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Urban Transport Expansions and Changes in the Spatial Structure of US Cities: Implications for Productivity and Welfare

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Abstract: Each new radial highway serving large US metro areas decentralized 14-16% of central city working residents and 4-6% of jobs in the 1960-2000 period. Model calibrations yield implied elasticities of central city TFP to central city employment relative to suburban employment of 0.04-0.09, meaning a large fraction of agglomeration economies operates at sub-metro area spatial scales. Each additional highway causes central city income net of commuting costs to increase by up to 2.4% and housing cost to decline by up to 1.3%. Factor reallocation toward land in housing production generates the plurality of the population decentralization caused by new highways.

1 Introduction

Between 1960 and 2000, each large US metro area experienced population decentralization and all but four experienced employment decentralization. Central cities of the largest 100 US metro areas collectively hosted 49 percent of the residents and 61 percent of the jobs in 1960. These numbers fell to just 24 percent and 34 percent respectively by 2000, with similar declines for the average metro area. There is a broad consensus that increased travel speeds have promoted urban population decentralization. Baum-Snow (2007a) and Baum-Snow et al. (2017) show that highways drove such decentralization in the US and China during the 1950-1990 and 1990-2010 periods respectively and Heblich et al. (2018) show that commuter railroads promoted population decentralization but employment centralization in London during the 1850-1920 period. However, there remains little unified empirical evidence on how changes in the joint spatial distributions of population and employment by industry

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within cities have been influenced by improved transport infrastructure. Moreover, while there exists a rich history of related urban theory going back to Fujita & Ogawa (1982), there remains little quantitative evidence on the productivity advantages of density at spatial scales below the metro area level for a broad range of cities. As quantifying the welfare impacts of new highways depends in part on knowledge of such agglomeration parameters, the literature also provides little evidence on welfare consequences that accrue via new highways' impacts on the internal organization of cities.

This paper employs treatment effects estimated from newly assembled data in a model to quantify the strengths of localized productivity spillovers by industry and the welfare consequences of new highways. The model additionally facilitates quantification of the relative importance of various mechanisms through which highways have promoted population decentralization. As in Baum-Snow (2007a), treatment effects of highways are recovered using planned portions of the US national highway system as a source of exogenous variation. Estimated treatment effects do not depend on model structure, and thus can be interpreted in the context of a wide range of theories of urban economic geography. The model developed for quantification is in the tradition of Roback (1982) and Fujita & Ogawa (1982) but is tailored to fit the spatial structure of the data used in the empirical work and accommodate calibration using the estimated treatment effects and standard cost and expenditure share parameters. The quantitative analysis incorporates the potential for new highways to influence agglomeration spillovers both within and between cities and their surrounding suburbs because of the shifts to firm and residential location incentives that come with reduced commuting costs. The focus is on each highway's impacts on spatial organization and welfare within a closed city setup, thereby complementing Duranton & Turner's (2012) analysis of transportation's impacts on urban growth in an open city environment.

Treatment effect estimates indicate that while each radial highway decentralized 14-16 percent of central city working residents to suburbs, only 4-6 percent of jobs were displaced. This statistically significant difference amounts to greater residential than employment decentral-

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ization 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.

Model calibrations yield elasticities of central city total factor productivity (TFP) with respect to central city employment that are 0.04 to 0.09 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 rent 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 metro sub-regions. As in Roback (1982), 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 metro 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 simultaneously consider population growth effects.

The estimated range of relative agglomeration spillovers indicate that most or all of the overall metro area level elasticity of TFP with respect to population is driven by sub-metro area scale interactions. Combes & Gobillon (2015) summarize consensus estimates of 0.04-0.07 for elasticities of TFP with respect to metro 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 metro area spatial scales, like labor

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market pooling, are its most important drivers.[1]

Calibrations of the full model reveal that each radial highway generates real income increases of up to 2.4 percent and housing cost declines of up to 1.3 percent for central city residents, while central city land rents decline by 4.3 to 8.6 percent with each 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. A plurality of the decentralization caused by each highway ray comes through reallocation toward land in housing production.

A large literature, including Ellison & Glaeser (1997), Rosenthal & Strange (2003), Duranton & Overman (2005), Arzaghi & Henderson (2008) and Ellison et al. (2010) uses observed spatial distributions of firms or employment to draw conclusions about the implied strength of agglomeration spillovers at local spatial scales. Related papers use plausibly exogenous 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 (2007a), Duranton & Turner (2012), Allen & Arkolakis (2014) and Heblich et al. (2018), 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 complements the existing literature in three ways. It provides the first estimates of the causal effects of highways on the spatial organization of economic activity by industry within metro areas, examining employment and residential location responses simultaneously.

[1] With additional structure, model calibration also delivers absolute levels of agglomeration spillovers but these are very sensitive to parameter chocies.

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It is the first paper to employ exogenous shocks to the environment in a large set of cities to facilitate recovery of productivity spillovers that operate at sub-metro area spatial scales. Finally, it 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 move only within an urban area.

2 Data and Descriptive Evidence

Data on the 1960 and 2000 joint spatial distributions of employment and resident worker locations by industry within the largest 100 metro areas in the US are central to the analysis. 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 metro areas. Commuting flows by industry within and between central cities, 1960 definition standard metro 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. All central cities in SMSAs with multiple central cities are necessarily treated as one spatial unit. For 2000, I take counts of workers and working residents by industry plus commuting flows from the Census Transportation Planning Package (CTPP). Year 2000 microgeographic units of tabulation – traffic analysis zones, census block groups or census tracts – were allocated to 1960 geographies and analogous counts were calculated through spatial aggregation. Each SMSA is assigned one central business district (CBD) location. This is the centroid of the census tracts in the SMSA's largest central city identified by local businesses in the 1982 Economic Census as being a CBD. As an example, Figure A1 shows the relevant 1960 and 2000 geographies for the Davenport-Rock Island-Moline IA-IL SMSA.

Figure 1 shows the magnitude of 1960-2000 decentralization of workers' residential locations within primary central cities and suburbs. CDFs of aggregate working residential

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population in 1960 and 2000 are depicted alongside changes in log aggregate working residents (right axis) by CBD distance for the 78 large SMSAs that were fully tracted in 1960. In order to make SMSAs of different shapes and sizes comparable, I index location to 0 for CBDs and 1 for the furthest census tracts in each SMSA's primary central city. We see that working residents live in 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. A large amount of population decentralization occurred within both central cities and suburban areas. Figure A2 depicts similar patterns by 1-digit industry.

Table 1 shows the extent of 1960-2000 decentralization of working residents, employment and commutes from cities to suburbs. 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 share living and working in the suburban ring rose from 28 percent to 43 percent. Aggregating over commute destinations and origins respectively, we see rapid decentralization of both jobs and residences, but with jobs remaining more clustered in central cities. The final column shows that the longest within-SMSA commutes are traditional suburb-central city commutes, at 24 percent longer than within central city commutes.

The primary treatment variable in the empirical work is the 1950-2000 change in radial limited access highways serving primary central city CBDs. As in Baum-Snow (2007a) highways from printed road maps (Rand McNally Co., 1960 & 2000) are counted if they connect from within 1 mile of the primary CBD of the SMSA to the suburbs of the SMSA. On average, sample SMSAs received 2.7 new rays between 1950 and 2000 and 2.0 new rays between 1960 and 2000, with standard deviations of 1.7 and 1.6 respectively (see Table A1). This growth almost fully reflects post-1950 construction, as only three cities had any radial highways in 1950.

To address potential endogeneity concerns, I instrument for the number of radial highways constructed prior to 2000 with that in a 1947 plan of the interstate highway system. As is discussed in Baum-Snow (2007a), this plan was developed by the federal Bureau of Public

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Roads to promote intercity trade and national defense. 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 0.3 for all coefficients. A regression of planned rays on log 1950 SMSA population and central city radius yields p-values of 0.179 and 0.007 for the two coefficient estimates respectively. 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 matter independently. 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. Inclusion of central city radius in regressions throughout the analysis controls for the fact that more important cities received more planned highways.

Table A2 Panel A presents first stage results. With 1950 as the base year, coefficients on planned rays are between 0.47 and 0.53, falling by 0.13 to 0.17 if 1960 is the base year. All are significant at the 1% level. Inclusion of 1960 central city radius and 1960-2000 SMSA population growth rate controls does not influence first stage coefficients. Additional inclusion of 1950 log SMSA population, 1940-1950 SMSA population growth and 1940 1-digit industry shares similarly does not significantly change coefficients on planned rays, nor are coefficients on any of these variables 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 and highways with the largest treatment effects were built first, results in the remainder of the paper therefore use 1950 to

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2000 radial highway construction as the endogenous variable of interest.

3 Empirical Strategy

The primary empirical goal is to recover 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, it may be important to hold SMSA employment by industry constant. Rather than use 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 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 incorporating the potential endogeneity of the SMSA employment mix and scale to the highway treatment.

In the following equations, ρ_{1k} and r_{1k} describe causal effects of highways on the allocations of employment emp^C_{ki} and working population pop^C_{ki} in industry k and SMSA i between central cities and suburbs, holding SMSA employment or working population in industry k constant.

$$\Delta \ln emp^C_{ki} = \rho_{0k} + \rho_{1k}\Delta hwy_i + \rho_{2k}\Delta \ln emp^M_{ki} + \sum_{j\neq k} \rho^j_{2k}\Delta \ln emp^M_{ji} + X_i\varrho_k + \upsilon_{ki} \quad (1)$$

$$\Delta \ln pop^C_{ki} = r_{0k} + r_{1k}\Delta hwy_i + r_{2k}\Delta \ln pop^M_{ki} + \sum_{j\neq k} r^j_{2k}\Delta \ln pop^M_{ji} + X_i R_k + u_{ki} \quad (2)$$

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, SMSA level objects $\Delta \ln emp^M_{ki}$ and $\Delta \ln pop^M_{ki}$ may be correlated with the error term, even after instrumenting for Δhwy_i with 1947 planned highways. This "bad control problem" occurs because $\Delta \ln emp^M_{ki}$ and $\Delta \ln pop^M_{ki}$ may respond to new highways,

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which are in turn influenced by the instrument. 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^j_{2k} and r^j_{2k}, are small.

To get around controlling for industry-specific SMSA employment, 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 et al. (2014). 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 metro area employment between 1960 and 2000. Combining estimates from these two steps yields effects of highways 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, I consider regressions of the form:

$$\Delta \ln emp^M_{ki} = \alpha_{0k} + \alpha_{1k}\Delta hwy_i + \alpha_{2k}\Delta \ln popemp^M_i + X_i\beta_k + \varepsilon_{ki} \quad (3)$$

$$\Delta \ln pop^M_{ki} = a_{0k} + a_{1k}\Delta hwy_i + a_{2k}\Delta \ln popemp^M_i + X_i B_k + e_{ki} \quad (4)$$

That is, the conceptual goal is recover impacts of an additional highway on SMSA employment or resident workers in each industry holding the total SMSA scale constant. Rather than using either SMSA employment or working population as this measure of scale, I instead use $\Delta \ln popemp^M$, 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 $\Delta \ln popemp^M_i$ is necessary for the coefficients α_{1k} and a_{1k} to capture the effects of highways

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on SMSA industry composition, thereby isolating reallocation from growth effects. 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.[2]

Several identification concerns arise in estimating Equations (3) and (4) by simple OLS. First is the endogeneity of Δhwy_i, which is addressed by instrumenting with the number of radial highways in the 1947 national plan. Second is the potential endogeneity of $\Delta \ln popemp^M$. 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 $\Delta \ln popemp^M$ may introduce a correlation with the error term since shocks to one industry of employment mechanically affect aggregate employment in all industries.

If highways cause SMSA population growth, it can be shown that excluding $\Delta \ln popemp_i^M$ 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), suppose that the underlying structural equation describing SMSA employment in industry k is

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

Here, Δhwy_i is instrumented with hwy_i^{47}, which is uncorrelated with ε_{ki}. The probability limit of the IV estimate of α_{1k} excluding $\Delta ln(popemp_i^M)$ from the regression equals

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

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

[2]With ideal data in a world perfectly described by land use models, Equations (3) and (4) would be identical. In practice, 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 avoids artificially constraining the analysis to SMSA geographies.

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written above, is[3]

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

That is, given that $Cov(hwy^{47}, \ln popemp^M) > 0$, as is true in the data and is also found by Duranton & Turner (2012), and $Cov(\ln popemp^M, \varepsilon_k) > 0$, as is true if unobservables driving variation in $\ln emp_k^M$ also influence the total SMSA employment, excluding versus including the control for metro area scale bookends true highway rays coefficients in (3) and (4).

There are two justifications for including variables in the control set X. 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, 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.

Second step estimation equations are expressed 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. Substitution of (3) and (4) into (1) and (2) yields a pair of equations that resemble (5) and (6).

$$\Delta \ln emp_{ki}^C = \omega_{0k} + \omega_{1k}\Delta hwy_i + \omega_{2k}\Delta \ln popemp_i^M + X_i D_k + \varpi_{ki} \quad (5)$$

$$\Delta \ln pop_{ki}^C = w_{0k} + w_{1k}\Delta hwy_i + w_{2k}\Delta \ln popemp_i^M + X_i \delta_k + v_{ki} \quad (6)$$

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 $\Delta \ln popemp^M$ in

[3] $D = Cov(hwy^{47}, \Delta hwy)Var(\Delta \ln popemp^M) - Cov(hwy^{47}, \Delta \ln popemp^M)Cov(\Delta hwy, \Delta \ln popemp^M)$

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the regressions and positive biases of these coefficients when excluding $\Delta \ln popemp^M$ from these regressions hold as for (3) and (4). In particular, since unobservables driving variation in outcomes are also likely to influence $\Delta \ln popemp^M$ in the same direction, $\Delta \ln popemp^M$ is likely to be positively correlated with the error terms.

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 local economy, and an additional adjustment for cross-industry effects. 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.

Implementation takes seriously the possibility that $\Delta \ln popemp_i^M$ may be endogenous using two strategies. Estimates of highway impacts α_{1k}, a_{1k}, ω_{1k} and w_{1k} are presented with and without inclusion of $\Delta \ln popemp_i^M$ as a control. The bounding argument laid out above indicates that the pairs of resulting coefficient estimates on highways bookend true reduced form treatment effects of interest. I refer to equations like (3), (4), (5) and (6) but excluding the control for $\Delta \ln popemp_i^M$ as "Specification 1," which generates upper bounds on highway effects of interest. "Specification 2" includes the control $\Delta \ln popemp_i^M$, generating lower bounds. Many treatment effects are discussed as being between the coefficients given by

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Specifications 1 and 2. I additionally consider "Specification 3," which moves $\Delta \ln popemp_i^M$ to the left hand sides in (3), (4), (5) and (6), thereby expressing the dependent variable as a log share. This is equivalent to restricting the coefficients on $\Delta \ln popemp_i^M$ (α_{2k}, a_{2k}, ω_{2k} and w_{2k}) to unity. If highways cause both growth and redistribution, the resulting highway coefficients are below their impacts holding SMSA scale constant. Specification 3 thus generates coefficients that are also lower bounds on true highways coefficients of interest.

4 Estimated Treatment Effects

4.1 Steps 1 and 2

Table 2 reports IV estimates from Equations (3), (4), (5) and (6). Within each panel, each row shows the highways coefficient from a different equation and each column is for a different industry, starting with all industries pooled in the first column. Each panel presents results for a different specification of the empirical model.

The top two coefficients in the first column of Panel A 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.[4] Results in remaining columns of the top row of each panel 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 7 to 10 percent of the manufacturing jobs and 10 to 14 percent of working residents to depart an SMSA, either to rural areas or abroad. While most rays coefficients for SMSA Employment are not statistically different from those for SMSA Working Residents, highways are estimated to cause greater declines in the latter in each industry.

[4]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 metro 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 metro 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.

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As predicted by the bounding argument given above, Use of Specification 1 always produces greater highway coefficients, with a maximum gap of 0.04 relative to Specification 2. In the top two rows of each panel, no 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 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 the top two rows of each panel in Table 2 yield similar and statistically indistinguishable results for all outcomes except the number of resident workers in manufacturing. 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.

The bottom two rows of each panel in Table 2 show estimated effects of radial highways on central city employment and working population by industry using Equations (5) and (6) respectively. Because highways coefficients in the top two rows are near 0 (except for manufacturing), these estimates 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.

Estimates in the first column in the bottom rows of Panels A and B indicate that each ray caused 14 to 16 percent of the working population of central cities to move to the suburbs. Estimated impacts of each ray on central city employment, reported in the third rows of Panels A and B, is much smaller in absolute value at –0.04 to -0.06. This difference of 0.10 is statistically significant; even considering the different central city bases, the gap far exceeds that which would be needed for a highway to move the same number of workers and jobs to the suburbs. Table A3 reports complete regression results for workers in all industries and Table A4 reports OLS results analogous to those reported in Table 2. Consistent with the bounding argument above, moving from Specification 1 to Specification 2 decreases highway coefficients in all cases except the residential locations of military workers, but only by up

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to 0.03. Inclusion of 1950 log SMSA population and 1940 employment shares in no case significantly changes these coefficients.

Analogous OLS rays coefficients reported in Table A4 are of smaller magnitudes than their IV counterparts. 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 highway construction is negative and the plan predicts positive suburban construction. In addition, Duranton & Turner (2012) provide evidence that struggling metro 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 metro 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.[5]

4.2 Main Estimates

I now examine the effects of highways on the allocation of employment and working population by industry between central cities and suburbs holding the SMSA industry mix constant. Table 3 Panel A shows results for Specification 1 and Panel B shows results for Specification 2. Industry-specific entries 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 em-

[5] Table A5 reports impacts of highways on the configuration of commutes using IV regression specifications analogous to those in the final row in Table 2 Panels A and B. These results indicate that each highway caused 14-15 percent fewer commutes within central cities, 10-14 percent more commutes within SMSA suburban rings and 22-26 percent more commutes from outside of SMSAs to the suburban ring, with other coefficients not significant.

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ployment 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.

Excluding agriculture and the public sector, point estimates indicate that each highway caused 4 to 14 percent of jobs and 12 to 22 percent of resident workers to suburbanize, depending on the industry. The smallest effect is for workers in FIRE. The largest effects are for those working in construction and wholesale & retail trade. Gaps between effects of highways on employment and residential locations are positive for each industry, statistically significant for many industries and stable across specifications.

Agriculture exhibits somewhat curious positive highways coefficients, implying that highways led to centralization of this industry. Enormous 1960-2000 changes in the occupational composition of agriculture explain this result. In 1960, farmers and farm workers dominated agricultural employment, accounting for 79% nationwide. In 2000, farmers and farm workers accounted for only 38% of agricultural employment. Instead, more urban oriented occupations expanded. Gardeners and groundskeepers increased from 1 to 17 percent and farm managers and supervisors increased from 0 to 8 percent. The remainder of the increase is made up by occupations not specific to agriculture, which are also more concentrated in urban areas. In central cities, the 33 percentage point 1960-2000 decline in farmers and farm workers was more than offset by the 36 point increase in gardeners and groundskeepers. With the residential decentralization brought on by new highways, urban lot sizes increased, requiring more groundskeeping services. Cities with more new highways had more of the farm employment loss replaced by gardeners and groundskeepers.

The model developed in the following section uses the estimated employment responses in Table 3 to recover information about agglomeration spillovers by the following logic. New highways reduce wage and rent gaps between cities and suburbs. To keep the marginal firm indifferent between city and suburban locations, employment decentralization must also occur, thereby reducing city-suburban productivity gaps to compensate for these relative

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input cost changes. Smaller employment decentralization responses are evidence of larger elasticities of productivity with respect to local employment.[6] This same logic holds when comparing employment responses across industries. While adjustments for variation in cost shares are needed to come to precise conclusions, the fact that central city employment in FIRE is estimated to decline by only 4-6 percent with each highway, less than other large private sector industries, is evidence of stronger agglomeration forces in FIRE.

Intuition from the classic monocentric model provides two mechanisms through which highways' impacts on population decentralization are of greater magnitudes than those on employment decentralization. Conditional on employment locations, new highways generate outward shifts in the supply of space available given commute times, thereby reducing land prices and inducing households to consume more space per-capita. Income effects from reduced commuting costs drive additional increases in per-capita space consumption.

4.3 Robustness

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 2 and 3. Figure A3 Panel A shows graphs of coefficients on radial highways in regressions identical to those reported for CC Working Residents in Table 2 Column 1 Panels A and B, except that the outcome is calculated for various central city radii. 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

[6] As long as highway treatments are uncorrelated with location fundamentals in cities and suburbs, this implication does not depend on the magnitudes of such fundamentals.

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effect of each highway by about 0.01. No coefficient on true 1960 central city radius is statistically significant in these regressions. Also evident is how similar coefficients are in Specification 1 (top, blue line) versus Specification 2 (bottom, red line). Remaining panels in Figure A3 show similar results using central city radii as defined by fraction of 1960 SMSA population in the central city and for the larger sample of 154 SMSAs of over 100,000 in population in 1960 for which some 1960 census tract data exists.

4.4 Discussion

This section has presented clear evidence that highways promoted the decentralization of both population and employment in post-WWII US metro areas. While other studies have also found that transport infrastructure decentralizes population, the literature presents more mixed evidence on employment impacts. For example, Heblich et al. (2018) finds that London's commuter railroads centralized employment while decentralizing population. It seems likely that in both environments, transport improvements promoted relative labor supply shifts to the city. If central city wages and rents fall as a result, the theoretical argument developed below is that a commensurate reduction in relative productivity must ensue in order to keep marginal firms indifferent across these two locations as long as they continue to locate in both. Because of agglomeration spillovers, this reduction is achieved in equilibrium through shifts of workers from cities to suburbs.

This narrative may apply better to 20th century US cities than to 19th century London. After 1960, central city wages and rents did indeed decline in US cities relative to the suburbs. However, late 19th century London is a story of firms decamping from rural areas for the City and structural change out of agriculture. Rural firms in many industries may have initially seen cost advantages from moving to the City once the railroads opened, such that outlying areas were completely abandoned by some industries. By 1920, few firms in these industries may have been indifferent between locating in the City of London and the suburbs. A monocentric equilibrium, with high wages, rents and employment in the City is approximately what ensued. As Fujita & Ogawa (1982) shows theoretically, monocentric

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equilibria are supported if agglomeration forces are sufficiently high and/or commuting costs are sufficiently low because firm profits are strictly higher if they locate downtown. It is possible that in 1920, agglomeration spillovers were stronger in some industries than they are today and operated at much smaller spatial scales, generating such a response.

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 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 can be calibrated with estimated treatment effects and commonly used cost share and housing demand parameters.

To match the fixed population environment explored in the empirical work, this is a closed city absentee landlord model with two metro 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 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 (2019) in some ways, though it considers the spatial equilibrium within rather than between metro 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

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heterogeneity would 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 unless there are commuting mode shifts (Glaeser et al., 2008).

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 US metro 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) presents compelling independent empirical evidence that worker heterogeneity does not drive productivity differences across space within metro areas.[7]

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 metro 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.

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

[7]Highways could cause higher skilled/income households to decentralize at higher rates if suburban amenities exceed urban amenities and amenities are normal goods. This would lead model calibrations to understate the strength of localized agglomeration economies if such agglomeration economies are skill-biased. They would also understate welfare increases for high income people.

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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.

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, 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, with k_c and k_s the analogous objects for capital. Profit functions for city and suburban firms respectively are

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

where w_c and w_s are wages and v is the uniform capital rental rate. Because firms are 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, in which ϕ_N is the cost share of labor and ϕ_L is the cost share of land in production.

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

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. (9)

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thus holds for firms in each industry across the locations in which that industry's employment is strictly positive.

Optimization over labor and capital inputs and 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 and mass of workers per central city firm as functions of rent are:

$$\begin{aligned} w_c &= \frac{A_c^{\frac{1}{\gamma}} v^{-\frac{\mu}{\gamma}} \mu^{\frac{\mu}{\gamma}} \gamma (1-\gamma-\mu)^{\frac{1-\gamma-\mu}{\gamma}}}{r^{\frac{1-\gamma-\mu}{\gamma}}} \\ n_c &= \frac{r^{\frac{1-\mu}{\gamma}}}{A_c^{\frac{1}{\gamma}} \left[\frac{\mu}{v}\right]^{\frac{\mu}{\gamma}} (1-\gamma-\mu)^{\frac{1-\mu}{\gamma}}}. \end{aligned} \tag{10}$$

Firms' demand for central city workers 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 decreasing in land rent r and shifts out with increases in total factor productivity.

Feasible recovery of a tractable full model solution below requires that all firms operate in a single industry. However, as shown below, interpreting responses of spatial distributions of employment by industry to new highways does not use the full model solution. As such, a portion of the calibration analysis below allows A_c, A_s, μ and γ to be indexed by industry.

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. Total differentiation of the indirect profit function 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.

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

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

5.1.3 Consumers

Each person is identical and has preferences over the numeraire traded good z, 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 to city commuters respectively as:

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

The utility function is concave in all three of its arguments. I ignore the possibility of reverse commuting as it has a small market share and would be difficult to rationalize with suburb to city commutes without adding individual-location match specific productivity and/or amenity shocks. 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 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. This pins down that the relative wage must equal the difference in commuting cost for

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the two types of suburban residents.

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

If commuting time is a small fraction of total time available, we can approximate the city-suburban log wage difference as the difference in commuting times for suburban residents.

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, must 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.

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

In this expression for city rent, 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.[8]

Following the literature (Mayo, 1981; Davis & Ortalo-Magné, 2011), 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 delivers 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.

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

[8] The utility function $U = qz^\alpha H^\beta$, as used in Ahlfeldt et al. (2015) and implicitly in Albouy (2016), among many other functions, has the property that σ_q is a constant.

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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

(9), (13) and (14) are combined into the first equilibrium condition of the 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 given knowledge of model parameters it provides an implicit solution for total city employment N_c that does not depend on wages, rents or the quantity of city land. Therefore, with appropriate adjustment of cost share parameters and positive employment in both locations, this expression also holds by industry. Firm indifference between city and suburban locations represented in (16) requires that productivity gaps match input cost gaps. Productivity gaps depend on relative location fundamentals α_c and α_s and scale, captured through number of workers N_c and potentially the commuting parameter t.

Taking N_c from (16), space market clearing in the city determines the number of city residents 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 (17) describes the amount of city land used in production. Unlike city employment N_c, central city space used by firms does depend on the city land rent r. The second term is the product of the number of city residents and consumer demand for land. In working with (17) below, I substitute (10) for central city wages w_c, (14) for rent r and (15) for $l^d(r,w_c)$.

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With equilibrium values of N_c and Q_c from (16) and (17), I derive analytical expressions for responses of 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 for recovery of 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 constant elasticity functional forms for the agglomeration functions.

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

Any changes in the natural productivity advantages of cities and suburbs α_c and α_s are assumed to be orthogonal to changes in t. The function $h(t)$ ($h' < 0$) captures the potential for transportation cost reductions to improve contact between all firms in a metro area, thereby enhancing agglomeration spillovers.

The elements of primary interest in the TFP functions are $g_c(N_c)$ and $g_s(N_c)$. 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 metro 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. Define $\widetilde{g}_c(N_c, N_s) \equiv g_c(N_c)$ and $\widetilde{g}_s(N_s, N_c) \equiv g_s(N_c)$, where $N_s = N - N_c$. Then, $\frac{d \ln g_c}{d \ln N_c} - \frac{d \ln g_s}{d \ln N_c} = \left[\frac{\partial \ln \widetilde{g}_c}{\partial \ln N_c} - \frac{N_c}{N_s}\frac{\partial \ln \widetilde{g}_c}{\partial \ln N_s}\right] + \left[\frac{N_c}{N_s}\frac{\partial \ln \widetilde{g}_s}{\partial \ln N_s} - \frac{\partial \ln \widetilde{g}_s}{\partial \ln N_c}\right]$. In the 1960 data, $\frac{N_c}{N_s} \approx 1$ in most SMSAs. 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.

Differentiating (16) yields (18), which is the partial elasticity of central city employment with respect to the fraction of central city residents' time endowment spent commuting.

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

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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-metro 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 applied separately for each industry.[9] [10]

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:

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

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

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,

[9]Below I present calibration results assuming all workers have the same σ_H and $c_{sc} - c_s$. If there is worker heterogeneity such that σ_H falls with income and/or $c_{sc} - c_s$ rises with income, implied values of $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$ are overstated for low wage industries and understated for high wage industries.

[10]If firms use intermediate inputs and highways cause intermediate input prices to converge between cities and suburbs, calibrations of (18) would overstate $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$. For such industries, this object can more broadly be viewed as an indicator of the relative strength of agglomeration economies and should not be interpreted as only reflecting TFP spillovers. If highways reduce gaps between city and suburban factory gate output prices, calibrations would understate $\frac{d\ln g_c}{d\ln N_c} - \frac{d\ln g_s}{d\ln N_c}$.

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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, (21) breaks out $\frac{d\ln Q_c}{dt}$ into a number of components, with indicated signs assuming $\frac{d\ln w_c}{dt} < 0$. X_c represents the central city land area devoted to production and $L_c - X_c$ is that devoted to residences.

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

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,

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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.

6 Model Calibration

6.1 Baseline Parameters

Coefficient estimates reported in Section 4 indicate that for all industries combined, $\frac{\Delta\ln N_c}{\Delta hwy} \approx -0.06$. The approximation $\frac{d\ln N_c}{dt} \approx \frac{\Delta\ln N_c}{\Delta hwy}\frac{\Delta hwy}{\Delta t}$ relates estimated coefficients to the theoretical results. Quantifying $\frac{\Delta hwy}{\Delta t}$ 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.[11]

η, ε and σ_H from consumer preferences, θ_L and θ_N from housing production and ϕ_L and

[11] Couture et al. (2018) estimate the elasticity of speed with respect to lane km of roads to be about 0.10, consistent with $\frac{\Delta t}{\Delta hwy} = -0.006$ for a city that goes from 1 to 2 radial highways.

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ϕ_N from traded goods production must also be calibrated. I take cost share parameters from Albouy (2016), with additional analysis using industry level shares from the KLEMS data. For the income elasticity of demand for housing, η, I use 0.7 as a compromise between Glaeser et al. (2008) and Davis & Ortalo-Magné (2011). Also following Davis & Ortalo-Magné (2011), I calibrate the price elasticity of housing demand ε to -1, though most results are insensitive to using $\varepsilon = -0.5$ instead. Based on the consumer expenditure survey, I calibrate σ_H, the share of income spent on housing services, to 0.17.

To calibrate the relative amount of city space in production versus residential use $\frac{X_c}{L_c - X_c}$, I begin with the number of working residents and jobs in each microgeographic unit in each central city from the 2000 CTPP. I regress unit area on the number of residents and employment in the unit, SMSA fixed effects and flexible controls for CBD distance. Coefficients on residents and employment capture the average amount of space occupied by each working resident and employee in central cities nationwide. I weight these estimates from 2000 by 1960 employment and residents in each unit to calculate $\frac{X_c}{L_c - X_c}$ for each city.[12]

I calibrate suburb-city and suburb-suburb commute costs relative to those within the city c_{sc} and c_s using 2000 CTPP data separately for each metro area, combining regions outside of SMSAs with suburbs. Finally, I set $\frac{d}{dt}[\ln q_c - \ln q_s]$ to 0, as such amenity effects are difficult to measure directly. If this object is positive, calibration results are lower bounds on true agglomeration spillover parameters. Table A6 reports baseline calibrated parameter values.

6.2 Strength of Local Agglomeration Economies

Using (18) and estimates in Table 3 Panel B, I recover values 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 SMSA and industry. Table 4 reports averages across SMSAs. Estimates for all industries collectively, reported in the third column, range from 0.040 to 0.087. 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 0.020 to 0.043 (half of

[12] Because components G, H and I in (21) are collectively small, results are insensitive to reasonable choices of $\frac{X_c}{L_c - X_c}$.

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these numbers). 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 4. Therefore, this is strong evidence that agglomeration spillovers within sub-metro regions represent a large fraction of the aggregate agglomeration economies in metro 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 is an important component of firm TFP.

Remaining columns of Table 4 report relative spillovers by industry. For all combinations of parameter values studied, FIRE has the largest localized agglomeration spillovers at 0.06 to 0.12 while wholesale & retail trade has the smallest at 0.01 to 0.03. Construction, services, transportation, communications and public utilities and manufacturing are in between, in order of least to most localized when using industry-specific cost shares. As the model incorporates neither variation in costs of intermediates goods nor variation in factory gate output prices between cities and suburbs, I emphasize that for some industries the estimates reported in Table 4 do not strictly reflect TFP spillovers but may reflect these other forces as well. In these cases, estimates should be interpreted as more reduced form measures that capture the strength of agglomeration forces that push the industry to remain localized.[13]

Results in Table 4 indicate that the majority of agglomeration spillovers operate within cities and indicate their variation across industries. Taking $\frac{\Delta t}{\Delta hwy}$ to be -0.005, this implies that the elasticity of central city TFP with respect to population is at least 0.015 across all industries - from 0.015 in wholesale/retail trade to 0.06 in FIRE. For each -0.005 increment in $\frac{\Delta t}{\Delta hwy}$, the implied magnitude of localized agglomeration spillovers in a metro area increases by 0.02-0.06 conditional on all other parameter values examined. As additional highways

[13] We observe positive industry-level central city and suburban employment in both 1960 and 2000 for each SMSA in our sample except the military. Allocations in public administration and the military are not likely to be determined by market forces and have no cost share information. Results for agriculture likely reflect the shift in employment from farming to groundskeeping and farm management.

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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. Additional calibration results are in Table A8.[14]

6.3 Why Did Highways Cause Suburbanization?

Table 5 reports calibrated values for each component of $\frac{\Delta \ln Q_c}{\Delta hwy}$ using (21), where $\frac{\Delta \ln Q_c}{\Delta hwy} \approx \frac{d \ln Q_c}{dt} \frac{\Delta t}{\Delta hwy}$. 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 $\frac{\Delta t}{\Delta hwy}$ to reflect the impact of one additional highway. 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. 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 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 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 4. 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 5 should be compared to the full treatment effect of -0.16 of each highway on central area working population reported in Table 3.

Following are the most important mechanisms through which highways caused urban population decentralization. Factor reallocation toward land in housing production (Component

[14] 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.

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F) is the largest negative component at between -0.033 and -0.066 depending on parameters, or up to 41 percent of the full estimated treatment effect. Firm adjustments to space per worker (Component G) adds -0.021 to -0.043 to this, but is 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 -0.03, 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 5 show the additional impacts that operate through shifts in firm productivity. Imposing $\frac{d\ln h}{dt} = -1$ generates up to an additional -0.021, or 5-13 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 0.006 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 4 are used instead, effects on population decentralization rise to less than 0.012. Note that the entries in Table 5 are not constrained to add to -0.16 and indeed they add to less in all cases. However with $\frac{\Delta t}{\Delta hwy} = -0.01$, they come close, adding to about -0.13. The model is missing some force, perhaps changes in consumer amenities, that rationalizes some of highways' impacts on urban population decentralization.

6.4 Evaluating Welfare Consequences

From (12), residents' willingness to pay for a new highway is:

$$\frac{\Delta V_c/\Delta[hwy]}{\lambda_c} \approx [w_c(1-t)]\,[\frac{d\ln w_c}{dt} - 1]\left[\frac{\Delta t}{\Delta hwy}\right] - [p_c H]\,[\theta_L \frac{d\ln r}{dt} + \theta_N \frac{d\ln w_c}{dt}]\left[\frac{\Delta t}{\Delta hwy}\right] \quad (22)$$

The first term captures the increase in income net of commuting cost that occurs both because the new highway increases commuting speed and because it raises wages through the three mechanisms specified in (20). This increase 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

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consequences of changes in housing cost, and can be expressed as a fraction of central city housing cost $p_c H = \sigma_H w_c(1-t)$. The change in housing cost reflects the change in land and labor costs given in (19) and (20) respectively, which push in opposite directions. 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 levels. While residents experience clear welfare gains from new highways, landowners experience clear welfare losses because central space declines in value. Central city owner-occupiers incur this capital loss along with the other welfare gains.

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 5, 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 4. Columns 4-7 of Table 6 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 income net of commuting cost by 0.6 to 1.3 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 2.7 percent (Column 5). However, incorporating local agglomeration spillovers instead lowers these gains to no more than 1.0 percent (Column 6). 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 2.4 percent per highway (Column 7). 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.

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Table 6 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 0.6 percent to a decline of 1.3 percent (Column 11), 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. Column 12 shows that capital losses through declines in central city rent are 4.3 to 8.6 percent with each new highway. Land represents only $\sigma_H \theta_L = 4\%$ of total expenditures, meaning this capital loss is negligible for homeowners relative to their gains in income net of commuting cost.

Taken together, results in Table 6 indicate that each new highway generates a willingness to pay of 1.2-2.6 percent of income for renters and 1.0-2.2 percent of income for homeowners. If the housing expenditure share were higher, as may be the case for poorer renters, and/or if highways reduce the prices of some additional goods, welfare gains would be even higher. This implies that even the most expensive highway projects serving US cities pass a cost-benefit test. With typical urban highway construction costs per mile of $100 million in medium sized cities, and the typical radial highway stretching 10 miles within built up areas, a new radial highway can cost up to $1 billion. Aggregate labor income in a medium sized city is $5 trillion per year, with a present value of about $100 trillion. If each highway increases income by only 1%, it easily passes a cost-benefit test for all but the very smallest cities.

7 Conclusions

Urban highway construction has dramatically changed the spatial structure of US cities. This paper demonstrates that new radial highways have caused significantly greater amounts of residential than job decentralization. Each radial highway displaced an estimated 14-16 percent of the central city working population but only 4-6 percent of the jobs to the suburbs. Viewed in the context of a calibrated urban model, these results provide evidence that local

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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 0.04-0.09, implying that a large fraction of overall agglomeration economies operate at spatial scales below the metro 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 from new highways, with only small additional effects due to employment relocations. Welfare analysis reveals that each radial highway causes the full income of metro area residents to increase by 1.0-2.6%.

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Table 1: Changes in Commuting Patterns, 1960-2000

		Millions (Fraction of Total)			Avg Commute
		1960	2000	Change	Time, 2000
Live in CC	Work in CC	16.5	12.0	-27%	27
		(0.43)	(0.16)	-0.27	1
Live in CC	Work in Ring	1.8	4.9	173%	30
		(0.05)	(0.07)	0.02	1.13
Live in CC	Work Outside SMSA	0.4	0.9	125%	46
		(0.01)	(0.01)	0.00	1.73
Live in Ring	Work in CC	5.9	10.5	79%	33
		(0.15)	(0.14)	-0.01	1.24
Live in Ring	Work in Ring	10.8	32.4	200%	22
		(0.28)	(0.43)	0.15	0.85
Live in Ring	Work Outside SMSA	0.9	4.4	381%	41
		(0.02)	(0.06)	0.04	1.53
Live Outside SMSA	Work in CC	1.0	3.0	206%	51
		(0.03)	(0.04)	0.01	1.93
Live Outside SMSA	Work in Ring	0.9	6.5	633%	42
		(0.02)	(0.09)	0.06	1.60
	Total	38.1	74.6	96%	

Each entry in the first two columns is the number of people with the indicated type of commute in the indicated year in millions, with the fraction of total commutes in the indicated year in parentheses. Those working at home are counted as commuting within their region 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. Commute times are not available for 1960.

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Table 2: Estimated IV Coefficients on Changes in Highway Rays, 1950-2000

Dependent Variable	All	Manuf	Services	Trade	TCPU	Const	Pub Admin	FIRE	Military	Agric
Panel A: Specification 1 -- No Control for $\Delta\ln(popemp^{SMSA})$ Included										
SMSA Employment	0.03	-0.07	0.02	0.02	0.05	0.05	-0.03	0.06	0.07	0.00
SMSA Working Residents	-0.00	-0.10	-0.00	-0.02	0.02	0.01	-0.07	0.02	-0.03	-0.03
CC Employment	-0.04	-0.13	-0.05	-0.12*	-0.04	-0.04	-0.02	-0.00	0.08	0.16
CC Working Residents	-0.14**	-0.23**	-0.15**	-0.20***	-0.12*	-0.21***	-0.15**	-0.11**	-0.14	-0.06
Panel B: Specification 2 -- Control for $\Delta\ln(popemp^{SMSA})$ Included										
SMSA Employment		-0.10***	-0.00	-0.01	0.02	0.03	-0.05	0.04	0.05	-0.01
SMSA Working Residents		-0.14***	-0.02	-0.05***	-0.01	-0.01	-0.09*	-0.00	-0.04	-0.05
CC Employment	-0.06*	-0.16***	-0.08**	-0.15***	-0.06	-0.06	-0.05	-0.03	0.06	0.14
CC Working Residents	-0.16***	-0.25***	-0.16***	-0.21***	-0.14**	-0.22***	-0.16***	-0.12**	-0.13	-0.07
Panel C: Specification 3 -- Dependent Variable Subtracts off $\Delta\ln(popemp^{SMSA})$										
SMSA Employment		-0.09**	-0.01	-0.01	0.02	0.03	-0.06	0.04	0.04	-0.03
SMSA Working Residents		-0.13***	-0.03	-0.05***	-0.01	-0.02	-0.09*	-0.00	-0.05	-0.06
CC Employment	-0.06*	-0.16***	-0.07**	-0.14***	-0.06	-0.05	-0.04	-0.02	0.07	0.15
CC Working Residents	-0.17***	-0.25***	-0.17***	-0.22***	-0.15**	-0.23***	-0.18***	-0.13**	-0.17	-0.09

Entries show IV coefficients on radial highways in variants of estimation equations (3), (4), (5) and (6) by industries indicated in column headers. Panels A and C control for central city radius only. Panel B additionally controls for $\Delta\ln(popemnp^{SMSA})$. The instrument is rays in the 1947 national plan. * 10% significance, ** 5%, *** 1% with robust standard errors. First-stage F-statistics are 16.51 (Panels A and C) and 16.77 (Panel B). Table A2 presents first stage results, Table A3 presents more complete results for all industries and Table A4 has OLS results. The sample size is 100, except 99 in Military CC Employment.

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Table 3: Causal Effects of Each Highway on Urban Decentralization, Holding the Industry Composition Constant

Dependent Variable	All	Manuf	Services	Trade	TCPU	Const	Pub Admin	FIRE	Military	Agric
Panel A: Specification 1 -- No Control for $\Delta\ln(popemp^{SMSA})$										
CC Employment	-0.04	-0.07	-0.08**	-0.14***	-0.08*	-0.09**	0.01	-0.06	0.01	0.16**
	(0.055)	(0.057)	(0.037)	(0.055)	(0.044)	(0.040)	(0.032)	(0.054)	(0.142)	(0.074)
CC Working Residents	-0.14**	-0.12**	-0.14***	-0.18***	-0.14**	-0.22***	-0.09*	-0.13**	-0.10	-0.03
	(0.061)	(0.053)	(0.051)	(0.058)	(0.056)	(0.061)	(0.051)	(0.054)	(0.136)	(0.068)
Difference	0.10**	0.06	0.07**	0.04	0.05	0.13***	0.10*	0.07	0.11	0.19**
	(0.041)	(0.056)	(0.032)	(0.043)	(0.049)	(0.047)	(0.053)	(0.047)	(0.170)	(0.082)
Panel B: Specification 2 -- Control for $D\ln(popemp^{SMSA})$ Included										
CC Employment	-0.06*	-0.08	-0.07**	-0.14**	-0.07*	-0.08**	0.01	-0.04	0.02	0.16**
	(0.033)	(0.054)	(0.034)	(0.054)	(0.039)	(0.038)	(0.031)	(0.051)	(0.149)	(0.073)
CC Working Residents	-0.16***	-0.15***	-0.15***	-0.18***	-0.13***	-0.21***	-0.13***	-0.12***	-0.14	-0.05
	(0.048)	(0.051)	(0.045)	(0.054)	(0.048)	(0.059)	(0.047)	(0.045)	(0.266)	(0.072)
Difference	0.10**	0.07	0.08**	0.05	0.06	0.14***	0.14**	0.07	0.16	0.21**
	(0.039)	(0.055)	(0.033)	(0.042)	(0.049)	(0.049)	(0.055)	(0.048)	(0.326)	(0.091)

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, 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. Analogous results using Specification 3 are almost identical to those reported in Panel B. The sample size is 100, except 99 in Military CC Employment.

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Table 4: Agglomeration Parameters by Industry

Parameters		$dlng_c/dlnN_c$ - $dlng_s/dlnN_c$							
ϕ_N, γ	$\Delta t/\Delta hwy$	All	Manuf	Services	Trade	TCPU	Const	FIRE	Agric
0.7	-0.005	0.040	0.030	0.034	0.017	0.034	0.030	0.060	-0.015
0.7	-0.01	0.080	0.060	0.069	0.034	0.069	0.060	0.120	-0.030
Ind-Spec	-0.005	0.044	0.028	0.024	0.015	0.024	0.023	0.060	-0.049
Ind-Spec	-0.01	0.087	0.055	0.048	0.029	0.048	0.046	0.119	-0.097

Entries quantify the aggregate own versus cross region agglomeration spillovers in an average metropolitan area, as is described in the text, for each listed industry and combination of parameter values. Results in Rows 3 and 4 use industry-specific cost shares. Calibrated parameter values are reported in Tables A6 and A7.

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Table 5: Mechanisms Through Which Highways Cause Suburbanization

Parameters			Components of $dlnQ_c/dhwy$ if $dlng_c/dN_c=0$ & $dlnh/dt=0$								Additional From	
			Price & Income Effects				Housing Factor Realloc.		Firm GE Effects			
ϕ_N, γ	$\Delta t/\Delta hwy$	η	A	B	C	D	E	F	G	H	$dlnh/dt=-1$	$dlng_c/dlnN_c$
0.7	-0.005	0.7	-0.004	-0.010	-0.001	0.001	-0.001	-0.033	-0.022	0.029	-0.008	0.002
0.7	-0.01	0.7	-0.007	-0.020	-0.002	0.002	-0.002	-0.066	-0.043	0.029	-0.017	0.004
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
0.825	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.066	-0.043	0.029	-0.018	0.005
0.7	-0.005	1	-0.005	-0.010	-0.002	0.001	-0.001	-0.033	-0.022	0.029	-0.011	0.003
0.7	-0.01	1	-0.010	-0.020	-0.003	0.002	-0.002	-0.066	-0.043	0.029	-0.021	0.005

Entries give components of the estimated treatment effect of each radial highway on the log of central city resident workers of -0.16 in an average metro area. 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 $dlng_c/dlnN_c$ is one-half of the numbers reported in the "All" column of Table 4.

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Table 6: Welfare Consequences of Each New Radial Highway

Parameters			increase in income net of commuting cost				increase in home cost				CC rent incr.
ϕ_N, γ	$\Delta t/\Delta hwy$	η	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
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%	-8.6%
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%	-8.6%
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%	-8.6%
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

Entries indicate elements of the three components of welfare consequences of one new highway ray in an average metro area given assumptions about dlnh/dt and the strength of the local agglomeration force $dlng_c/dlnN_c$. Columns (4)-(7) show calibrated values of $[dlnw_c/dt - 1][\Delta t/\Delta hwy]$. Columns (8)-(11) show calibrated values of $[q_L dlnr/dt+q_N dlnw_c/dt][\Delta t/\Delta hwy]$. Column (12) shows calibrated values of $[dlnr/dt][\Delta t/\Delta hwy]$. 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 4 for all employment and indicated parameter values. Entries in the final column do not depend on these two quantities.

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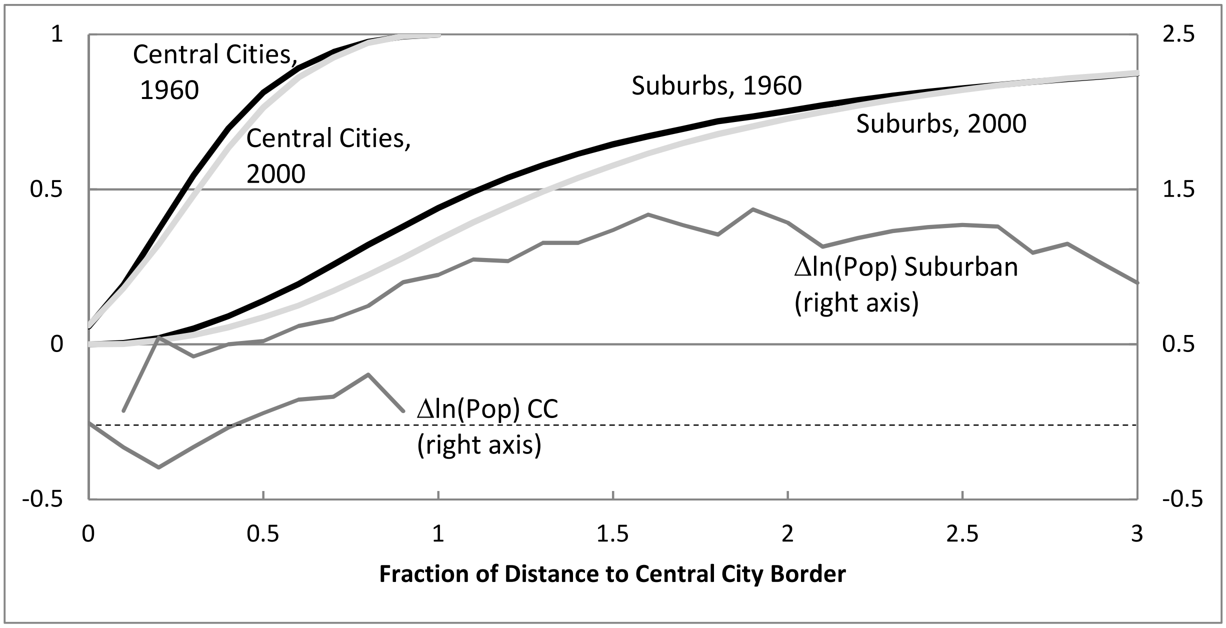
Figure 1: CDFs and Changes in Working Residential Population by Residential Location

1960-2000 (0=CBD, 1=Central City Edge)



The distance index on the x-axis is 0 at the CBD and 1 at the furthest location on the edge of the primary central city. 78 of the 100 SMSAs with at least 250,000 residents in 1960 contribute to the plots.