways were typically built later, connect to less suburban highway infrastructure and were lower quality than planned highways, as most were constructed primarily with state and local funds.[12] Thus, the actual treatment effects of these highways is likely to be smaller in absolute value than highways that are part of the national interstate system.[13]

I now examine the effects of highways on the allocation of employment and working population by industry between central cities and suburbs holding the industry mix strictly constant. Equations (7) and (8) indicate the potential importance of adjusting the coefficients reported in Table 6 for the endogenous change in the industry mix induced by new highways in constructing such measures, though evidence in Table 5 indicates that such changes are small in most industries. Table 7 reports causal effects of each radial highway on central city employment in Column 1 and resident workers by industry in Column 2 holding the industry mix constant. Industry specific entries in Table 7 are constructed by estimating a five equation system for each industry (including a "first stage") by three-stage least squares and calculating causal effects of interest using (7) and (8), ignoring any potential cross-industry effects. The delta method is used to calculate standard errors, with SMSA clustering. Since own-industry SMSA employment composition adjustments are negligible for all industries except manufacturing, and are small for manufacturing, any cross industry adjustments to causal effects of interest must be negligible.[14]

The first row of results in Table 7 is for all workers and matches up exactly to the first column of Table 6, reiterating the headline estimated decentralization of 16 percent of central city residents

[12] The fact that the 1947 plan is a much stronger instrument for 1956-1960 highway construction than for 1956-2000 highway construction, as seen in Table 4, indicates that highways built later were much more likely to be endogenous.

[13] Attempts to precisely estimate nonlinear effects of highways are unsuccessful because of large standard errors.

[14] Estimating the same set of systems of equations by GMM yields almost identical results.

and 6 percent of central city employment caused by each radial highway. The second row also applies to all workers but excludes the potentially endogenous control for $\Delta \ln popemp_i^{SMSA}$ in the estimation equations. Commensurate with the result from Table 5 that highways had little effect on $\Delta \ln popemp_i^{SMSA}$, these estimates are only 0.02 greater than those implied by the primary specification, at -0.04 for employment and -0.14 for residents. The bounding argument developed in Section 3 above indicates that the true treatment effects are between these two statistically indistinguishable sets of numbers. Section 4.4 below further demonstrates robustness to exclusion of $\Delta \ln popemp_i^{SMSA}$ as a control and to central city definition.

As the model developed in the following section demonstrates, magnitudes of employment responses to highways in different industries are directly related to strengths of localized agglomeration economies provided the industry produces tradeable goods. Smaller effects of highways on employment decentralization are evidence of stronger agglomeration forces keeping firms in the central city. Estimated coefficients on radial highways for central city employment in manufacturing, services, TCPU and construction are about -0.08 and statistically significant in most cases. Central city employment in finance insurance & real estate is estimated to decline by only about 4 percent with each highway whereas employment in retail & wholesale trade declines by about 14 percent. Evidence of associated relatively strong local agglomeration forces in finance insurance & real estate is quantified more carefully in Section 6 using the model developed in Section 5. Because a large component of output in wholesale and retail trade is not tradeable, it is natural that this industry's employment responses are more closely related to residential population responses to highways. Central city employment in agriculture, public administration and the military have slightly positive estimated responses to highways. These are the industries in which the market probably has the least influence on employment location. Except for manufacturing, industry specific treatment effect estimates are very similar to coefficients in Table 6 because highways had only a small effect on the SMSA industry mix.

The second column of Table 7 presents causal effects of each highway on central city working residents by industry. These effects exhibit much less variation across industries than do responses of employment locations. Other than agriculture, which has a statistically insignificant treatment effect of -0.05, point estimates indicate that each highway caused between 12 and 21 percent of central city workers to suburbanize, depending on industry. The smallest effect is for workers in finance, insurance & real estate, which likely incorporates the relatively small response of firm location as well in this industry. The largest effects are for those working in construction and wholesale & retail trade. Gaps between effects of highways on employment and residential locations, reported in the third column of Table 7, are positive for each industry and statistically significant for many industries.

4.3 Commuting Mechanisms

Shifts in commuting patterns go along with the residential and employment decentralization effects of highways in Tables 6 and 7. Table 8 examines the effects of radial highways on the eight types of commuting flows described in Table 3 using IV regression specifications analogous to those in the first column of Table 6. These results indicate that highways had statistically significant effects on three types of commuting flows. Each highway caused 16 percent fewer commutes within central cities, 11 percent more commutes within SMSA suburban rings and 22 percent more commutes from outside of SMSAs to the suburban ring. Interestingly, the coefficient estimate for traditional suburb to central city commutes is not statistically significant.[15]

Though they match up well to the resident worker population decentralization results in Tables 6 and 7, the commuting results may seem to be at odds with the much smaller estimated treatment effect of highways on central city employment. The following decomposition, in which r indexes place of residence, helps in showing how these two sets of results can be reconciled:

$$\Delta \ln emp_i^{CC} \approx \sum_{r \subseteq \{CC, ring, out\}} S_{ri}^{emp^{CC}} \Delta \ln pop^r\_emp_i^{CC}.$$

The percent change in central city employment is the average of percent changes in the three types of commuting flow that involve working in the central city, weighted by their shares. The three relevant dependent variables for this decomposition are in the first column of Table 8. Regressions using the same dependent variables multiplied by 1960 shares, as indicated in the decomposition, yield highway coefficients of -0.10, 0.01 and 0.02 for central city, suburban ring and outside SMSA residential locations respectively, adding up to -0.07. Only the last one is significantly different from its Table 8 counterpart. Discrepancies between these coefficients from those in Table 8 are accounted for by correlations between 1960 residential location shares for central city employees $S_{ri}^{emp^{CC}}$ and the planned rays instrument conditional on central city radius and overall SMSA growth. Planned rays significantly predict the 1960 fraction living outside of an SMSA and working in the central city conditional on controls, accounting for the significant difference with the result for this outcome in Table 8. This highlights the importance of estimating results in differences rather than levels, thereby conditioning out fixed effects that are correlated with the roads instrument.

One set of results in Table 8 is of note for conceptualizing a process that potentially generates the data. While Table 3 shows that reverse commuting from central cities to suburbs rose relative to other types of commuting flows, results in Table 8 demonstrate that new highways cannot explain this phenomenon. Instead, other changes in urban environments must be driving the rise in reverse commuting. For example, increases in the relative consumer amenity values of cities versus suburbs for some types of people (Couture & Handbury, 2016) may be one important explanation. Whatever the explanations, because they are orthogonal to changes in commuting costs, such mechanisms could not be central in the specification of a model that focuses on understanding the effects on urban structure of reducing commuting costs.

[15] Similar regression results are reported in Baum-Snow (2010). While the two sets of results provide the same general picture of commuting decentralization, they are not identical. There are two reasons for discrepancies. First, this paper uses all central cities whereas Baum-Snow (2010) uses just the primary central city. Second, Baum-Snow (2010) uses a broader sample of metropolitan areas.

4.4 Robustness to Specification and Central City Definition

To this point, I have necessarily defined central cities to correspond to their 1960 census geographies. However, when examining effects of highways on residential location, it is possible to redefine each SMSA's central city as being within a fixed radius of SMSA central business districts in tracted SMSAs. While the limited availability of census tract data in 1960 reduces sample sizes to between 78 and 93 depending on CBD distance, I use such alternative central city geographies to demonstrate that central city geographic definition does not drive the results in Tables 6 and 7. Figure 4 Panel A graphs coefficients on radial highways in regressions identical to those reported in Table 6 Panel B Column 1 except that log central city working population for different central city radii are the outcomes. If the central city radius is between 2 and 11 km from the CBD, each radial highway is estimated to cause decentralization of 17 to 20 percent of central city resident workers. Beyond 11 km, the addition of each km in central city radius reduces the estimated effect of each highway by about 0.01. No coefficient on true 1960 central city radius is statistically significant in these regressions. Also evident in Figure 4 is how similar coefficients are when total SMSA working population is excluded (top, blue line) versus included (bottom, red line) in the regression. Under reasonable assumptions discussed in Section 4, true causal effects of highways are bounded by these two lines.

Figure 4 Panel B presents similar coefficient estimates but when central city radius is determined separately for each SMSA such that 10, 20, 30, 40 or 50 percent of SMSA employment in 2000 is within the given radii, as calculated separately for each SMSA. The typical central city jurisdiction hosted 34 percent of SMSA employment in 2000. This normalization indicates that the drift upwards in coefficient as a function of central city size seen in Panel A begins at radii below which 10 percent of employment is in the central city, for which each radial highway causes about 25 percent of central city working residents to move to the suburbs. The highways coefficient levels off at -0.16 for radii containing 40-50 percent of year 2000 employment, which is the same estimate reported in Table 6 Panel B. Figure A3 shows similar results using data from the larger sample of 154 SMSAs of over 100,000 in population in 1960 for which some 1960 census tract data exist.[16] Unfortunately, an analogous exercise for job location is not possible because of data limitations in 1960. Attempts to use data only from 2000 for such an exercise were unsuccessful and again highlight the importance of first differencing in order to control for unobserved fixed factors that influenced allocations of planned highways.

5 Model

This section provides a framework for evaluating how the treatment effects of transport improvements on employment and population decentralization presented in the previous section can be

[16] Because of data limitations from 1960, it is not possible to include those who commute into SMSAs from outside in the $\Delta \ln popemp_i$ control used for Figure A3. This omission may explain the fact that rays coefficients excluding this control are slightly greater in absolute value, in contrast to the discussion in Section 4 and the results in Figure 4.

used to recover information about the spatial scope of local agglomeration economies, mechanisms through which highways drive urban population decentralization and welfare gains from new highways. The model is sufficiently stylized such that comparative statics involving transport costs have clear interpretations and the model can be calibrated with estimated treatment effects along with standard cost shares and housing demand parameters. Unlike many other land use models with endogenous firm location, this model is also simple enough such that it has a unique equilibrium given transport cost and agglomeration forces.

To match the fixed population environment explored in the empirical work, this is a "closed city" absentee landlord model with two metropolitan regions: the city and the suburbs. The model is in the spirit of Rosen (1979) and Roback (1982) but with the addition of two types of fundamental spillovers that exist between these two regions. First, there is commuting from the suburbs to the city, allowing the number of residents not to equal the number of jobs. Second, there are agglomeration spillovers between workers in the two regions which themselves may also depend on the transportation cost. Because it is set up to be calibrated primarily using quantities rather than prices, this model resembles Albouy & Stuart (2016) in some ways, though it considers the spatial equilibrium within rather than between metropolitan areas.

The model is a spatially aggregated version of the land use models developed by Fujita & Ogawa (1982) and Lucas & Rossi-Hansberg (2002), in which both firm and residential locations are endogenous in continuous space. Spatial delineation in the model mimics the nature of the data used to recover treatment effects explored in the previous section. Like its predecessors, this model features no underlying worker or firm heterogeneity. While such heterogeneity would certainly be important for more richly characterizing equilibrium land use and commuting patterns, it is immaterial for characterizing how such an equilibrium changes with reductions in commuting costs. This is because textbook land use models with worker heterogeneity predict that the spatial ordering of types does not change with secular declines in commuting costs. Empirically, the spatial ordering of households by income has changed remarkably little since 1960. In 1960 and 2000 alike, average family or per-capita income in U.S. metropolitan areas increases with CBD distance within central cities, levels off in the suburbs and declines into rural portions of SMSAs regardless of the strength of the highway treatment received (Baum-Snow & Lutz, 2011). Various dimensions of unobserved heterogeneity, while not modeled explicitly, can thus be thought of as being differenced out via the exogenous highway shocks. Fu and Ross (2013) provide compelling independent empirical evidence that worker heterogeneity does not drive productivity differences across space within metropolitan areas.

5.1 Setup

Workers and firms compete for an exogenous amount of central city land L_c with market price r per unit. The suburbs extend as far out as necessary to satisfy firm and worker demand such that there is no competition for space in the suburbs. As such, suburban land rent is determined exogenously, and is denoted $\underline{r}$. Of the exogenous population of the metropolitan area N, measure

N_c works in the city and measure $N_s = N - N_c$ works in the suburbs. Q_c is the total residential population of the city and $Q_s = N - Q_c$ is the suburban residential population.

Central to model calibration is the time cost of commuting within the central city t, which is 0 for costless travel and 1 if it takes a worker's full time endowment to make a round trip. Times for commutes involving the suburbs are modeled as scalar multiples of t. To connect to the empirical work, comparative statics will be evaluated with respect to t , as this is the variable for which we have exogenous variation through the highway treatments. In particular, empirical estimates of $\frac{dN_c}{dt}$ and $\frac{dQ_c}{dt}$, calculated from regression results reported in Section 5, are used below as inputs to model calibration.

5.1.1 The Tradeable Sector

Tradeable sector firms produce the numeraire good using a constant returns to scale technology with land, labor and capital. City firms' total factor productivity incorporates a Hicks neutral agglomeration force $A_c(N_c, t)$ that is likely increasing in the total number of workers in the city N_c in which the firm is located. Because metro population is fixed, $\not{A}_c$ also implicitly depends on suburban workers, where $\frac{dA_c}{dN_c}$ incorporates both the direct effect of increases in N_c and the indirect effect of reductions in N_s. Productivity also depends negatively on the unit time cost of travel t. For notational convenience, I also express suburban firm TFP $A_s(N_c, t)$ as depending on city employment, where $\frac{dA_s}{dN_c}$ is likely negative.

Because of the constant returns to scale technology, we can conceptualize each firm as operating on one unit of space. I denote n_c as workers per unit space in the city and n_s as workers per unit space in the suburbs. k_c and k_s are capital per unit space in each region respectively. Labor, capital and location are firms' only choice variables. Profit functions for city and suburban firms respectively are thus:

$$\begin{aligned} \pi_c &= A_c(N_c, t) f(n_c, k_c) - r - w_c n_c - v k_c \\ \pi_s &= A_s(N_c, t) f(n_s, k_s) - \underline{r} - w_s n_s - v k_s. \end{aligned}$$

In these expressions, w_c and w_s are wages and v is the capital rental rate, which does not differ by location. Because firms are fully mobile, they must earn the same profit in each location. Total differentiation of the indirect profit function given input costs yields the following equilibrium relationship between productivity, wages and rents between the city and suburbs. This equation is a within-metro version of one central Rosen (1979) and Roback (1982) equilibrium condition, in which ϕ_N is the cost share of labor and ϕ_L is the cost share of land in production.

$$d \ln A = \phi_N d \ln w + \phi_L d \ln r \tag{9}$$

This equation indicates that the higher wage and rent location (the city) must also have higher total factor productivity in order for firms to be willing to locate there simultaneously as in the lower cost suburbs. Because capital has the same cost in both locations, it drops out of this equation.

Optimization over the labor and capital inputs while imposing 0 profits pins down the number of workers hired at each firm and the equilibrium wage. For these calculations, I employ the Cobb-Douglas production technology $f(n,k) = n^{\gamma}k^{\mu}$. The central city wage as a function of rent is

$$w_c = \frac{A_c^{\frac{1}{\gamma}} v^{-\frac{\mu}{\gamma}} \mu^{\frac{\mu}{\gamma}} \gamma (1-\gamma-\mu)^{\frac{1-\gamma-\mu}{\gamma}}}{r^{\frac{1-\gamma-\mu}{\gamma}}}. \tag{10}$$

The resulting mass of workers hired by each central city firm is

$$n_c = \frac{r^{\frac{1-\mu}{\gamma}}}{A_c^{\frac{1}{\gamma}} \left[\frac{\mu}{v}\right]^{\frac{\mu}{\gamma}} (1-\gamma-\mu)^{\frac{1-\mu}{\gamma}}}.$$

This factor demand function is increasing in central city land rent r since higher rents induce firms to substitute toward labor and away from land. Because each firm operates on one unit of space, the implied amount of central city space devoted to production is the same as the number of firms, given by $\frac{N_c}{n_c}$. This aggregate factor demand function for city land is downward sloping in land rent r and shifts out with increases in total factor productivity.

5.1.2 The Housing Sector

Housing is produced with a different constant returns to scale technology over the same three inputs as traded goods production. As with traded goods, total differentiation of indirect profit functions yields an equation that relates the difference in housing prices p between a central city and surrounding suburban area with differences in land rents and wages weighted by input cost shares θ_L and θ_N.

$$d\ln p = \theta_L d\ln r + \theta_N d\ln w \tag{11}$$

Key to this equation is the assumption that firm productivities in the housing sector do not differ across space. Therefore, any differences in rents and wages must be reflected in housing price differences.[17]

5.1.3 Consumers

Each person in each metropolitan region is identical and has preferences over the traded good z of price 1, housing H and a local amenity q. Each individual is endowed with one unit of time that is allocated toward working or commuting. People have the option of commuting to a firm in their residential region at time cost t within the city, $c_s t$ within the suburbs or from the suburbs to the city at time cost $c_{sc}t$, where $c_{sc} > c_s > 1$. In equilibrium, all people have the same endogenous utility level. We can express indirect utilities of city commuters, suburban commuters, and suburb

[17] Rather than assume they are zero, it would be possible to recover housing sector productivity differences between cities and suburbs with home price data. Unfortunately, quality adjusted home value information for sub-metropolitan area regions is difficult to construct in 1960.

to city commuters respectively as:

$$
\begin{aligned}
V_c &= \max_{z,H} \left[U(z,H,q_c) + \lambda_c(w_c(1-t) - z - p_c H)\right] = V(p_c, w_c(1-t), q_c) \\
V_s &= \max_{z,H} \left[U(z,H,q_s) + \lambda_s(w_s(1-c_s t) - z - p_s H)\right] = V(p_s, w_s(1-c_s t), q_s) \\
V_{sc} &= \max_{z,H} \left[U(z,H,q_s) + \lambda_{sc}(w_c(1-c_{sc} t) - z - p_s H)\right] = V(p_s, w_c(1-c_{sc} t), q_s)
\end{aligned} \tag{12}
$$

The utility function is concave in all three of its arguments. I ignore the possibility of reverse commuters. Reverse commuting has a small market share and would be difficult to rationalize at the same time as suburb to city commutes without adding individual-location match specific productivity and/or amenity shocks, as in Ahlfeldt et al. (2015). As long as the distribution of such shocks is not a function of t, which is exogenously changed with new highways, their addition would add no insights to the model. Moreover, empirical evidence on commuting flows in Table 8 discussed above reveals no estimated relationship between t and the prevalence of reverse commutes.

Since all suburban residents face the same prices and have the same utility, they must consume the same bundle (z_s, H_s) and therefore have the same income net of commuting cost. Analogous to Ogawa and Fujita (1980) which explores a continuous city, this pins down that the relative wage must equal the difference in commuting cost for the two types of suburban residents. If commuting times are small fractions of total time available, or are near 0, we can approximate the city-suburban log wage difference as the difference in commuting times for suburban residents:

$$
\ln(w_c) - \ln(w_s) \approx (c_{sc} - c_s)t \tag{13}
$$

Given equal utility for city and suburban residents, without even considering the production side of the model it is clear that there are three potential reasons why cities have higher home prices than the suburbs: wages are higher, commuting costs may be lower and local consumer amenities q may be higher. If the city home price were not higher to compensate, everyone would choose to live in the city. This observation about relative home prices can be formalized by imposing the $V_c = V_{sc}$ or $V_c = V_s$. Differentiating either of these equilibrium conditions yields an equation which states that the percent difference across locations in home prices, normalized by the expenditure share on housing, has to equal the percent difference across locations in wages net of commuting costs plus an adjustment for amenity differences. Substituting in for $d\ln p$ from (11) yields an equation that pins down equilibrium rent differences between the city and the suburbs. Using this equality implies an expression for city rents, where σ_H is the housing expenditure share and $\sigma_q = \frac{\partial \ln U / \partial \ln q}{d \ln U / d \ln[w(1-t)]}$ is a constant that does not depend on t.[18]

$$
\ln r \approx \ln \underline{r} + \frac{1 - \sigma_H \theta_N}{\sigma_H \theta_L}(c_{sc} - c_s)t + \frac{\sigma_q}{\sigma_H \theta_L}(\ln q_c - \ln q_s) \tag{14}
$$

[18] The utility function $U = qz^{\alpha}H^{\beta}$, as used in Ahlfeldt et al. (2012) and implicitly in Albouy (2016), among many other functions, has the property that σ_q is a constant.

In considering the equilibrium allocation of production across space below, these equilibrium conditions on relative wages and rents will prove useful.

Following the literature, of which Mayo (1981) provides a review updated by Davis & Ortalo-Magné (2008), I assume that housing demand is constant elasticity in price and income. Substituting the equilibrium condition from the housing sector (11) into this constant elasticity demand function recovers the consumer demand function for central city land. In this expression, R is a constant, ε is the price elasticity of demand for housing and η is its income elasticity of demand.

$$\ln l^d(r, w_c) = R + \eta \ln[w_c(1-t)] + \varepsilon(\theta_L \ln r + \theta_N \ln w_c) - (\theta_K + \theta_N) \ln r + \theta_N \ln w_c \tag{15}$$

The constant incorporates the cost of capital. The second term captures the direct influence on land demand of consumers' income net of commuting cost. The third term captures the fact that land costs and wages contribute to housing costs, which influences demand for space via its price elasticity. The remaining terms capture the general equilibrium effects that as land costs rise, home builders substitute toward capital and labor and away from land, whereas as wages rise home builders substitute away from labor and toward land.

5.2 Model Solution

5.2.1 Equilibrium

The previous sub-section developed Equations (9), (13) and (14), which are combined into the first equilibrium condition of this model.

$$\ln A_c(N_c, t) - \ln A_s(N_c, t) = [\phi_N + \phi_L \frac{1 - \sigma_H \theta_N}{\sigma_H \theta_L}](c_{sc} - c_s)t + \frac{\phi_L \sigma_q}{\theta_L \sigma_H}[\ln q_c - \ln q_s] \tag{16}$$

One remarkable feature of this expression is that it provides an implicit solution for total city employment N_c that does not depend on the levels of wages, rents or the quantity of city land.[19] Therefore, this expression also holds by industry. The following sub-section shows how the estimated responses of the number of central city workers to urban highway infrastructure is combined with this expression to recover properties of $A_c(N_c, t)$ and $A_s(N_c, t)$.

Given N_c from (16), imposing market clearing for space in the city allows us to determine the number of residents in the city Q_c. This equation represents the equilibrium relationship between

[19] To keep the model simple and tractable, I impose that all metropolitan area residents work in the tradeable sector. Housing sector labor can be thought of as coming from reducing the exogenous metro area population N by a small amount. Though this amount is technically endogenous to t, because it is a small fraction of N, incorporating it explicitly in the model will not affect results much. The construction industry employed an average of 6 percent of urban workers in primary sample metropolitan areas in both 1960 and 2000. Alternatively, one could respecify preferences to be over land rather than housing. This adjustment leads to very similar results, though with a less rich interpretation.

the number of jobs and residents in the central city, given respectively by N_c and Q_c.

$$N_c \left[\frac{1-\gamma-\mu}{r}\right]^{\frac{1-\mu}{\gamma}} A_c(N_c,t)^{\frac{1}{\gamma}} \left[\frac{\mu}{v}\right]^{\frac{\mu}{\gamma}} + Q_c l^d(r,w_c) = L_c \tag{17}$$

The first term in this expression describes the amount of city land used in production. Unlike the total amount of central city employment N_c, the amount of central city space used by firms does depend on the level of suburban rent. Higher city land rents lead firms to economize on space and hire more workers per unit area. The second term is the product of the number of city residents and consumer demand for land. In working with this expression below, I substitute (10) for central city wages w_c, (14) for rent r and (15) for $l^d(r,w_c)$.

5.2.2 Specifying the Agglomeration Function

With equilibrium values of N_c and Q_c determined from (16) and (17), we are in a position to derive analytical expressions for responses of these quantities of central city residents and workers to changes in transportation costs t. Comparing these theoretical changes to actual changes measured in the data will allow us to recover elements of interest that capture agglomeration spillovers and are contained in the functions $A_c(N_c,t)$ and $A_s(N_c,t)$.

I use the following generalized constant elasticity functional forms for the agglomeration functions.

$$A_c(N_c,t) = \alpha_c h(t) g_c(N_c),\ \ A_s(N_c,t) = \alpha_s h(t) g_s(N_c)$$

α_c and α_s capture natural productivity advantages of cities and suburbs respectively. The function $h(t)$, $h' < 0$ captures the potential for transportation cost reductions to improve contact between all firms in a metropolitan area, thereby enhancing agglomeration spillovers. As with local consumer amenities q_c and q_s, I assume that any difference across equilibria (over time) in local productive amenities α_c and α_s is orthogonal to changes in t.

The element of primary interest in the TFP functions are the g_c and g_s functions. As is shown below, recovery of $\frac{d\ln g_c}{d\ln N_c}$ and $\frac{d\ln g_s}{d\ln N_c}$ is possible through combining treatment effect estimates and calibrated parameters. One simple specification of such functions is constant elasticity in N_c and N_s:

$$g_c(N_c) = N_c^{\beta_c}(N-N_c)^{\rho_c}, g_s(N_c) = (N-N_c)^{\beta_s} N_c^{\rho_s}$$

Given this specification, we can recover the parameter combinations $\beta_c - \frac{N_c}{N_s}\rho_c > 0$ and $\rho_s - \frac{N_c}{N_s}\beta_s < 0$, which capture the relative strength of agglomeration forces within versus across regions. Indicated signs assume that within region agglomeration spillovers exceed across region agglomeration spillovers.

More standard specifications of the agglomeration spillover functions, used for example in Ahlfeldt et al. (2015) are:

$$g_c(N_c) = [N_c + \rho_c(N-N_c)]^{\beta_c}, g_s(N_c) = [N - N_c + \rho_s N_c]^{\beta_s}$$

For these specifications, $\frac{d\ln g_c}{d\ln N_c} = \frac{\beta_c N_c(1-\rho_c)}{N_c+\rho_c N_s} > 0$ and $\frac{d\ln g_s}{d\ln N_c} = \frac{\beta_s N_c(\rho_s-1)}{N_s+\rho_s N_c} < 0$. If $\beta_c = \beta_s$ and $\rho_c = \rho_s$, both parameters are just identified by the calibration procedure employed below.

Analytical results presented below show how to recover estimates of the object $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$ under general conditions and without solving the full model. Because total metropolitan area employment is fixed, $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$ can be thought of as the total sum of agglomeration forces in the own region relative to that in the other region of the metro area, with an adjustment for regions' relative size. In mathematical terms $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c} = \left[\frac{\partial\ln\widetilde{g}_c}{\partial\ln N_c} - \frac{N_c}{N_s}\frac{\partial\ln\widetilde{g}_c}{\partial\ln N_s}\right] + \left[\frac{N_c}{N_s}\frac{\partial\ln\widetilde{g}_s}{\partial\ln N_s} - \frac{\partial\ln\widetilde{g}_s}{\partial\ln N_c}\right]$, where $\widetilde{g}_c(N_c, N-N_c) \equiv g_c(N_c)$ and $\widetilde{g}_s(N-N_c, N_c) \equiv g_s(N_c)$. In the 1960 data, N_c and N_s are similar in magnitude. Therefore, if $\widetilde{g}_c(\cdot)$ and $\widetilde{g}_s(\cdot)$ are the same functions $\widetilde{g}(N_1, N_2)$, $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c} \approx 2\left[\frac{\partial\ln\widetilde{g}}{\partial\ln N_1} - \frac{\partial\ln\widetilde{g}}{\partial\ln N_2}\right]$, or twice the difference between within and cross-region spillovers. If cross-region spillovers are 0, $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$ thus represents about twice within-region spillovers. If there are no suburban spillovers (or $g_s(N_c) = 1$), then $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$ measures the full within city agglomeration force.

5.2.3 Comparative Statics

Differentiating (16) yields the following equation, which is the partial elasticity of central city employment with respect to the fraction of central city residents' time endowment spent commuting.

$$\frac{d\ln N_c}{dt} = \frac{[\phi_N + \phi_L\frac{1-\sigma_H\theta_N}{\sigma_H\theta_L}](c_{sc} - c_s) + \frac{\phi_L\sigma_q}{\theta_L\sigma_H}\frac{d}{dt}[\ln q_c - \ln q_s]}{\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}} \tag{18}$$

The intuition behind this expression is as follows. Transport cost increases drive up central city wages and rents relative to suburban wages and rents. This means that in order for firms to continue to exist in both the central city and the suburbs, the relative size of agglomeration spillovers must also increase to compensate. This increase in relative agglomeration forces is facilitated by increasing central city employment as long as the agglomeration spillovers within the city exceeds those between the city and suburbs. Using calibrated values for elements of the numerator, empirical estimates of $\frac{d\ln N_c}{d[hwy]}$ and calibrated values of $\frac{d[hwy]}{dt}$, we can therefore recover a value for $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$. Because $c_{sc} > c_s$, the derivative $\frac{d\ln N_c}{dt}$ is positive if agglomeration economies are stronger locally than between cities and suburbs. Because this object only depends on a few parameters, model simulations presented below can quantify the extent to which agglomeration spillovers operate at sub-metropolitan area scales with reasonably tight bounds. Moreover, because (18) is not derived from any conditions which use the allocation of workers or residents between cities and suburbs, it can be directly applied separately for each industry.

Differentiating (17) yields an expression for the partial elasticity of central city (working) population with respect to commuting time. The resulting expression depends crucially on comparative statics of log central city rents and wages with respect to commuting costs:

$$\frac{d\ln r}{dt} = \frac{1-\sigma_H\theta_N}{\sigma_H\theta_L}(c_{sc}-c_s) + \frac{\phi_L\sigma_q}{\theta_L\sigma_H}\frac{d}{dt}[\ln q_c - \ln q_s] > 0 \quad (19)$$

$$\frac{d\ln w_c}{dt} = \frac{1}{\gamma}\frac{d\ln h}{dt} + \frac{1}{\gamma}\frac{d\ln g_c}{d\ln N_c}\frac{d\ln N_c}{dt} - \frac{1-\gamma-\mu}{\gamma}\frac{d\ln r}{dt} < 0 \quad (20)$$

As transport costs increase, central city land rents increase because there is more competition for central city space to avoid the higher commuting cost from the suburbs and, potentially, because central city amenities increase relative to suburban amenities. The wage response has three components. First, transportation costs have a direct negative effect on agglomeration spillovers and worker productivity. Calibrating this element will require choosing $\frac{d\ln h}{dt}$, for which I explore values of -1 and 0. Second, agglomeration spillovers increase as employment location centralizes. Third, the amount of land per worker decreases as the price of central city space increases, making workers less productive. The magnitude of the second effect is small in calibrations, allowing us to sign this wage response as negative.

Given these central city wage and rent responses, the following expression breaks out $\frac{d\ln Q_c}{dt}$ into a number of components. In this expression, X_c represents the central city land area devoted to production and $L_c - X_c$ is the central city land area devoted to residences.

$$\begin{aligned}
\frac{d\ln Q_c}{dt} = \; & \eta && \text{A. standard income effect (+)}\\
& -\varepsilon\theta_L\frac{d\ln r}{dt} && \text{B. rent changes and price effect (+)}\\
& -\eta\frac{d\ln w_c}{dt} && \text{C. wage changes and income effect (+)}\\
& -\varepsilon\theta_N\frac{d\ln w_c}{dt} && \text{D. wage changes and price effect (-)}\\
& -\theta_N\frac{d\ln w_c}{dt} && \text{E. wage changes and housing factor reallocation (+)}\\
& +[1-\theta_L]\frac{d\ln r}{dt} && \text{F. rent changes and housing factor reallocation (+)}\\
& +\frac{X_c}{L_c-X_c}\left[\frac{1-\mu}{\gamma}\frac{d\ln r}{dt}\right] && \text{G. firm land use change because of rents (+)}\\
& -\frac{X_c}{L_c-X_c}\frac{d\ln N_c}{dt} && \text{H. firm land use change because of employment (-)}\\
& -\frac{X_c}{L_c-X_c}\left(\frac{1}{\gamma}\frac{d\ln g_c}{d\ln N_c}\frac{d\ln N_c}{dt}+\frac{1}{\gamma}\frac{d\ln h}{dt}\right) && \text{I. firm land use change b/c of agglom (?)} \quad (21)
\end{aligned}$$

A brief summary of each mechanism is indicated next to each term with the sign of the effect assuming that $\frac{d\ln w_c}{dt} < 0$. Components A and B reflect standard income and price effects of an increase in transport costs. Higher t increases commuting costs and reduces real income, causing space per-capita to fall and central city population to rise. The city-suburban rent gap also increases, thereby inducing central city residents to economize on space, mediated by the share of land in housing production. Component C captures the direct impact the change in the wage has on income. Unless agglomeration spillovers are very strong, commuting cost increases cause central city wages to fall, leading individuals to economize on housing and space. Component D captures how central city wage declines pass through to lower housing costs, causing consumers to consume more housing and space. Component E captures how land intensity in housing production decreases as wages fall. Component F captures the substitution away from land in housing production that occurs with rent increases. Finally, Components G, H and I reflect that commuting cost increases lead firms to economize on space per worker, freeing up more space for residents, but also influence worker productivity through the potential reorientation of employment into the central city and direct changes captured in the $h(t)$ function. Magnitudes of these final three components are mediated by the fraction of central city land in production.

As the strength of localized agglomeration economies approaches 0, the sign of $\frac{d\ln Q_c}{dt}$ is unambiguously positive, since the force keeping workers and firms in the central city disappears. Indeed, greater estimates of both $\frac{d\ln Q_c}{dt}$ and $\frac{d\ln N_c}{dt}$ are evidence of weaker local agglomeration forces, as they reflect weaker forces keeping firms and workers in central cities in the face of commuting cost reductions. As $\frac{d\ln N_c}{dt}$ approaches 0, the percent difference in within versus cross-region agglomeration forces approaches infinity.

Substituting for $\frac{d\ln N_c}{dt}$ from (18) into (21) yields $\frac{d\ln Q_c}{dt}$ as a function solely of exogenous elements and parameters. Given a value for $\frac{d\ln h}{dt}$, this system of equations can then be solved for parameter combinations that describe the relative agglomeration force $\frac{d\ln g_c}{d\ln N_c}$.

6 Model Calibration

6.1 Baseline Parameters

Regression estimates reported in Section 4 indicate that for all industries combined, $\frac{\Delta\ln N_c}{\Delta hwy} \approx 0.06$. To relate this derivative to the empirical results, we can write $\frac{d\ln N_c}{dt} \approx \frac{\Delta\ln N_c}{\Delta hwy}\frac{\Delta hwy}{\Delta t}$. Determining a value to use for $\frac{\Delta hwy}{\Delta t}$ requires a more complete specification of urban spatial structure than exists in this model. In a continuous space monocentric city, like that studied in Baum-Snow (2007b), each highway roughly doubles commuting speed for those who live and work on it, reducing the fraction of time spent commuting by 0.03 on average from a base of 0.06, or 18 minutes in a 10 hour day. However, each radial highway with such a speed ratio to surface streets only serves any part of commutes for about one-fifth of the population in a circular city. Therefore, $\frac{\Delta t}{\Delta hwy}$ is about 0.005 when averaged across all central city commuters. I present results over the range of values 0.005 to 0.015.[20] Note that reductions in t are reflected in reduced times for all types of commutes.

Additional parameters that must be calibrated are η, ε and σ_H from consumer preferences, θ_L and θ_N from housing production, and ϕ_L and ϕ_N from traded goods production. I begin with cost share parameters from Albouy (2016), with some analysis using industry level shares from the

[20] Couture, Duranton & Turner (2016) estimate the elasticity of speed with respect to lane km of roads to be about 0.10. Taking $t = 0.06$, this is consistent with $\frac{\Delta t}{\Delta hwy} = -0.006$ for a city that goes from 1 to 2 radial highways. The typical SMSA received about 2.5 new radial highways between 1950 and 2000.

KLEMS data. For the income elasticity of demand for housing, η, I start with 0.7 as a compromise between Glaeser, Kahn & Rappaport (2008) and Davis & Ortalo-Magné (2011), though I study sensitivity of results to this parameter. Also following Davis & Ortalo-Magné (2011), I calibrate the price elasticity of housing demand ε to -1.[21] Based on data in the consumer expenditure survey, I calibrate σ_H, the share of income spent on housing services, to 0.17.[22]

I calculate X_c and $L_c - X_c$, fractions of central city space devoted to production and housing, separately for each SMSA using 2000 census data. To calculate X_c I begin with information on the number of working residents and jobs in each microgeographic unit (TAZ, tract or block group) in each central city from the 2000 census. Using this information, I estimate β_1 and β_2 in a regression of unit area L_{ij} on the number of residents and amount of employment in the unit, SMSA fixed effects and flexible controls for CBD distance

$$L_{ij} = \alpha_{0i} + \alpha_{1i} dis_{ij}^{CBD} + \alpha_{2i} \left(dis_{ij}^{CBD}\right)^2 + \beta_1 res_{ij} + \beta_2 emp_{ij} + \varepsilon_{ij},$$

where i indexes SMSA and j indexes TAZ, tract or block group. The parameters β_1 and β_2 capture the average amount of space occupied by each working resident and each employee nationwide.[23] Applying these estimates of per-capita space consumption to 1960 central city employment and working residents yields the following expression for the relative intensity of central city land used in production versus consumption:

$$\left[\frac{X_c}{L_c - X_c}\right]_i = \frac{\beta_2 emp_i^{CC60}}{\beta_1 res_i^{CC60}}$$

This of course is not the ideal measure of the relative land use of firms and residents because β_1 and β_2 reflect post-transport infrastructure land use. However, without microgeographic information about the location of employment in 1960, this is a viable measure. Moreover, because components G, H and I in (21) are collectively small, results are insensitive to reasonable choices of $\frac{X_c}{L_c - X_c}$.

I calculate parameters c_{sc} and c_s, which capture suburb-city and suburb-suburb commuting costs relative to those within the city, using 2000 census data separately for each metropolitan area. For the purpose of these calculations, I combine regions outside of SMSAs to or from which commutes involving the SMSA take place with suburbs. Averages across the 100 largest SMSAs of all calibrated parameters are reported in Table 9. Therefore, results reported below apply for an average large metropolitan area.[24]

Finally, $\sigma_q \frac{d}{dt}[\ln q_c - \ln q_s]$ directly influences the response of central city rent to new roads,

[21] Most results are insensitive to using $\varepsilon = -0.5$ instead.

[22] This number crucially excludes utilities and financing costs, which do not make up part of housing production in the model.

[23] While the model does analytically deliver the amount of central city space used by firms, the requisite α_c parameter is not easily calibrated. Attempts to index β_1 and β_2 by SMSA produce coefficients that differ too widely across city to be credible.

[24] The relative commute time numbers reported in Table 9 do not match those in Table 3 because the Table 9 numbers consolidate all commutes with origins or destinations in suburbs with origins or destinations outside of SMSAs.

feeding through to wages and agglomeration. This object may be positive or 0, as new roads may cause relative reductions of the amenity value of central cities. For the purpose of calibration, I set $\frac{d}{dt}[\ln q_c - \ln q_s]$ to 0, as such amenity effects are difficult to measure directly. As a result, reported effects of new roads represent lower bounds on agglomeration spillover parameters.

6.2 Recovering Agglomeration Parameters

Using (18) plus empirical estimates reported in Table 7, I recover estimates of $\frac{d \ln g_c(N_c)}{d \ln N_c} - \frac{d \ln g_s(N_c)}{d \ln N_c}$ for each industry. Table 10 Panel A reports results for each industry as functions of the effect of labor's share of production $\phi_N = \gamma$ and the response of average central city commute times to each additional highway, the two model parameters to which the results are most sensitive. Table 10 Panel B reports results using industry-specific input cost shares. As discussed in the end of Section 5.2.2 above, entries in Table 10 equal twice $\frac{\partial \ln \widetilde{g}_c}{\partial \ln N_c}$ if city and suburb agglomeration functions are symmetric and no cross-region spillovers exist. Entries equal $\frac{\partial \ln \widetilde{g}_c}{\partial \ln N_c}$ if no cross-region spillovers exist and there are no agglomeration economies enjoyed by suburban firms.

Estimates of $\frac{d \ln g_c(N_c)}{d \ln N_c} - \frac{d \ln g_s(N_c)}{d \ln N_c}$ for all industries, reported in the third column of Table 10, range from 0.044 to 0.131. Consensus estimates of the metropolitan area level elasticity of productivity with respect to population are in the 0.05 to 0.15 range (Combes et al., 2010). Symmetric $\widetilde{g}(\cdot)$ functions for the city and suburbs would thus mean that the elasticity of city TFP with respect to city population minus that with respect to suburban population is 0.022 to 0.065 (half of the numbers in Table 10). This is likely a lower bound on the true relative effect for two reasons. First, spillovers within suburbs are likely smaller due to lower employment densities there. Second, highways may negatively affect city amenities, which, if true, would increase all numbers in Table 10. Therefore, this is strong evidence that agglomeration spillovers within sub-metropolitan regions represent a large fraction of the aggregate agglomeration economies in metropolitan areas. The model structure reinforces the intuition coming from relatively small estimated response of firm location choices to reductions in transportation costs that being spatially clustered below the metropolitan area scale is an important component of firms' total factor productivities.

The remaining columns of Table 10 report relative spillovers by industry. For all combinations of parameter values studied, finance, insurance and real estate has the largest localized agglomeration spillovers at 0.06 to 0.18 while wholesale & retail trade has the smallest at 0.01 to 0.04. Construction, services, transportation, communications and public utilities and manufacturing are in between, in order of most to least localized.[25]

Results in Table 10 indicate that the majority of agglomeration spillovers operate within cities and indicate their variation across industries. Taking $\frac{\Delta t}{\Delta hwy}$ to be -0.01, this implies that the elasticity of central city TFP with respect to population is at least 0.045 across all industries - from 0.014 in wholesale/retail trade to 0.060 in finance, insurance and real estate. Estimates in Table 10 are most sensitive to $\frac{\Delta t}{\Delta hwy}$. For each increment of $\frac{\Delta t}{\Delta hwy}$ by -0.005, the implied magnitude

[25] Allocations in public administration and the military are not likely to be determined by market forces and have no cost share information, so they are not reported.

of localized agglomeration spillovers in a metropolitan area increases by 0.03-0.05 conditional on all other parameter values examined. As additional highways cause commuting times to fall more quickly (and $\frac{\Delta t}{\Delta hwy}$ rises in absolute value), we infer a smaller change in central city employment for a given change in t. The model interprets this smaller change as evidence of stronger agglomeration forces keeping firms in the central city.

By making use of (21) jointly with (18), it is in principle possible to recover separate estimates for $\frac{d\ln g_c}{d\ln N_c}$ and $\frac{d\ln g_s}{d\ln N_c}$. However, carrying out this exercise yields implied values for $\frac{d\ln g_c}{d\ln N_c}$ that depend very sensitively on $\frac{\Delta t}{\Delta hwy}$. In particular, each reduction in $\frac{\Delta t}{\Delta hwy}$ of 0.0025 results in an increase of $\frac{d\ln g_c}{d\ln N_c}$ by 0.44. Therefore, separating precise quantification of $\frac{d\ln g_c}{d\ln N_c}$ from $\frac{d\ln g_s}{d\ln N_c}$ is impossible using this framework. However, beyond its information on the relative magnitudes of agglomeration spillovers, we can also use this framework to learn quantitatively about the mechanisms driving urban decentralization and the welfare consequences of new highways.

6.3 Why Did Highways Cause Suburbanization?

Table 11 reports calibrated values for each component of $\frac{\Delta\ln Q_c}{\Delta hwy}$ using (21), where $\frac{\Delta\ln Q_c}{\Delta hwy} \approx \frac{d\ln Q_c}{dt}\frac{\Delta t}{\Delta hwy}$ under different assumptions about the labor share γ, how highways affect commute times $\frac{\Delta t}{\Delta hwy}$, and the income elasticity of demand for housing η. Results in columns A-H match the same components of $\frac{\Delta\ln Q_c}{\Delta hwy}$ enumerated in (21), with each element of (21) multiplied by $\frac{\Delta t}{\Delta hwy}$. For columns A-H, I impose that $\frac{d\ln g_c}{d\ln N_c} = 0$ and $\frac{d\ln h}{dt} = 0$, assumptions that are relaxed in the remaining columns of Table 11. Given a value for $\frac{d\ln N_c}{dt}$, smaller working population responses to new highways indicates more localized agglomeration spillovers for central city firms. By imposing $\frac{d\ln g_c}{d\ln N_c} = 0$, each entry thus provides an upper bound on the true magnitude of each component. The first column in the right block in Table 11 separately reports the additional contribution assuming $\frac{d\ln h}{dt} = -1$ through wage effects in Components C,D and E plus firm land use changes in I. The final column of Table 11 reports the countervailing positive contribution of $\frac{d\ln g_c}{d\ln N_c}$, assuming that $\frac{d\ln g_c}{d\ln N_c}$ is one-half of the corresponding value for $\left[\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}\right]$ reported in Table 10, meaning central area and suburban agglomeration functions are symmetric and cross-region spillovers are 0. These are conservative estimates, as weaker suburban agglomeration spillovers would cause the true value of $\frac{d\ln g_c}{d\ln N_c}$ to be larger. In the extreme, if only within-city spillovers existed, the effects of relaxing $\frac{d\ln g_c}{d\ln N_c} = 0$ would be twice as large as those reported in the final column. Components listed in Table 11 should be compared to the full treatment effect of -0.16 of each highway on central area working population reported in Table 7.

Following are the most important mechanisms through which highways caused urban population decentralization. Factor reallocation toward land in housing production (Component F) is the largest negative component at between -0.033 and -0.098 depending on parameters, or up to 60 percent of the full estimated treatment effect. Firm adjustments to space per worker (Component G) adds -0.021 to -0.064 to this, but is somewhat counterbalanced by the crowd-in effect of firms moving operations to the suburbs (Component H) of 0.029. Price & income effect mechanisms and factor reallocation in housing production because of wage changes sum to no more than -0.05, mostly because of components A and B. These results indicate that key to understanding urban decentralization is the high land share in the production of housing. People live on more space as highways cause central area rents to decline, thereby generating lower densities and population decentralization.

The final two columns of Table 11 show the additional impacts that operate through shifts in firm productivity. Imposing $\frac{d\ln h}{dt} = -1$ generates up to an additional -0.032 or 5-20 percent of the full treatment effect. As seen in the final column, imposing $\frac{d\ln g_c}{d\ln N_c}$ as one-half of $\left[\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}\right]$ results in small *positive* impacts of less than 0.01 to $\frac{\Delta\ln Q_c}{\Delta hwy}$. If the maximum possible estimates of $\frac{d\ln g_c}{d\ln N_c}$ from Table 10 are used instead, effects on population decentralization rise to less than 0.02.

6.4 Evaluating Welfare Consequences

In this sub-section, I evaluate the welfare consequences of new highways using the model. From (12), residents' willingness to pay for a new highway (on the margin) is:

$$\frac{\Delta V_c/\Delta[hwy]}{\lambda_c} \approx [w_c(1-t)]\,[\frac{d\ln w_c}{dt} - 1]\left[\frac{\Delta t}{\Delta hwy}\right] - [p_c H]\,[\theta_L\frac{d\ln r}{dt} + \theta_N\frac{d\ln w_c}{dt}]\left[\frac{\Delta t}{\Delta hwy}\right] \quad (21)$$

Analogous expressions for commutes involving the suburbs yield identical implications. The first term captures the increase in real income that occurs both because the new highway increases commuting speed and because it raises wages through the three mechanisms specified in (20). This increase in real income can be expressed as a fraction of initial central city income net of commuting cost $w_c(1-t)$. The second term captures the welfare consequences of changes in housing cost, and can be expressed as a fraction of central city housing cost $p_c H$. The change in housing cost reflects the change in land and labor costs given in (19) and (20) respectively, which push in opposite directions. With sufficiently strong productivity gains from new highways, housing costs can actually increase. Expressed in this way, welfare implications can be applied broadly to cities of different income levels and housing costs, though putting them in dollar terms requires knowledge of wage and house price levels.

While residents experience clear welfare gains from new highways, landowners experience clear welfare losses because central space declines in value. The aggregate capital loss for absentee landlords is $rL_c\frac{d\ln r}{dt}\left[\frac{\Delta t}{\Delta hwy}\right]$. Of course, central city owner-occupiers will incur this capital loss along with the other welfare gains.

Table 12 presents the welfare results. A central input into welfare calculations is how much central city wages are affected by reductions in transport costs. Such wage responses depend crucially on assumptions about $\frac{d\ln h}{dt}$ and $\frac{d\ln g_c}{d\ln N_c}$. As in Table 11, I determine the influences of each of these components by presenting results with and without their inclusion and assuming that $\frac{d\ln g_c}{d\ln N_c}$ equals one-half of $\left[\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}\right]$ reported in Table 10. Columns 4-7 of Table 12 break down how real income changes in percentage terms with each additional radial highway assuming no productivity changes, productivity changes through changes in metro level agglomeration $h(t)$ only, productivity changes through changes in local spillovers $g_c(N_c)$ only, and those through both together, respectively.

The reduction in commuting cost plus increase in the land/labor ratio associated with each new highway raises real income by 0.6 to 2 percent, depending on parameter values (Column 4). Addition of the direct effect of transport costs on TFP, assuming that $\frac{d\ln h}{dt} = -1$, raises this to up to 4.1 percent. However, incorporating local agglomeration spillovers instead lowers these gains to no more than 1.4 percent. This is because such spillovers decline with the employment decentralization that happens because of the new highways. Incorporating all three mechanisms simultaneously yields estimated real income increases of 1.1 to 3.6 percent per highway. These are upper bounds since $\frac{d\ln h}{dt}$ is likely to be between 0 and 1 and $\frac{d\ln g_c}{d\ln N_c}$ is larger if suburban agglomeration spillovers are weaker.

Table 12 Columns 8-11 report impacts of one new radial highway on real housing cost in percentage terms. Because wages are only a small component of housing cost, housing cost effects vary less across parameter values and considered mechanisms, from a decline of 0.5 percent to a decline of 3 percent, with the greatest declines occurring in environments in which wages rise the least. Given that only 17 percent of income goes to housing services, the impacts of housing cost declines on overall welfare are much smaller than the associated income gains. Central city rent declines of 4 to 13 percent with each new highway means that the associated total impact on housing costs of each new highway for owner-occupiers is negligible relative to the associated impact on income. Table 12 Column 12 shows the effects of a new highway on central city rents. These declines range from 8% to 13%.

Taken together, results in Table 12 indicate that each new highway generating a willingness to pay of 1-4 percent of income for renters. The capital loss from reduced city land values reduces this amount by less than one percentage point for owners.

7 Conclusions

This paper demonstrates that new radial highways have caused significantly greater amounts of residential than job decentralization. Each radial highway displaced an estimated 16 percent of the central city working population but only 6 percent of the jobs to the suburbs. These estimates are fairly consistent across industry, though are larger in absolute value for retail and wholesale trade and smaller for finance, insurance and real estate.

Viewed in the context of a calibrated urban model, these results provide evidence that local spillovers are an important incentive for firms to cluster spatially. Using estimated treatment effects and calibrated cost and expenditure shares, the implied elasticity of central city TFP to central city employment relative to suburban employment is 0.02-0.05, meaning that a large fraction of overall agglomeration economies operate at spatial scales below the metropolitan area level.

Model calibration results also bring forth reasons for the success of the monocentric model for understanding urban population decentralization, despite its restrictive assumption that all employment is located at the center. Results indicate that factor reallocation toward land in housing and traded goods production generates the majority of population decentralization with new highways, with only small additional effects due to employment relocations.

Welfare analysis reveals that each radial highway causes central city income net of commuting costs to increase by up to 3.6% and housing cost to decline by up to 3.0%. Therefore, each radial highway increased metropolitan area output by 1 to 4 percent on the margin.

References

Ahlfeldt, Gabriel, Stephen Redding, Daniel Sturm and Niko Wolf (2015) "The Economics of Density: Evidence from the Berlin Wall," Econometrica, 83(6): 2127-2189.

Albouy, David (2016) "What Are Cities Worth? Land Rents, Local Productivity, and the Total Value of Amenities," Review of Economics and Statistics, 98(3): 477-487.

Albouy, David and Bryan Stuart (2016) "Urban Population and Amenities: The Neoclassical Model of Location," manuscript.

Allen, Treb & Costas Arkolakis (2014) "Trade and the Topography of the Spatial Economy," 129(3), 1085-1140.

Allen, Treb, Costas Arkolakis & Xiangliang Li (2015) "Optimal City Structure," manuscript.

Alonso, William (1964) "Location and Land Use" (Cambridge: Harvard University Press).

Arzaghi, Mohammad & J. Vernon Henderson (2008) "Networking off Madison Avenue," Review of Economic Studies, 75(4): 1011-1038.

Bartik, Timothy J. (1991) "Who Benefits from State and Local Economic Development Policies?" Upjohn Press. W.E. Upjohn Institute for Employment Research.

Baum-Snow, Nathaniel (2007a) "Did Highways Cause Suburbanization?" Quarterly Journal of Economics 122(2): 775-805.

Baum-Snow, Nathaniel (2007b) "Suburbanization and Transportation in the Monocentric Model" Journal of Urban Economics, 62(3): 405-423.

Baum-Snow, Nathaniel (2010) "Changes in Transportation Infrastructure and Commuting Patterns in U.S. Metropolitan Areas, 1960-2000," American Economic Review Papers & Proceedings, 100(2): 378-382.

Baum-Snow, Nathaniel, Loren Brandt, J. Vernon Henderson, Matthew A. Turner and Qinghua Zhang (2016) "Roads, Railways and Decentralization of Chinese Cities," Review of Economics and Statistics, forthcoming.

Baum-Snow, Nathaniel and Byron Lutz (2011) "School Desegregation, School Choice and Changes in Residential Location Patterns by Race," American Economic Review, 101(7): 3019-3046.

Billings, Stephen and Erik Johnson (2016) "Agglomeration within an urban area," Journal of Urban Economics 91:13-25.

Brinkman, Jeffrey (2016) "Congestion, Agglomeration, and the Structure of Cities," Journal of Urban Economics, 94, 13-31.

Brinkman, Jeffrey, Daniele Coen-Pirani and Holger Sieg (2015) "Firm Dynamics in an Urban Economy," International Economic Review, 56:4, 1135–1164.

Carliner, Michael (2003) "New Home Cost Components." Housing Economics, 51: 7-11.

Combes, Pierre-Philippe, Gilles Duranton, Laurent Gobillon and Sébastien Roux (2010) "Estimating Agglomeration Economies with History, Geology, and Worker Effects." In Agglomeration Economics, Edward L. Glaeser (ed.), NBER, Cambridge, MA.

Combes, Pierre-Philippe & Laurent Gobillon (2015) "Empirics of Agglomeration Economies," in Handbook of Urban and Regional Economics Vol. 5, Duranton, Gilles, Henderson, J.Vernon & William Strange eds., Elsevier, Amsterdam.

Couture, Victor, Gilles Duranton & Matthew A. Turner (2016) "Speed," Review of Economics and Statistics, forthcoming.

Couture, Victor & Jessie Handbury (2016) "Urban Revival in America," manuscript.

Davis, Morris and François Ortalo-Magné (2011) "Household Expenditures, Wages, Rents" Review of Economic Dynamics 14(2), 248-261.

Davis, Morris and Michael Palumbo (2007) "The Price of Residential Land in Large U.S. Cities." Journal of Urban Economics 63, 352-384.

Duranton, Gilles & Henry Overman (2005) "Testing for Localization Using Microgeographic Data," Review of Economic Studies, 72 (4): 1077-1106.

Duranton, Gilles, Peter Morrow & Matthew A. Turner (2014) "Roads and Trade: Evidence from the U.S." Review of Economic Studies, 81(2), 681-724.

Duranton, Gilles & Matthew A. Turner (2012) "Urban Growth and Transportation," Review of Economic Studies, 79(4): 1407-1440.

Ellison, Glenn & Edward Glaeser (1997) "Geographic concentration in US manufacturing industries: a dartboard approach," Journal of Political Economy, 105(5): 889-927.

Ellison, Glenn, Edward Glaeser & William Kerr (2010) "What causes industry agglomeration? Evidence from coagglomeration patterns," American Economic Review, 100(3): 1195-1213.

Fu, Shihe and Stephen L. Ross. (2013) "Wage Premia in Employment Clusters: How Important is Worker Heterogeneity?" Journal of Labor Economics 31:2, 271-304.

Fujita, Masahisa & H. Ogawa (1982) "Multiple Equilibria and Structural Transition of Non-monocentric Urban Configurations," Regional Science and Urban Economics 12(1): 161-196.

Fujita, Masahisa (1989) "Urban Economic Theory: Land Use and City Size" (Cambridge: Cambridge University Press)

Glaeser, Edward & Joseph Gyourko (2005) "Urban Decline and Durable Housing" Journal of Political Economy, 113(2): 345-375.

Glaeser, Edward & Matthew E. Kahn (2001) "Decentralized Employment and the Transformation of the American City" Brookings-Wharton Papers on Urban Affairs 2: 1-63.

Glaeser, Edward, Matthew Kahn & Jordan Rappaport (2008) "Why Do the Poor Live in Cities? The Role of Public Transportation" Journal of Urban Economics 63(1), 1-24.

Glaeser, Edward, Jed Kolko & Albert Saiz (2001) "Consumer City" Journal of Economic Geography 1(1), 27-50.

Greenstone, Michael, Richard Hornbeck & Enrico Moretti (2010) "Identifying agglomeration spillovers: Evidence from winners and losers of large plant openings," Journal of Political Economy, 118(3): 536-598.

Helsley, Robert W. and William C. Strange (2014) "Coagglomeration and the Scale and Composition of Clusters," Journal of Political Economy, 122(5): 1064-1093.

Lucas, Robert E. & Esteban Rossi-Hansberg (2002) "On the Internal Structure of Cities," Econometrica 70(4): 1445-1476.

Mayo, Stephen (1981) "Theory and Estimation in the Economics of Housing Demand," Journal of Urban Economics 10: 95-116.

Michaels, Guy (2008) "The Effect of Trade on the Demand for Skill - Evidence from the Interstate Highway System," Review of Economics and Statistics, 90(4): 683-701.

Mills, Edwin S. (1967) "An Aggregative Model of Resource Allocation in a Metropolitan Area," American Economic Review, LVII: 197-210.

Muth, Richard F. (1969) "Cities and Housing" (Chicago: University of Chicago Press).

Ogawa, H. & Masahisa Fujita (1980) "Equilibrium Land Use Patterns in a Non-monocentric City," Journal of Regional Science 20: 455-475.

Rossi-Hansberg, Esteban, Pierre-Daniel Sarte and Raymond Owens III (2009) "Firm Fragmentation and Urban Patterns," International Economic Review 50(1): 143-186.

Rand McNally Co. (1960) Leahy's Hotel-Motel Guide and Travel Atlas of the United States, Canada and Mexico, American Hotel Register Company. Chicago, IL.

Rand McNally Co. (2000) Rand McNally Road Atlas: United States, Canada, Mexico. Rand McNally Co., New York, NY

Rosen, Sherwin (1979) "Wage-Based Indexes of Urban Quality of Life," in Peter Mieszkowski and Mahlon Straszheim eds. Current Issues in Urban Economics, Baltimore: Johns Hopkins University Press.

Rosenthal, Stuart & William Strange (2003) "Geography, Industrial Organization, and Agglomeration," Review of Economics and Statistics, 85(2): 377-393.

Roback, Jennifer (1982) "Wages, Rents and the Quality of Life," Journal of Political Economy 90: 1257-1278.

Saiz, Albert (2010) "The Geographic Determinants of Housing Supply," Quarterly Journal of Economics 125 (3): 1253-1296.

U.S. Department of Transportation (1977) America's Highways: 1776-1976: A History of the Federal-Aid Program, U.S. Government Printing Office, Washington.

Figure 1: Davenport SMSA

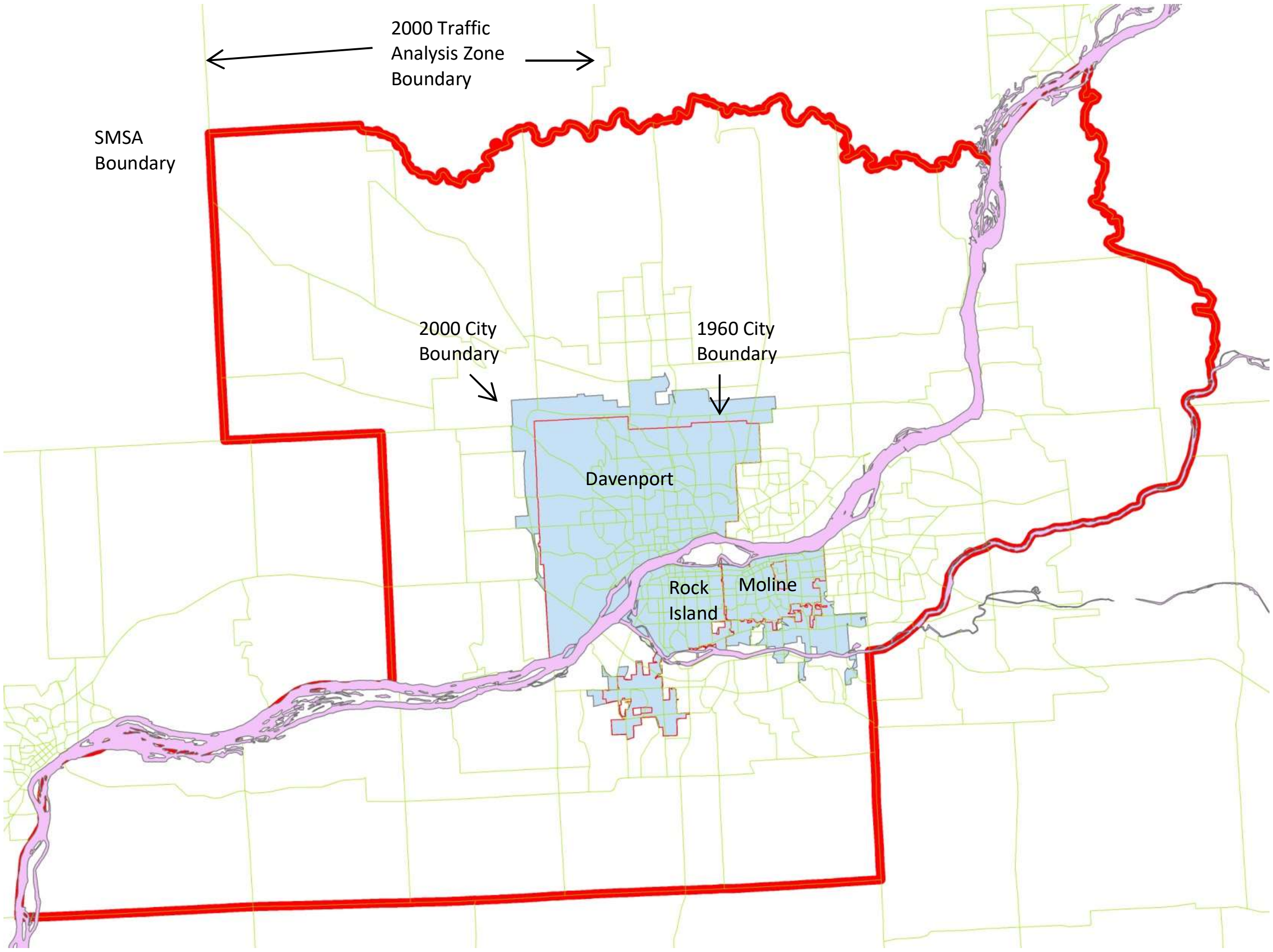
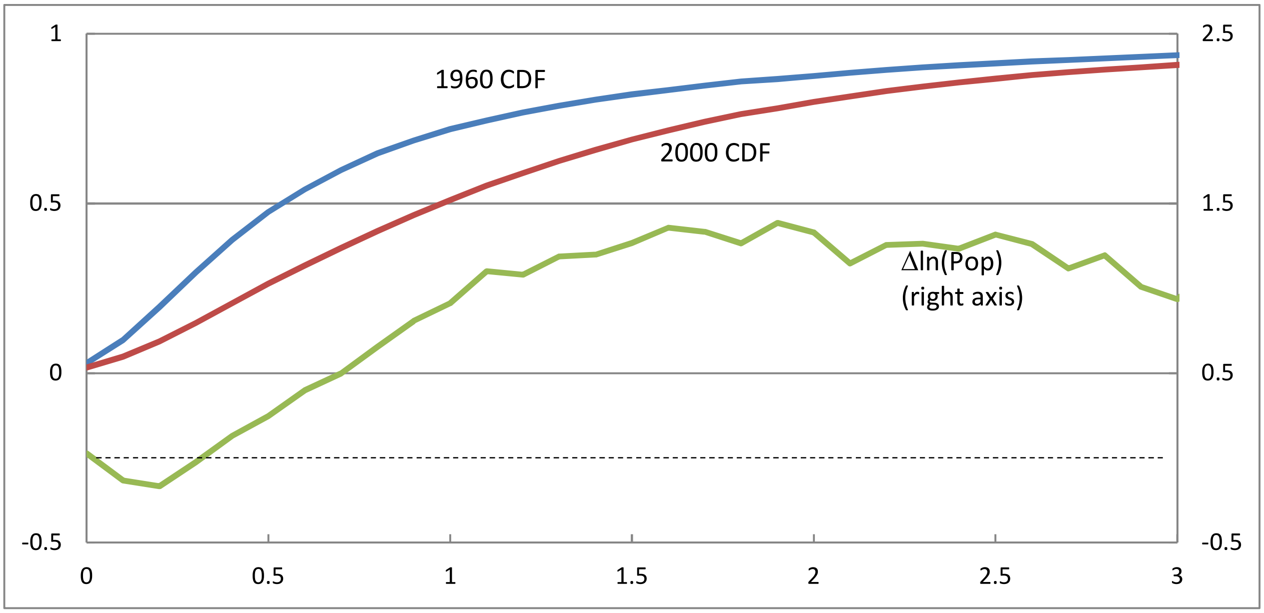
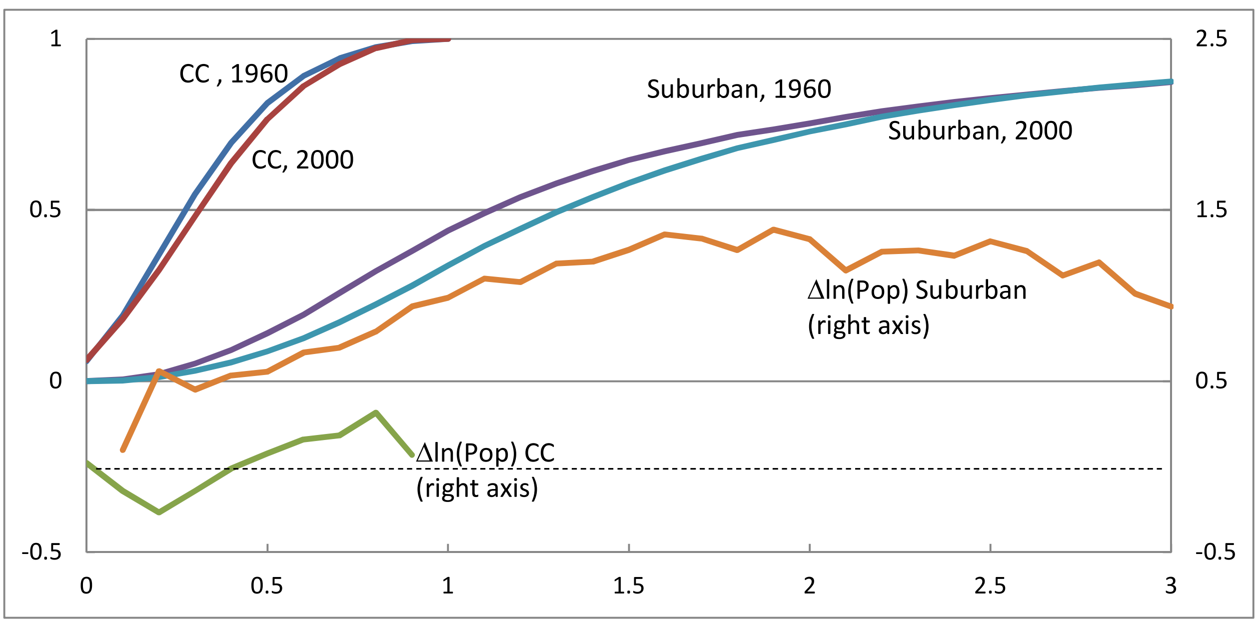


Figure 2: CDFs and Changes in Working Residential Population by Residential Location 1960-2000 (0=CBD, 1=Central City Edge)

Panel A: All Locations Pooled



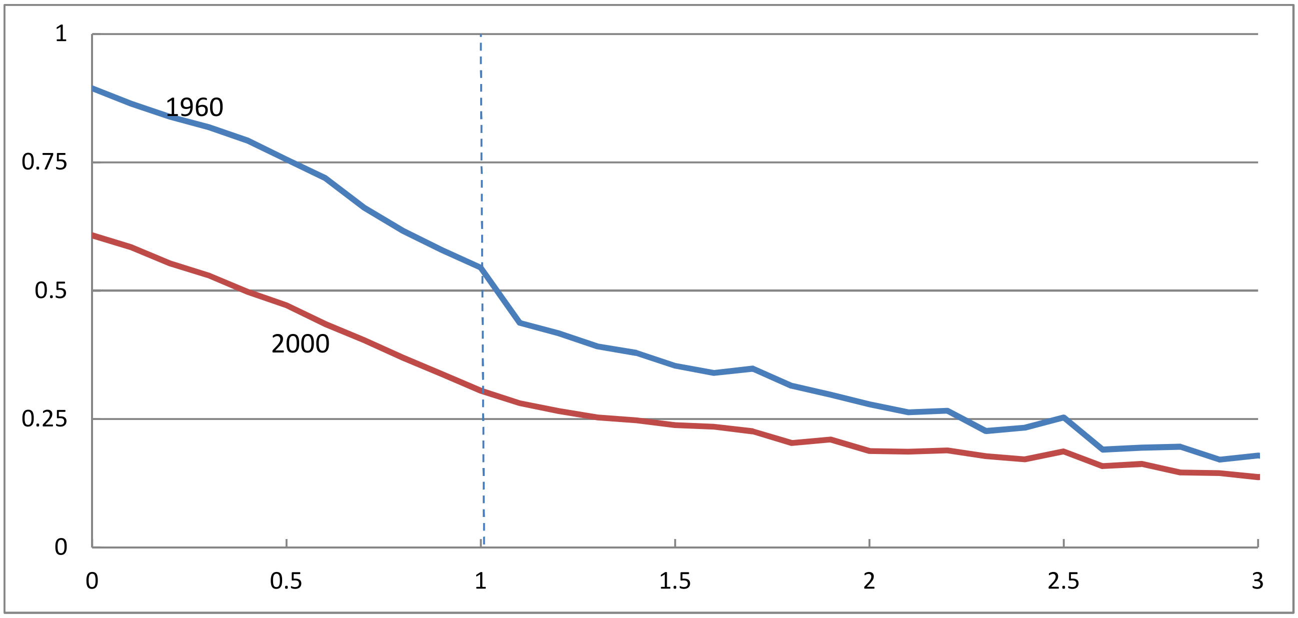
Panel B: Primary Central City and Suburban Residents Broken Out



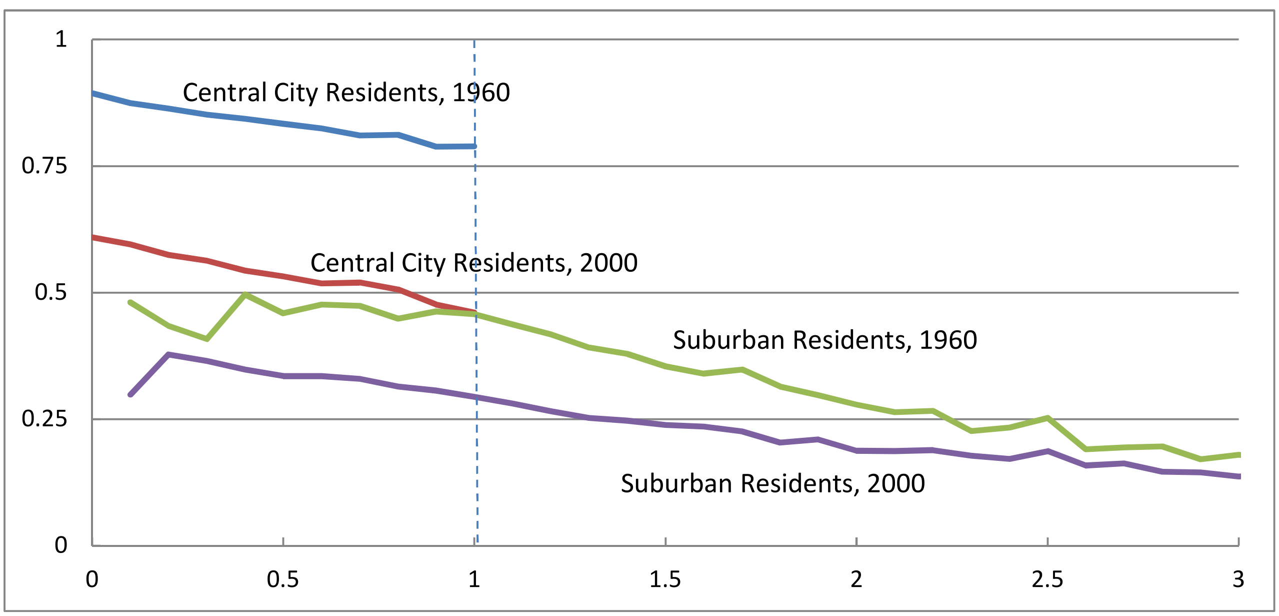
Notes: Plots show cumulative distribution functions of SMSA residents in 1960 and 2000. The distance index on the horizontal axis is 0 at the CBD and 1 at the furthest location on the edge of the primary central city. Suburban tracts with index values of less than 1 are closer to the CBD than the furthest central city location. 78 of the 100 SMSAs with at least 250,000 residents in 1960 contribute to the plots. The remaining 22 are not included because of missing or incomplete 1960 census tract information.

Figure 3: Average Fraction Commuting to Primary Central City by Residential Location (0=CBD, 1=Central City Edge)

Panel A: All Locations Pooled



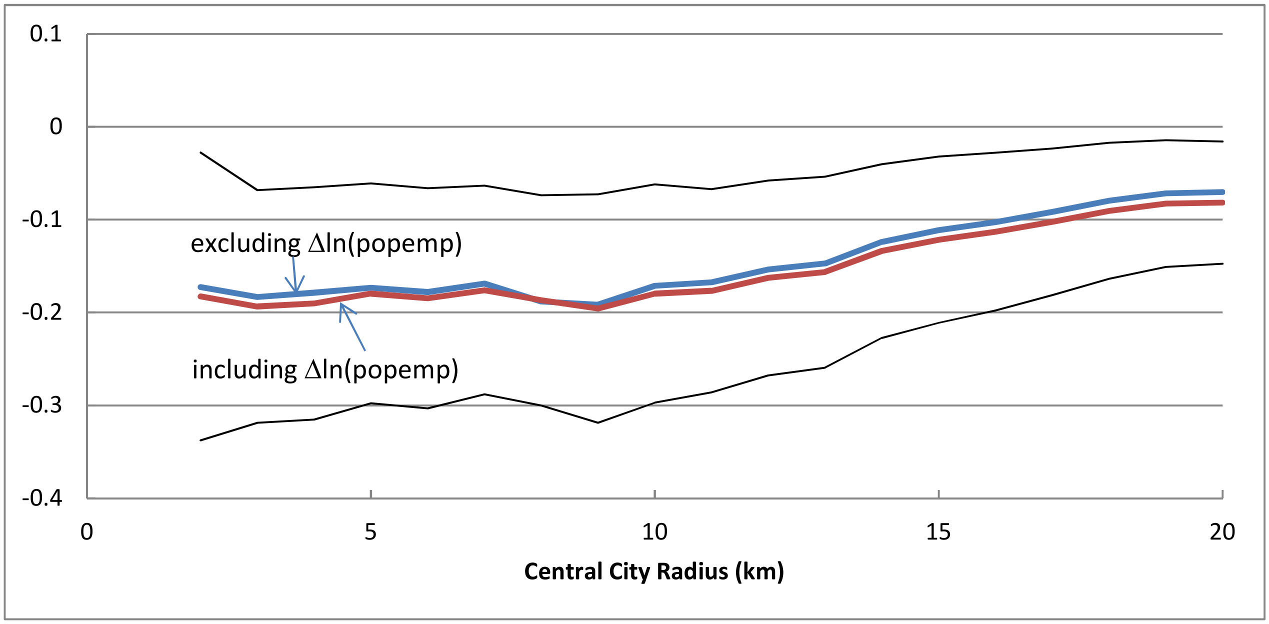
Panel B: Central City and Suburban Residents Broken Out



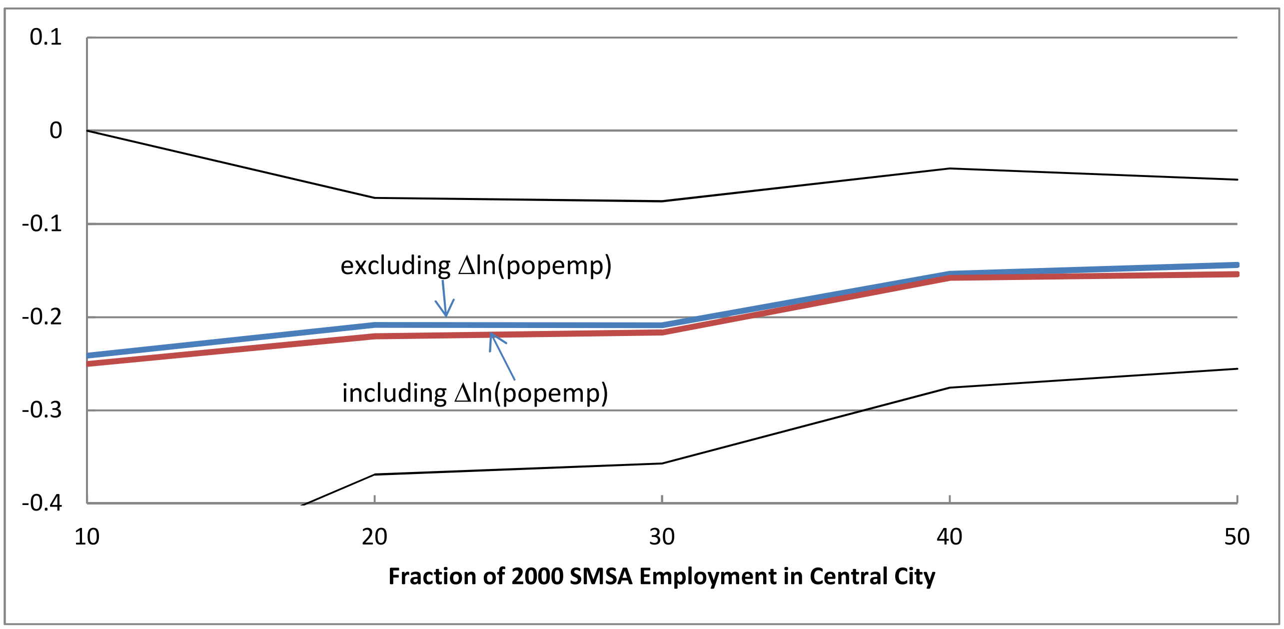
Notes: Plots show the fraction of workers in 1960 and 2000 commuting to a primary central city averaged across SMSAs The distance index on the horizontal axis is 0 at the CBD and 1 at the furthest location on the central city edge.

Figure 4: Estimated Effects of Highways on Central City Working Residents
Alternative Central City Definitions

Panel A: Central City Defined as Within Set Distances (km)



Panel B: Central City Defined as Containing Set Percentages of 2000 Employment



Notes: Each panel shows highway coefficients and 95 percent confidence intervals from regressions analogous to those in Table 6 Panel B Column 1 including (red lines) and exluding (blue lines) the control for change in log SMSA employment and residents, with robust standard errors. In Panel A, central cities are defined as being within the number of km of the CBD listed on the horizontal axis. In Panel B, central cities are defined as being within the radius associated with which each fraction of 2000 SMSA employment listed on the horizontal axis, calculated separately for each SMSA. Sample size ranges from 78 to 93, depending on 1960 census tract availability within the given CBD radius.

Table 1: Changes in Residential and Work Locations, 1960-2000
100 Metropolitan Areas With 1960 Populations Over 250,000

	1960	2000	Percent Change	Change in Fraction
Live in Central City	18.7	18.4	-0.01	-0.25
(fraction of total)	(0.49)	(0.24)		
Work in Central City	23.3	26.2	0.12	-0.28
(fraction of total)	(0.61)	(0.34)		
Live in SMSA	36.3	66.8	0.84	-0.10
(fraction of total)	(0.95)	(0.86)		
Work in SMSA	36.8	71.1	0.93	-0.05
(fraction of total)	(0.96)	(0.91)		
Live or Work in SMSA	38.1	78.1	1.05	

Notes: Counts are aggregates from the 100 metropolitan areas with 1960 populations over 250,000, expressed in millions of workers. Counts are calculated using 1960 and 2000 census journey to work data using 1960 SMSA definitions. Those contributing to residential counts may work anywhere and those contributing to worker counts may live anywhere. Data from 1960 incorporate the author's imputations for nonreported work locations. Data from 2000 incorporate such imputations done by the Census Bureau and the author.

Table 2: Changes in Residential and Work Locations by Industry, 1960-2000

	All	Manuf-acturing	Services	Trade	TCPU	Const-ruction	Public Admin.	FIRE	Military	Agric-ulture
Live in Central City										
1 1960 Fraction in CC	0.52	0.49	0.56	0.54	0.55	0.45	0.56	0.57	0.39	0.20
2 1960-2000 Change in CC Fraction	-0.24	-0.25	-0.25	-0.30	-0.26	-0.20	-0.28	-0.30	-0.18	-0.04
Work in Central City										
3 1960 Fraction in CC	0.63	0.60	0.64	0.67	0.73	0.56	0.68	0.79	0.40	0.21
4 1960-2000 Change in CC Fraction	-0.27	-0.33	-0.24	-0.39	-0.32	-0.24	-0.16	-0.37	-0.09	0.00
Live in Entire SMSA										
5 1960 Fraction of All	1.00	0.30	0.22	0.19	0.08	0.06	0.06	0.05	0.02	0.02
6 1960-2000 Change in Fraction of All	0.00	-0.17	0.21	-0.04	0.01	0.00	-0.01	0.03	-0.01	-0.01
Work in Entire SMSA										
7 1960 Fraction of All	1.00	0.30	0.22	0.19	0.08	0.06	0.06	0.05	0.02	0.02
8 1960-2000 Change in Fraction of All	0.00	-0.18	0.21	-0.04	0.01	0.01	-0.01	0.03	-0.01	-0.01

Notes: Counts used to construct entries are aggregated over all primary sample SMSAs. See the notes to Table 1 for an explanation of the sample and data sources. Because the 2000 Census Transportation Planning Package does not report commuting flows by industry, changes in counts of people by industry who either live or work in SMSAs are not available.

Table 3: Changes in Commuting Patterns, 1960-2000

		1960	2000	Change	Avg. 2000 Commute Time Weighted	Unweighted
Live in CC	Work in CC	16.5	12.0	-27%	27	19
		(0.43)	(0.16)	-0.28	1	1
Live in CC	Work in Ring	1.8	5.0	177%	30	26
		(0.05)	(0.06)	0.02	1.13	1.38
Live in CC	Work Outside SMSA	0.4	1.0	127%	46	46
		(0.01)	(0.01)	0.00	1.73	2.46
Live in Ring	Work in CC	5.9	10.7	82%	33	27
		(0.15)	(0.14)	-0.01	1.25	1.46
Live in Ring	Work in Ring	10.8	32.4	200%	22	20
		(0.28)	(0.42)	0.14	0.85	1.07
Live in Ring	Work Outside SMSA	0.9	4.4	384%	41	40
		(0.02)	(0.06)	0.03	1.53	2.14
Live Outside SMSA	Work in CC	1.0	3.9	294%	54	47
		(0.03)	(0.05)	0.02	2.02	2.52
Live Outside SMSA	Work in Ring	0.9	7.4	735%	43	41
		(0.02)	(0.10)	0.07	1.63	2.19
	Total	38.1	76.7	101%		

Notes: Each entry in the first two columns is the number of people with the indicated type of commute in the indicated year in millions. The fraction of total commutes in the indicated year is in parentheses. The 2000 total does not exactly match the total in Table 1 because the Census Bureau omits some difficult to impute flows in its Census Transportation Planning Package tables. Those working at home are counted as commuting within their regions of residence. Column 4 shows one-way commute times averaged across all workers in sampled SMSAs and ratios relative to the average within central city commute time. Column 5 shows mean SMSA one-way commute times averaged across sampled SMSAs and ratios relative to this measure of within central city commute time. Commuting times are not available for 1960.

Table 4: First Stage Results

Panel A: 1950 Base Year

	(1)	(2)	(3)
Planned Rays	0.53***	0.47***	0.47***
	(0.12)	(0.12)	(0.11)
1960 Central City Radius		0.11	0.10
		(0.10)	(0.09)
Change in Log SMSA Employment			0.32
+Workers, 1960-2000			(0.44)
Constant	1.13***	0.80*	0.62
	(0.33)	(0.44)	(0.52)
Adj. R-Squared	0.23	0.24	0.25

Panel B: 1960 Base Year

Planned Rays	0.36***	0.34***	0.33***
	(0.11)	(0.11)	(0.11)
1960 Central City Radius		0.04	0.03
		(0.09)	(0.09)
Change in Log SMSA Employment			0.29
+Workers, 1960-2000			(0.41)
Constant	0.94***	0.81*	0.65
	(0.31)	(0.43)	(0.53)
Adj. R-Squared	0.11	0.12	0.12

Notes: Regression results are of changes in actual radial highways constructed between 1950 and 2000 (Panel A) or 1960 and 2000 (Panel B) on the listed variables for the 100 SMSAs in the primary sample. Robust standard errors are in parentheses. Regressions using the number of radial highways in 2000 instead are statistically indistinguishible from those in Panel A. Additional inclusion of log 1950 SMSA population, 1940-1950 SMSA population growth and 1 digit SMSA employment shares from 1940 do not statistically influence planned rays coefficient estimates. Coefficients on planned rays in analogous regressions using a more complete sample of 164 SMSAs are statistically significant at 0.42 and 0.28 in Columns 2 or 3 of Panels A and B respectively.

Table 5: Effects of Highways on SMSA Employment and Working Residents by Industry
IV Estimates

	All	Manuf-acturing	Services	Trade	TCPU	Const-ruction	Public Admin.	FIRE	Military	Agric-ulture
Panel A: SMSA Employment										
Change in Rays	0.03	-0.11***	-0.00	-0.01	0.01	0.03	-0.06	0.04	0.05	-0.01
1950 to 2000	(0.05)	(0.04)	(0.01)	(0.01)	(0.03)	(0.03)	(0.04)	(0.03)	(0.13)	(0.06)
1960 Central City Radius	0.04*	0.05**	0.00	-0.01	-0.00	0.01	-0.02	-0.03**	-0.11**	0.03
	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.06)	(0.03)
Change in Log SMSA Employment		1.40***	0.82***	0.94***	1.15***	0.80***	0.83***	0.89***	0.51	0.39***
+Workers, 1960-2000		(0.09)	(0.03)	(0.02)	(0.05)	(0.05)	(0.07)	(0.05)	(0.35)	(0.13)
Constant	0.43***	-1.03***	0.74***	-0.18***	-0.07	0.01	0.21**	0.52***	-0.41	-1.18***
	(0.13)	(0.09)	(0.03)	(0.04)	(0.08)	(0.07)	(0.11)	(0.07)	(0.29)	(0.17)
Adj. R-Squared	0.07	0.75	0.91	0.93	0.84	0.80	0.54	0.77	0.06	0.17
Panel B: SMSA Working Residents										
Change in Rays	-0.00	-0.14***	-0.03	-0.05***	-0.02	-0.01	-0.09*	-0.00	-0.04	-0.05
1950 to 2000	(0.05)	(0.04)	(0.02)	(0.02)	(0.03)	(0.03)	(0.05)	(0.03)	(0.12)	(0.06)
1960 Central City Radius	0.05*	0.05**	0.01	-0.00	0.00	0.01	-0.01	-0.02*	-0.08	0.03
	(0.02)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.02)	(0.01)	(0.06)	(0.03)
Change in Log SMSA Employment		1.38***	0.81***	0.94***	1.12***	0.80***	0.81***	0.90***	0.52	0.43***
+Workers, 1960-2000		(0.10)	(0.04)	(0.03)	(0.05)	(0.06)	(0.07)	(0.05)	(0.36)	(0.13)
Constant	0.44***	-0.99***	0.74***	-0.17***	-0.07	0.01	0.21*	0.52***	-0.40	-1.18***
	(0.13)	(0.10)	(0.04)	(0.04)	(0.07)	(0.08)	(0.11)	(0.06)	(0.27)	(0.17)
Adj. R-Squared	0.05	0.71	0.85	0.87	0.83	0.75	0.51	0.78	0.07	0.12

Notes: Regressions are of the change in the log of outcomes listed in column headers on variables listed at left. These are Equations (3) and (4) in the text. The sample includes the same 100 SMSAs used for Tables 1 through 4. The change in the number of rays is instrumented with rays in the 1947 national plan. Robust standard errors are in parentheses. The estimated effect of highways on total SMSA employment plus resident workers is identical to that for all employment in Panel A. Excluding the change in log SMSA employment+workers yields no significant change in any highways coefficient. The first-stage F statistic for all industry level regressions is 16.75.

Table 6: Effects of Highways on Central City Employment and Working Residents by Industry
IV Estimates

	All	Manuf-acturing	Services	Trade	TCPU	Const-ruction	Public Admin.	FIRE	Military	Agric-ulture
Panel A: Central City Employment										
Change in Rays	-0.06*	-0.16***	-0.07**	-0.15***	-0.06	-0.05	-0.04	-0.02	0.07	0.15
1950 to 2000	(0.03)	(0.06)	(0.03)	(0.06)	(0.05)	(0.04)	(0.04)	(0.06)	(0.17)	(0.10)
1960 Central City Radius	0.05***	0.11***	0.05***	0.10***	0.07***	0.06***	-0.04**	0.05**	-0.11	-0.01
	(0.01)	(0.04)	(0.02)	(0.03)	(0.02)	(0.02)	(0.02)	(0.02)	(0.07)	(0.04)
Change in Log Total	0.81***	1.01***	0.58***	0.77***	0.87***	0.58***	0.78***	0.59***	0.48	0.37**
Employment+Residents	(0.07)	(0.12)	(0.06)	(0.10)	(0.06)	(0.08)	(0.08)	(0.09)	(0.34)	(0.15)
Constant	-0.56***	-1.71***	0.37***	-1.14***	-0.58***	-0.43***	0.06	-0.20	-0.70*	-1.44***
	(0.08)	(0.16)	(0.07)	(0.13)	(0.09)	(0.10)	(0.10)	(0.14)	(0.39)	(0.28)
Adj. R-Squared	0.66	0.43	0.50	0.44	0.63	0.46	0.50	0.36	0.04	0.13
Panel B: Central City Working Residents										
Change in Rays	-0.16***	-0.26***	-0.16***	-0.21***	-0.14**	-0.22***	-0.16***	-0.12**	-0.13	-0.07
1950 to 2000	(0.05)	(0.07)	(0.05)	(0.06)	(0.06)	(0.07)	(0.06)	(0.05)	(0.16)	(0.08)
1960 Central City Radius	0.09***	0.11***	0.09***	0.08***	0.09***	0.11***	0.05*	0.07***	-0.00	-0.04
	(0.02)	(0.03)	(0.02)	(0.03)	(0.02)	(0.03)	(0.03)	(0.02)	(0.08)	(0.03)
Change in Log Total	0.62***	1.02***	0.41***	0.52***	0.65***	0.61***	0.27***	0.42***	-0.50	0.14
Employment+Residents	(0.09)	(0.16)	(0.09)	(0.12)	(0.10)	(0.13)	(0.10)	(0.08)	(0.44)	(0.15)
Constant	-0.51***	-1.50***	0.30***	-0.65***	-0.57***	-0.45***	-0.29**	-0.12	-0.46	-0.66**
	(0.11)	(0.19)	(0.12)	(0.14)	(0.13)	(0.17)	(0.14)	(0.11)	(0.35)	(0.26)
Adj. R-Squared	0.32	0.22	0.06	-0.04	0.32	0.04	-0.04	0.21	0.01	-0.02

Notes: Regressions are of the change in the log of outcomes listed in column headers on variables listed at left. These are Equations (5) and (6) in the text. The sample includes the same 100 SMSAs used for Tables 1 through 4. The change in the number of rays is instrumented with rays in the 1947 national plan. Robust standard errors are in parentheses. Excluding the change in log SMSA employment+residents yields no significant change in any highways coefficient. The first stage F statistics for all regressions is 16.75. Each regression has 100 observations except that for the military in Panel A, which is missing Canton, OH because it had 0 reported central city military jobs in 2000.

Table 7: Implied Effects of Each Highway on Urban Decentralization by Industry

	Employment	Working Residents	Difference
All	-0.06*	-0.16***	0.10**
	(0.03)	(0.06)	(0.04)
All (Excluding control for	-0.04	-0.14**	0.10**
Δln popempSMSA)	(0.06)	(0.06)	(0.04)
Manufacturing	-0.08	-0.15***	0.07
	(0.05)	(0.05)	(0.06)
Services	-0.07**	-0.15***	0.08**
	(0.03)	(0.05)	(0.03)
Retail and Wholesale Trade	-0.14**	-0.19***	0.05
	(0.05)	(0.05)	(0.04)
TCPU	-0.07*	-0.13***	0.06
	(0.04)	(0.05)	(0.05)
Construction	-0.08**	-0.21***	0.14***
	(0.04)	(0.06)	(0.05)
Public Administration	0.01	-0.13***	0.14**
	(0.03)	(0.05)	(0.06)
FIRE	-0.04	-0.12***	0.07
	(0.05)	(0.05)	(0.05)
Military	0.01	-0.14	0.16
	(0.15)	(0.27)	(0.33)
Agriculture	0.16**	-0.05	0.21**
	(0.07)	(0.07)	(0.09)

Notes: Entries give estimated effects of one radial highway on the log of central city employment or working residents in the indicated industry holding the composition of SMSA industries constant. Equations (3), (4), (5) and (6) in the text plus a first stage equation that are jointly estimated by three-stage least squares are used along with (7) and (8) to generate reported coefficients and standard errors clustered by SMSA. GMM point estimates are identical.

Table 8: Estimated Effects of Highways on Aggregate Commuting Flows

	Work in Central City	Work in Ring	Work Outside SMSA
Panel A: Central City Residents			
Change in Rays	-0.16***	-0.03	-0.03
1950 to 2000	(0.05)	(0.06)	(0.07)
1960 Central City Radius	0.14***	0.07**	0.07***
	(0.02)	(0.03)	(0.02)
Change in Log Total	0.50***	0.77***	0.07
Employment+Residents	(0.10)	(0.10)	(0.14)
Constant	-1.11***	0.22	0.66***
	(0.12)	(0.14)	(0.17)
Panel B: Suburban Residents			
Change in Rays	-0.06	0.11**	0.07
1950 to 2000	(0.08)	(0.05)	(0.08)
1960 Central City Radius	0.10**	0.02	0.05
	(0.04)	(0.02)	(0.03)
Change in Log Total	1.08***	1.25***	0.84***
Employment+Residents	(0.16)	(0.09)	(0.12)
Constant	-0.36**	-0.14	0.95***
	(0.18)	(0.12)	(0.16)
Panel C: Residents Outside SMSA Who Work in SMSA			
Change in Rays	-0.09	0.22**	
1950 to 2000	(0.06)	(0.08)	
1960 Central City Radius	0.13***	0.02	
	(0.02)	(0.03)	
Change in Log Total	0.88***	1.32***	
Employment+Residents	(0.11)	(0.14)	
Constant	0.36**	0.52**	
	(0.14)	(0.21)	

Notes: Each column in each panel shows regression results of the change in the log number of indicated commuters between 1960 and 2000 on variables listed at left. Radial highways in the 1947 national plan instruments for the change in the number of rays 1950 to 2000. Robust standard errors are in parentheses. The first-stage F-statistic for each regression is 16.75.

Table 9: Base Parameter Values

Parameter	Description		Man.	Services	Trade	TCPU	Cons.	FIRE	Agric.
$\Delta t/\Delta hwy$	Change in central city commuting time for each additional highway	-0.01							
η	Income elasticity of demand for housing	0.7							
ε	Price elasticity of demand for housing	-1							
σ_H	Share of income spent on housing	0.17							
θ_L	Land share in production of housing	0.233							
θ_K	Capital Share in the production of housing	0.15							
θ_N	Labor share in the production of housing	0.617							
ϕ_L	Land share in production of tradeables	0.025	0.024	0.005	0.015	0.015	0.007	0.038	0.161
ϕ_K, μ	Capital Share in the production of tradeables	0.15	0.349	0.223	0.244	0.428	0.165	0.555	0.354
ϕ_N, γ	Labor share in the production of tradeables	0.825	0.627	0.772	0.741	0.556	0.828	0.407	0.485
$X_c/(L_c-X_c)$	Fraction of CC space taken up by production	0.48							
t	Fraction of time spent commuting for within central city commuters	0.06							
c_{sc}	Ratio of commuting time suburb-city versus city-city	1.75							
c_s	Ratio of commuting time suburb-suburb versus city-city	1.36							
dlnh/dt	The direct elasticity of TFP with respect to commuting time	-1							

Notes: Parameters' base calibration values are based on estimates in the literature, as explained in the text. Commuting cost parameters are calibrated using 2000 commuting data for primary sample SMSAs. Industry cost shares are taken from the KLEMS data.

Table 10: Agglomeration Parameters by Industry

Parameters		$dlng_c/dlnN_c$ - $dlng_s/dlnN_c$							
ϕ_N, γ	$\Delta t/\Delta hwy$	All	Manufacturing	Services	Trade	TCPU	Construction	FIRE	Agriculture
Panel A: Common Cost Share Parameters									
0.6	-0.01	0.073	0.055	0.063	0.031	0.063	0.055	0.110	-0.027
0.65	-0.01	0.076	0.057	0.065	0.033	0.065	0.057	0.114	-0.029
0.7	-0.01	0.079	0.060	0.068	0.034	0.068	0.060	0.119	-0.030
0.75	-0.01	0.083	0.062	0.071	0.035	0.071	0.062	0.124	-0.031
0.8	-0.01	0.086	0.064	0.073	0.037	0.073	0.064	0.129	-0.032
0.85	-0.01	0.089	0.067	0.076	0.038	0.076	0.067	0.133	-0.033
0.825	-0.005	0.044	0.033	0.037	0.019	0.037	0.033	0.065	-0.016
0.825	-0.01	0.087	0.065	0.075	0.037	0.075	0.065	0.131	-0.033
0.825	-0.015	0.131	0.098	0.112	0.056	0.112	0.098	0.196	-0.049
0.7	-0.005	0.040	0.030	0.034	0.017	0.034	0.030	0.060	-0.015
0.7	-0.01	0.079	0.060	0.068	0.034	0.068	0.060	0.119	-0.030
0.7	-0.015	0.119	0.089	0.102	0.051	0.102	0.089	0.179	-0.045
Panel B: Industry-Specific Cost Share Parameters									
	-0.005	0.044	0.028	0.024	0.015	0.024	0.023	0.060	-0.049
	-0.0075	0.065	0.041	0.036	0.022	0.036	0.035	0.089	-0.073
	-0.01	0.087	0.055	0.048	0.029	0.048	0.046	0.119	-0.097
	-0.0125	0.109	0.069	0.060	0.036	0.060	0.058	0.149	-0.121
	-0.015	0.131	0.083	0.071	0.044	0.072	0.070	0.179	-0.146

Notes: Entries quantify the aggregate own versus cross region agglomeration spillovers in a metropolitan area, as is described in the text, for each listed industry and combination of parameter values. Results in Panel A use common cost share parameters across columns. Results in Panel B use industry-specific cost shares taken from KLEMs data for the U.S. Additional calibrated parameter values are in Table 9.

Table 11: Mechanisms Through Which Highways Cause Suburbanization

			Components of $d\ln Q_c/dhwy$ if $d\ln g_c/dN_c=0$ & $d\ln h/dt=0$								Additional	Additional	
	Parameters		Price & Income Effects				Housing Factor Realloc.		Firm GE Effects		From	From	
ϕ_N, γ	$\Delta t/\Delta hwy$	η	A	B	C	D	E	F	G	H	$d\ln h/dt=-1$	$d\ln g_c/d\ln N_c$	
0.6	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.043	0.029	-0.020	0.004	-0.123
0.65	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.043	0.029	-0.018	0.004	-0.114
0.7	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.043	0.029	-0.017	0.004	-0.106
0.75	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.043	0.029	-0.016	0.004	-0.099
0.8	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.042	0.029	-0.015	0.004	-0.092
0.85	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.042	0.029	-0.014	0.004	-0.087
0.825	-0.005	0.7	-0.004	-0.010	-0.001	0.001	-0.001	-0.033	-0.021	0.029	-0.007	0.002	-0.045
0.825	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.042	0.029	-0.014	0.004	-0.090
0.825	-0.015	0.7	-0.011	-0.030	-0.003	0.002	-0.002	-0.098	-0.064	0.029	-0.022	0.006	-0.135
0.7	-0.005	0.7	-0.004	-0.010	-0.001	0.001	-0.001	-0.033	-0.021	0.029	-0.008	0.002	-0.053
0.7	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.065	-0.043	0.029	-0.017	0.004	-0.106
0.7	-0.015	0.7	-0.011	-0.030	-0.003	0.003	-0.003	-0.098	-0.064	0.029	-0.025	0.006	-0.159
0.6	-0.01	1	-0.010	-0.020	-0.004	0.002	-0.002	-0.065	-0.043	0.029	-0.025	0.005	-0.155
0.65	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.043	0.029	-0.023	0.005	-0.143
0.7	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.043	0.029	-0.021	0.005	-0.132
0.75	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.043	0.029	-0.020	0.005	-0.124
0.8	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.042	0.029	-0.019	0.005	-0.116
0.85	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.042	0.029	-0.017	0.005	-0.109
0.825	-0.005	1	-0.005	-0.010	-0.001	0.001	-0.001	-0.033	-0.021	0.029	-0.009	0.002	-0.056
0.825	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.042	0.029	-0.018	0.005	-0.112
0.825	-0.015	1	-0.015	-0.030	-0.004	0.002	-0.002	-0.098	-0.064	0.029	-0.027	0.007	-0.169
0.7	-0.005	1	-0.005	-0.010	-0.002	0.001	-0.001	-0.033	-0.021	0.029	-0.011	0.003	-0.066
0.7	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.065	-0.043	0.029	-0.021	0.005	-0.132
0.7	-0.015	1	-0.015	-0.030	-0.005	0.003	-0.003	-0.098	-0.064	0.029	-0.032	0.008	-0.199

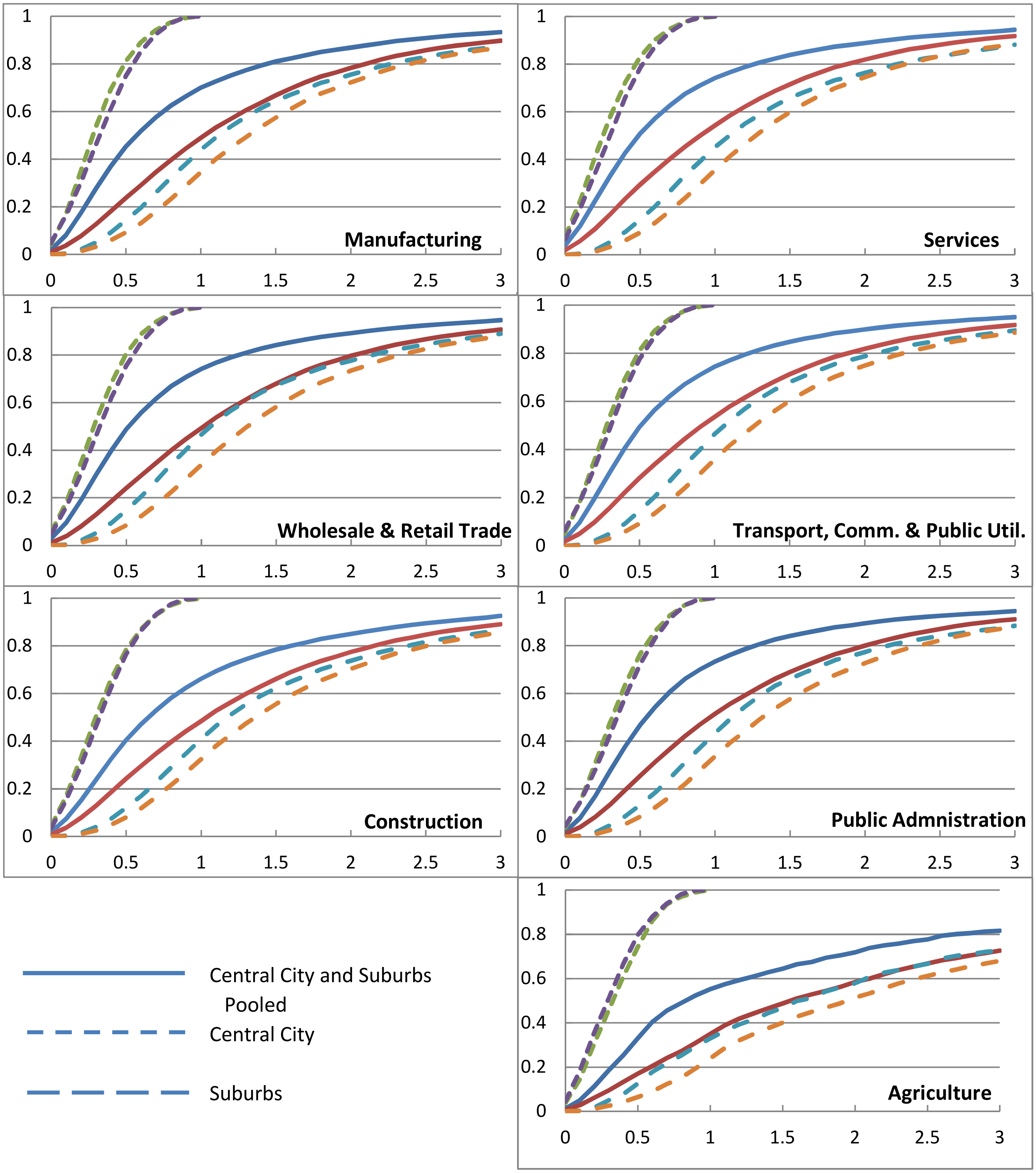
Notes: Entries give components of the estimated treatment effect of each radial highway on the log of central city resident workers of -0.16. Each component A through H is mathematically specified in (21) and explained in the text. Contributions from component I are incorporated in the final columns of the table. Entries in the final column assume that $d\ln g_c/d\ln N_c$ is one-half of the numbers reported in the "All" column of Table 10.

Table 12: Welfare Consequences of Each New Radial Highway

Parameters			increase in real income				increase in real home cost				CC rent incr.
ϕ_N, γ	$\Delta t/\Delta hwy$	h	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
0.6	-0.01	0.7	1.4%	3.0%	1.0%	2.7%	-1.8%	-0.7%	-2.0%	-1.0%	-8.5%
0.65	-0.01	0.7	1.3%	2.9%	1.0%	2.5%	-1.8%	-0.8%	-2.0%	-1.1%	-8.5%
0.7	-0.01	0.7	1.3%	2.7%	1.0%	2.4%	-1.8%	-0.9%	-2.0%	-1.1%	-8.5%
0.75	-0.01	0.7	1.3%	2.6%	1.0%	2.3%	-1.8%	-1.0%	-2.0%	-1.2%	-8.5%
0.8	-0.01	0.7	1.3%	2.5%	0.9%	2.2%	-1.8%	-1.0%	-2.0%	-1.2%	-8.5%
0.85	-0.01	0.7	1.3%	2.4%	0.9%	2.1%	-1.8%	-1.1%	-2.0%	-1.3%	-8.5%
0.825	-0.005	0.7	0.6%	1.2%	0.5%	1.1%	-0.9%	-0.5%	-1.0%	-0.6%	-4.3%
0.825	-0.01	0.7	1.3%	2.5%	0.9%	2.2%	-1.8%	-1.1%	-2.0%	-1.3%	-8.5%
0.825	-0.015	0.7	1.9%	3.7%	1.4%	3.2%	-2.7%	-1.6%	-3.0%	-1.9%	-12.8%
0.7	-0.005	0.7	0.7%	1.4%	0.5%	1.2%	-0.9%	-0.5%	-1.0%	-0.6%	-4.3%
0.7	-0.01	0.7	1.3%	2.7%	1.0%	2.4%	-1.8%	-0.9%	-2.0%	-1.1%	-8.5%
0.7	-0.015	0.7	2.0%	4.1%	1.4%	3.6%	-2.7%	-1.4%	-3.0%	-1.7%	-12.8%
0.6	-0.01	1	1.4%	3.0%	1.0%	2.7%	-1.8%	-0.7%	-2.0%	-1.0%	-8.5%
0.65	-0.01	1	1.3%	2.9%	1.0%	2.5%	-1.8%	-0.8%	-2.0%	-1.1%	-8.5%
0.7	-0.01	1	1.3%	2.7%	1.0%	2.4%	-1.8%	-0.9%	-2.0%	-1.1%	-8.5%
0.75	-0.01	1	1.3%	2.6%	1.0%	2.3%	-1.8%	-1.0%	-2.0%	-1.2%	-8.5%
0.8	-0.01	1	1.3%	2.5%	0.9%	2.2%	-1.8%	-1.0%	-2.0%	-1.2%	-8.5%
0.85	-0.01	1	1.3%	2.4%	0.9%	2.1%	-1.8%	-1.1%	-2.0%	-1.3%	-8.5%
0.825	-0.005	1	0.6%	1.2%	0.5%	1.1%	-0.9%	-0.5%	-1.0%	-0.6%	-4.3%
0.825	-0.01	1	1.3%	2.5%	0.9%	2.2%	-1.8%	-1.1%	-2.0%	-1.3%	-8.5%
0.825	-0.015	1	1.9%	3.7%	1.4%	3.2%	-2.7%	-1.6%	-3.0%	-1.9%	-12.8%
0.7	-0.005	1	0.7%	1.4%	0.5%	1.2%	-0.9%	-0.5%	-1.0%	-0.6%	-4.3%
0.7	-0.01	1	1.3%	2.7%	1.0%	2.4%	-1.8%	-0.9%	-2.0%	-1.1%	-8.5%
0.7	-0.015	1	2.0%	4.1%	1.4%	3.6%	-2.7%	-1.4%	-3.0%	-1.7%	-12.8%
Impose dlnh/dt=0?			Yes	No	Yes	No	Yes	No	Yes	No	Yes/No
Impose $dlng_c/dlnN_c$=0?			Yes	Yes	No	No	Yes	Yes	No	No	Yes/No

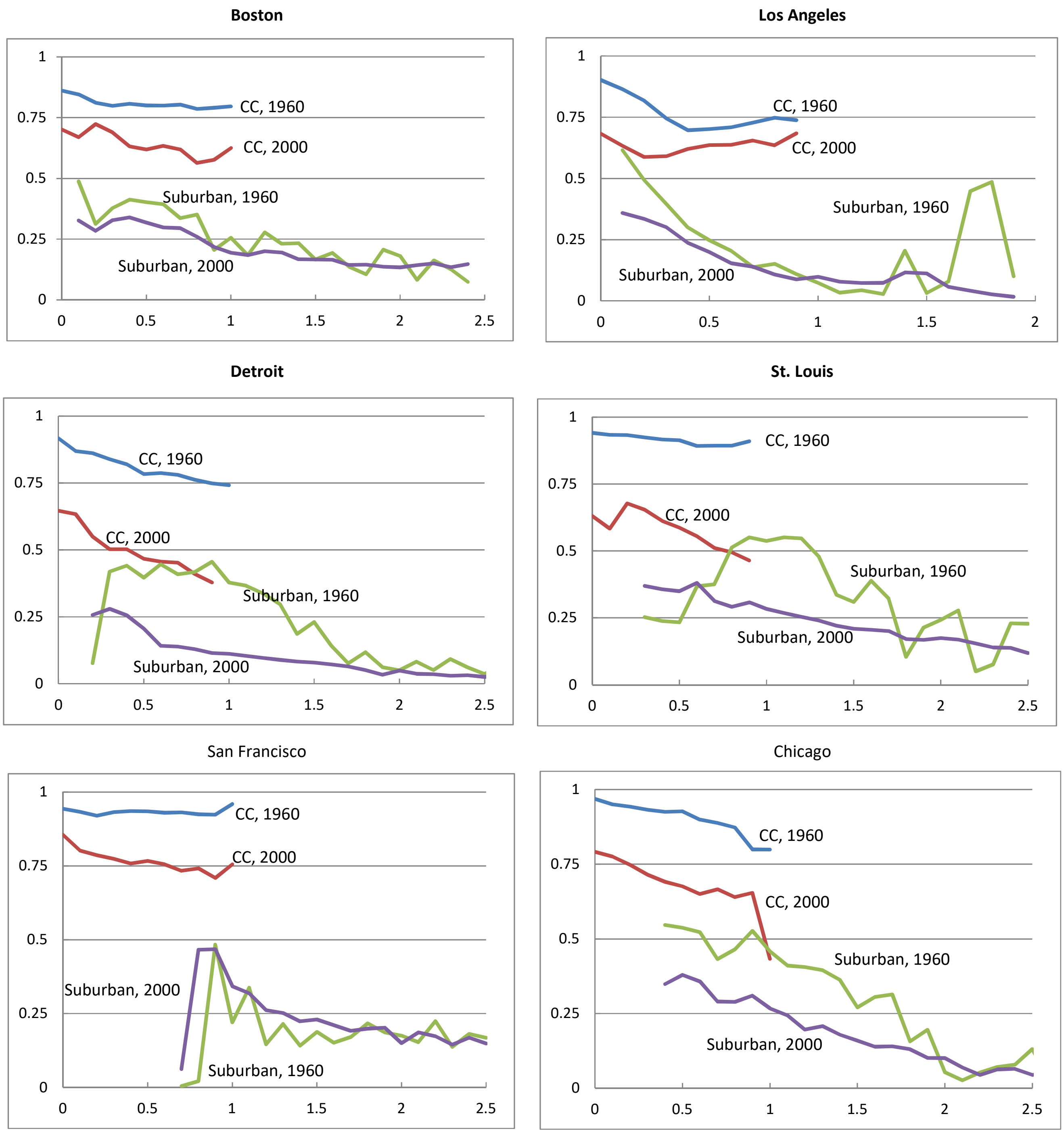
Notes: Entries indicate elements of the three components of welfare consequences of one new highway ray given assumptions about dlnh/dt and the strength of the local agglomeration force $dlng_c/dlnN_c$. For columns in which dlnh/dt is nonzero, it is set to -1. For columns in which $dlng_c/dlnN_c$ is nonzero, it is set to one-half of the entry in Table 10 for all employment and indicated parameter values. Entries in the final column do not depend on these two quantities.

Figure A1: CDFs of Working Residents by Residential Location and Industry (1=Central City Edge)



Notes: Plots are analogous to those in Figure 2 except they are broken out by industry of resident workers. Within spatially defined category, the upper left plot always applies to 1960 and the lower right plot always applies to 2000.

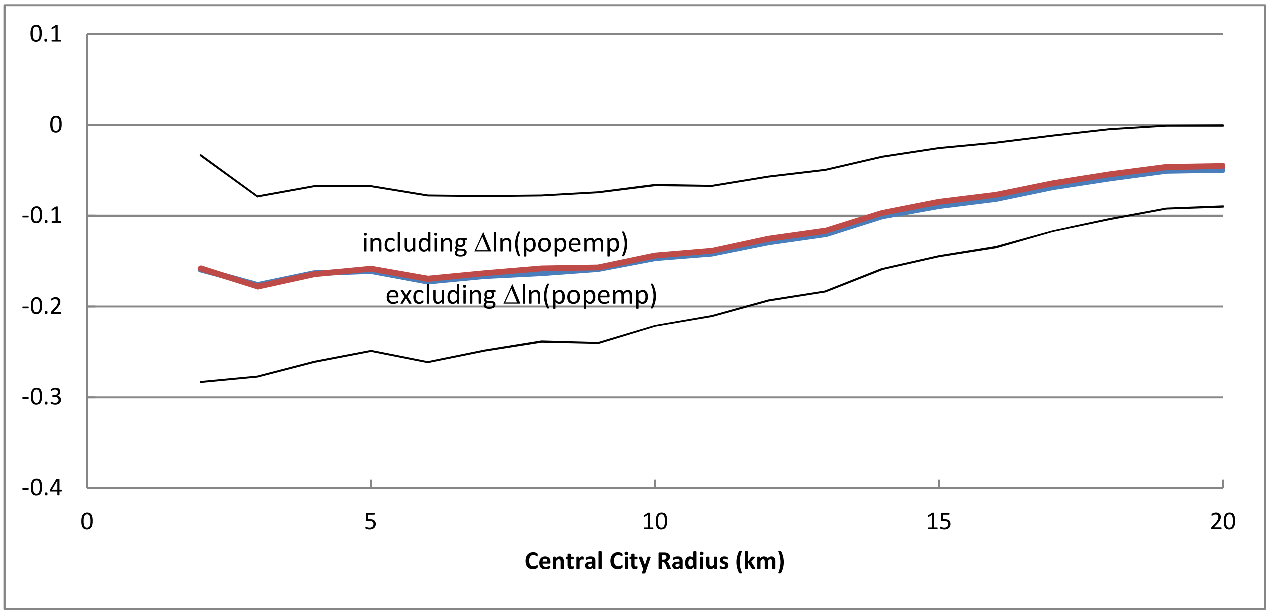
Figure A2: Fraction Commuting to Primary Central City: Example Cities



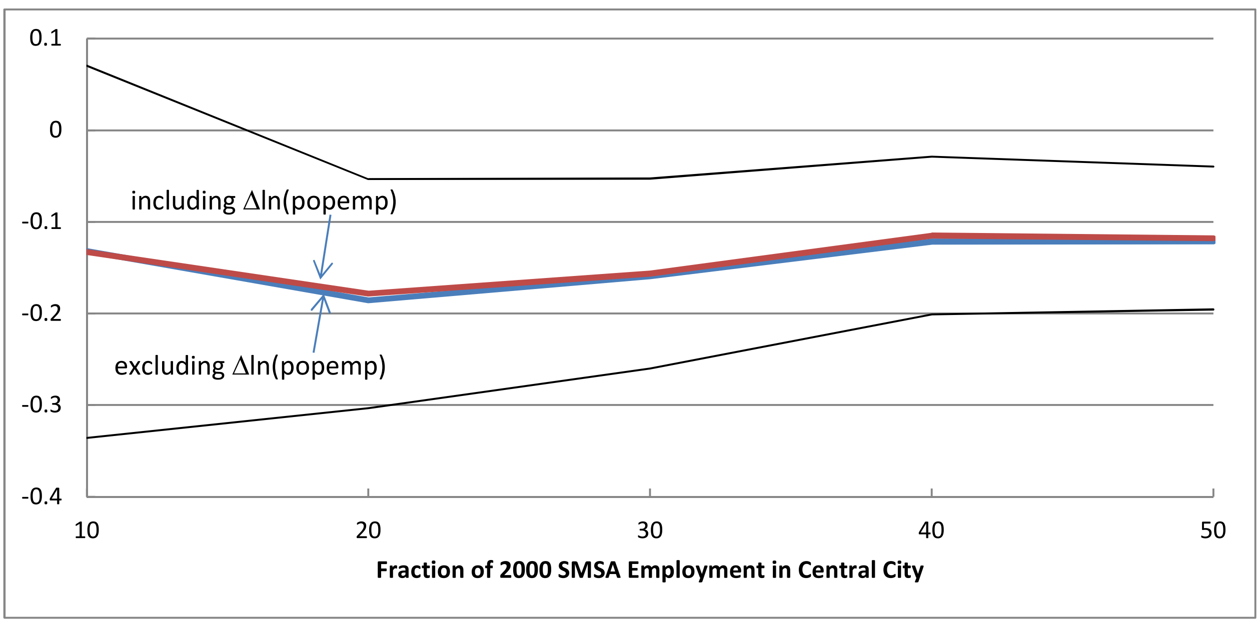
Notes: Each plot is analogous to Figure 3, Panel B but for one SMSA only. The Los Angeles SMSA only extends out to about twice the radius of the Los Angeles city limits. Other SMSAs are truncated at index value 2.5.

Figure A3: Estimated Effects of Highways on Central City Working Residents
Alternative Central City Definitions - Complete Sample

Panel A: Central City Defined as Within Set Distances (km)



Panel B: Central City Defined as Containing Set Percentages of 2000 Employment



Notes: Graphs are analogous to those in Figure 4, except that they use a more complete sample of SMSAs and only control for the change in SMSA population, rather than the number of people who live or work in the SMSA. Confidence intervals reflect robust standard errors. Depending on availability of 1960 tract data at different CBD distances, the sample size ranges from 125 to 154.

Table A1: Summary Statistics

Variable	Industry	Mean	Sd	p25	p50	p75
Planned Rays	NA	2.9	1.5	2	3	4
1960 Central City Radius	NA	4.4	2.1	2.9	4.1	5.2
Change in log Total Employment+Residents	NA	0.73	0.41	0.44	0.65	0.96
Change in Rays 1950 to 2000	NA	2.7	1.7	2	2	4
Change in Rays 1960 to 2000	NA	2.0	1.6	0.5	2	3
Change in log SMSA Employment	All	0.68	0.42	0.37	0.60	0.91
	Manufacturing	-0.07	0.63	-0.53	-0.15	0.39
	Services	1.36	0.35	1.13	1.28	1.53
	Trade	0.46	0.39	0.16	0.39	0.69
	TCPU	0.81	0.51	0.49	0.78	1.07
	Construction	0.72	0.37	0.45	0.70	0.88
	Public Admin.	0.57	0.44	0.30	0.55	0.82
	FIRE	1.15	0.41	0.85	1.08	1.40
	Military	-0.39	0.97	-1.00	-0.26	0.25
	Agriculture	-0.76	0.43	-1.03	-0.80	-0.52
Change in log SMSA Residents	All	0.63	0.41	0.33	0.52	0.85
	Manufacturing	-0.11	0.62	-0.56	-0.28	0.34
	Services	1.31	0.35	1.05	1.23	1.50
	Trade	0.41	0.39	0.14	0.30	0.65
	TCPU	0.74	0.50	0.41	0.67	0.99
	Construction	0.64	0.38	0.39	0.61	0.82
	Public Admin.	0.51	0.43	0.24	0.49	0.76
	FIRE	1.10	0.41	0.79	1.02	1.36
	Military	-0.47	0.94	-1.21	-0.28	0.16
	Agriculture	-0.85	0.42	-1.08	-0.89	-0.64
Change in log Central City Employment	All	0.11	0.42	-0.17	0.04	0.39
	Manufacturing	-0.88	0.64	-1.38	-0.91	-0.46
	Services	0.84	0.33	0.61	0.80	1.01
	Trade	-0.51	0.50	-0.89	-0.55	-0.15
	TCPU	0.20	0.47	-0.12	0.10	0.48
	Construction	0.11	0.38	-0.17	0.08	0.38
	Public Admin.	0.34	0.44	0.05	0.30	0.60
	FIRE	0.41	0.45	0.09	0.43	0.70
	Military	-0.65	1.10	-1.14	-0.45	0.07
	Agriculture	-0.81	0.61	-1.13	-0.80	-0.39
Change in log Central City Resident Workers	All	-0.09	0.36	-0.35	-0.14	0.11
	Manufacturing	-0.91	0.59	-1.32	-0.99	-0.57
	Services	0.58	0.34	0.34	0.54	0.80
	Trade	-0.46	0.39	-0.75	-0.51	-0.21
	TCPU	-0.06	0.44	-0.32	-0.12	0.21
	Construction	-0.09	0.44	-0.42	-0.09	0.17
	Public Admin.	-0.29	0.38	-0.53	-0.26	-0.07
	FIRE	0.19	0.36	-0.08	0.20	0.40
	Military	-1.18	1.17	-1.73	-1.15	-0.31
	Agriculture	-0.89	0.56	-1.26	-0.91	-0.54

Notes: Summary statistics are given for the primary sample of 100 SMSAs.

Table A2: Effects of Highways on Central City Workers and Residents by Industry
OLS Estimates

	All	Manuf-acturing	Services	Trade	TCPU	Const-ruction	Public Admin.	FIRE	Military	Agric-ulture
Panel A: Central City Workers in Listed Industry										
Change in Rays	-0.02*	-0.06**	-0.02	-0.06***	-0.01	-0.03	-0.03*	-0.01	-0.00	0.09**
1950 to 2000	(0.01)	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.06)	(0.04)
1960 Central City Radius	0.04***	0.09***	0.04***	0.08***	0.05***	0.05***	-0.05***	0.05**	-0.09	0.00
	(0.01)	(0.03)	(0.01)	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)	(0.07)	(0.03)
Change in Log Total	0.79***	0.97***	0.56***	0.74***	0.85***	0.57***	0.78***	0.59***	0.51	0.40**
Employment+Residents	(0.06)	(0.11)	(0.05)	(0.08)	(0.06)	(0.08)	(0.08)	(0.09)	(0.33)	(0.16)
Constant	-0.61***	-1.85***	0.30***	-1.25***	-0.64***	-0.47***	0.04	-0.20	-0.61*	-1.36***
	(0.06)	(0.13)	(0.06)	(0.10)	(0.07)	(0.09)	(0.09)	(0.12)	(0.31)	(0.24)
R-Squared	0.68	0.50	0.58	0.52	0.66	0.47	0.50	0.36	0.05	0.15
Panel B: Central City Residents Working in Listed Industry										
Change in Rays	-0.05***	-0.06***	-0.04**	-0.06***	-0.04**	-0.06***	-0.06***	-0.05**	0.01	0.01
1950 to 2000	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.07)	(0.03)
1960 Central City Radius	0.06***	0.07***	0.06***	0.05***	0.07***	0.07***	0.03*	0.05***	-0.03	-0.05**
	(0.01)	(0.02)	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.06)	(0.02)
Change in Log Total	0.58***	0.94***	0.36***	0.46***	0.61***	0.54***	0.23**	0.39***	-0.55	0.11
Employment+Residents	(0.08)	(0.12)	(0.07)	(0.10)	(0.09)	(0.09)	(0.11)	(0.07)	(0.45)	(0.13)
Constant	-0.66***	-1.76***	0.14**	-0.85***	-0.70***	-0.66***	-0.43***	-0.21**	-0.64**	-0.76***
	(0.06)	(0.11)	(0.07)	(0.09)	(0.09)	(0.11)	(0.09)	(0.09)	(0.30)	(0.21)
R-Squared	0.59	0.51	0.37	0.34	0.45	0.42	0.14	0.31	0.04	0.04

Notes: Regression models are identical to those estimated in Table 6 except that the change in rays 1950 to 2000 is not instrumented.