

Freeway revolts!

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Abstract

We present theory and evidence highlighting the disamenity effects of freeways on city centers and the structure of cities. In our model, disamenity effects from land use exclusion, negative externalities, or barriers between neighborhoods dominate access benefits in downtown neighborhoods compared with outlying areas, where access benefits are greater. These margins are especially relevant for understanding the nationwide *freeway revolts* that spread after 1955, setting central-city residents concerned about quality of life against regional planners who saw expanding transportation networks as key to urban growth. We confirm several predictions of the model using panel data on U.S. cities and neighborhoods, 1950–2010. To address the endogenous allocation of highways to cities and neighborhoods, we use planned-route and historical-route instrumental variables. We also present evidence that the revolts and subsequent policy responses in the 1960s pushed freeway construction to initially less educated, lower income, and more black neighborhoods. Finally, we plan to use a calibrated city structure model to quantify the effects of freeways, via amenity and commuting cost channels, on both central neighborhood and citywide outcomes.

Keywords: central cities, urban growth, amenities, commuting costs, suburbanization, highways
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1 Introduction

The Interstate Highway System has been called “the greatest public works project in history” (Federal Highway Administration, 2016). The Federal-Aid Highway Act of 1956 authorized and provided a funding structure for 38,000 miles of Interstate freeways to be completed by 1969. Commensurate with the scale of the project, freeways caused large changes in the economic geography of the United States. The Interstate Highway System led to both metropolitan growth and decentralization. A 10 percent increase in a metropolitan area’s stock of interstate highways in 1983 caused metro employment to increase by 1.5 percent over 20 years (Duranton and Turner, 2012). And had the interstate highway system not been built, aggregate U.S. population in central cities would have been 25 percent higher in 1990 (Baum-Snow, 2007).

Highway planners faced little early opposition as they moved to build the Interstates in 1956. A prevailing view among engineers and policy makers was that highways would ease congestion and revitalize downtowns. Lewis Mumford, later an important critic of urban freeways, initially “viewed the automobile as a beneficent liberator of urban dwellers from the cramped confines of the industrial city” (DiMento and Ellis, 2013, p. 38). But mass construction soon led to skepticism, especially among residents of dense urban areas, then outright protest. *Freeway revolts* soon spread to at least 50 U.S. cities. A short-lived U.S. Department of Transportation survey between October 1967 and June 1968 recorded 123 separate freeway revolts (Mohl, 2002). These movements pitted central-city residents concerned about local quality of life against regional planners who saw expanding transportation networks as key to regional growth. Mass construction sharpened the side effects of freeways—land use exclusion, negative externalities from pollution and noise, and barriers between neighborhoods—to a nationwide audience. Early freeway opposition in San Francisco in the middle 1950s led the Board of Supervisors to halt further freeway construction in January 1959, famously leaving the Embarcadero Freeway permanently unfinished. Neighborhood advocates, including Jane Jacobs, fought the construction of central-city freeways such as the Lower Manhattan Expressway. Aided by subsequent federal highway legislation in 1962 and 1966 and other policy changes in the 1960s, they often significantly altered, or stopped outright, proposed freeway routes.

In this paper, we shed light on the causes and the consequences of these freeway revolts by presenting theory and evidence highlighting the disamenity effects of highways on neighborhoods

and overall city structure. In our theory, access benefits from highways are dominated by disamenity effects in central cities. The model generates several predictions that we confirm using panel data on U.S. cities and neighborhoods, 1950–2010. First, downtown neighborhoods closer to newly-opened highways declined more in population compared with neighborhoods further away. But in the suburbs, proximity to a highway has no such effect. Intuitively, in downtown neighborhoods, the disamenity value of a highway dominates its access benefits. But in outlying neighborhoods, access benefits are greater. These findings can be easily explained by disamenity effects but are more difficult to reconcile with standard city structure models that focus exclusively on highways’ effects on reducing access costs.

To address the endogenous allocation of highways to cities and neighborhoods, we use planned-route and historical-route instrumental variables (following the typology of Redding and Turner, 2015). We also use historical travel surveys to construct data on trip flows and job locations prior to the construction of the Interstates to provide evidence on mechanisms for population declines near highways in central cities.

Finally, using these estimates and a calibrated city structure model, we (plan to) quantify the impact of freeways on neighborhoods and overall city structure, via amenity and community cost channels, on both central neighborhood and citywide outcomes.

1.1 Related work

Our paper makes contributions to several literatures.

There is a literature on highways and economic geography (Chandra and Thompson, 2000, Michaels, 2008, Allen and Arkolakis, 2014). For example, Duranton and Turner (2012) estimate the impact of Interstate highways on the distribution of employment across cities, and Baum-Snow (2007) estimates the effects on highways on the movement of population from central cities to the suburbs. Traditionally, these highway effects have been understood as a result of reduced costs of transporting goods and people (see the review by Redding and Turner, 2015). Our paper contributes to this literature by emphasizing that highways may also affect the spatial organization of economic activity by changing relative amenity values. Further, we provide evidence at a finer spatial scale (census tracts or neighborhoods) compared with previous work.

There is previous work on negative externalities of highways. For example, Anderson (2016)

identifies increased mortality from particulate pollution among elderly residents near highways using wind patterns. Our paper adds to these results by considering their implications for the spatial distribution of economic activity.

Finally, there is a literature on the political economy of infrastructure investment (Glaeser and Ponzetto, 2017). We add to this literature by providing evidence on the types of neighborhoods that received urban freeways in the 1950s and 1960s, and by showing changes over time in these patterns.

2 A Simple Model of Freeways in Cities

This section presents a simple city structure model to more precisely illustrate the effects of adding a freeway to a city. The model takes into account the importance of both decreased commuting costs and the disamenity effects experienced by neighborhoods near the freeway.

Consider a city with locations defined on a grid with coordinates denoted (x, y) . All jobs are located in the central business district (CBD) at $(x, y) = (0, 0)$ and pay a wage w_0 . Workers commute to the CBD and pay the commuting cost out of their wages.¹ A freeway may be added parallel to the x-axis at some distance, defined by the line $y = d_F$, with a travel speed v_F . In addition, surface streets run parallel and perpendicular to the highway with speed v_S , where $v_S < v_F$. We will consider v_S to be fixed and exogenous, and therefore it will be suppressed in subsequent notation.

Without loss of generality, we will only consider the effect of adding a highway for locations along the positive x-axis defined by $y = 0$. The wage net of commuting costs delivered to a location, denoted $w(x; d_F, v_F)$, will vary by distance to the CBD and also depends on the location and speed of the highway. Implicit in the net wage function is the assumption that workers will choose the path that minimizes the cost of traveling to work. Specifically, workers will take the freeway if the benefit of the faster travel speed on the freeway offsets the cost of traveling to and from the freeway. For example, in the case of linear transportation cost, workers will take the freeway if $\frac{2d_F}{v_S} < \frac{x}{v_S} - \frac{x}{v_F}$.² We do not impose functional forms on commuting costs, but do assume that the net wage function has several standard characteristics stated formally in Assumption 1.

Assumption 1 *Characteristics of the net wage function:* a) $\frac{\partial \ln w(x; d_F, v_F)}{\partial x} < 0$, b) $\frac{\partial \ln w(x; d_F, v_F)}{\partial d_F} \leq 0$, c) $\frac{\partial \ln w(x; d_F, v_F)}{\partial v_F} \geq 0$, d) $\frac{\partial \ln w(x; d_F, v_F)}{\partial v_F \partial x} \geq 0$, e) $\frac{\partial \ln w(0; d_F, v_F)}{\partial v_F} = \frac{\partial \ln w(0; d_F, v_F)}{\partial d_F} = 0$, f) $\frac{\partial \ln w(x; d_F, v_F)}{\partial v_F \partial d_F} \leq 0$, and g) $\frac{\partial \ln w(x; d_F, v_F)}{\partial v_F \partial d_F \partial x} \leq 0$.

In words, these assumptions state the following: a) net wages decline with distance from the CBD, b) net wages weakly decrease with distance to the freeway, as there is less benefit for com-

¹This analysis pertains not only to a CBD, but can be applied more generally to any regional amenity that will be more accessible with the addition of a freeway.

²This discrete choice will technically introduce a discontinuity in the derivative of the net wage function. This is not crucial for the discussion here, and we will assume that the wage function is differentiable everywhere. A probabilistic specification for the commuting path such as a standard discrete choice logit function would achieve the desired smoothness.

muting, c) net wages weakly increase everywhere when a freeway is added, d) the change in net wages after a freeway is built is weakly increasing in the distance to the CBD, e) the speed and location of the freeway have no effect on net wages at the center of the city, f) the change in net wages after a freeway is built is weakly decreasing in the distance to the freeway, d_H , and g) The change in net wages with respect to freeway distance after the freeway is built is weakly increasing in distance to the CBD.

More plainly, these assumptions imply that commuting costs are higher in locations farther away from the CBD. Furthermore, when a freeway is added, commuting costs decrease relatively more at locations far away from the CBD, and decrease more at locations closer to a freeway. Lastly, there is an interaction effect between distance to the CBD and distance to the freeway on the change in net wages (Assumption 1 g). For locations far away from the CBD it is much more beneficial for commuting to have the freeway built next door than for locations near the CBD. In fact, locations very close to the CBD would get no travel time reduction at all from having a freeway built near by. Finally, note that the effect of adding a freeway on net wages, is weakly positive for all locations.

Workers have preferences over land, l , a numeraire consumption good, c , and a location-specific amenity, $z(x; d_F, v_F)$, which we model as the following.

$$U(c, l) = z(x; d_F, v_F)^\gamma c^\beta l^{1-\beta}, \quad (1)$$

where β is the expenditure share on the numeraire, and γ , is a parameter that describes the importance of local amenities in the utility function.³ The amenity function $z(x; d_F, v_F)$, like the net wage function, depends on the distance to the CBD x , the freeway distance d_F , and the speed of the freeway v_F . The interpretation of the amenity function is that it captures access to both endogenous and exogenous amenities, as well as negative externalities from the freeway. For example, it may depend on nearby population density, or it may depend on proximity to a beach.

Crucially, the amenity function also depends on the speed of the freeway in that there is a tradeoff between freeway speed and the amenities offered by nearby neighborhoods. Again, this may be due to land use exclusions, negative externalities, or barrier effects, where the freeway limits

³The assumption of Cobb-Douglas utility is not crucial for the qualitative analysis here, but it is useful to simplify exposition.

access to nearby neighborhood amenities. We make no assumptions about the characteristics of the amenity function at this time, but show subsequently that certain observed outcomes in the economy imply that proximity to a freeway is a disamenity.

Finally, to close the model, we will assume that the city has a fixed amount of land that is owned by an absentee landlord who collects rent $q(x, y)$ at each location. In addition, we assume that workers are freely mobile and that the city exists in a larger economy, such that all workers must achieve a reservation utility, $\bar{u}$, thus effectively considering long-run equilibrium outcomes.⁴

Informally, the equilibrium of this economy requires that 1) workers choose land consumption to maximize utility subject to their budget constraint, 2) land rents adjust such that utility is equal to the reservation utility, $\bar{u}$, everywhere, 3) land markets clear, and 4) the amenity function, $z(x, y)$ is internally consistent. The last condition is required in the case of endogenous amenities, where, for example, $z(x, y)$ depends on the distribution of population.⁵

By imposing the reservation utility condition and solving the optimization problem of a worker, we can derive the land demand conditional on the net wage function and the amenity function. The reciprocal of land demand gives us the population density. In log form, this is given by,

$$\ln n(x; d_F, v_F) = \ln C_n + \frac{1}{1 - \beta} (\beta \ln w(x; d_F, v_F) + \gamma \ln z(x; d_F, v_F)), \quad (2)$$

where,

$$\ln C_n = \frac{1}{1 - \beta} (\beta \ln \beta - \ln \bar{u}). \quad (3)$$

The population density function is then increasing in both the net wage and the amenity value of a location, which agrees with intuition. The question that we then want to investigate is the following. What is the effect on the spatial distribution of population when a freeway is added, or how does density, $n(x; d_F, v_F)$, change as v_F increases and how does this depend on the location of the freeway and distance to the CBD? We show that certain observed outcomes on the change in population density when a freeway is added are only consistent with a disamenity from freeways, given the assumptions on commuting costs through the net wage function.

⁴Alternative modeling assumptions such as endogenous land area or fixed population do not change the essence of the arguments presented in this section.

⁵For formal equilibrium definitions of city structure models see Ahlfeldt et al. (2015), Brinkman (2016) and Lucas and Rossi-Hansberg (2002).

Proposition 1 *The change in density after a freeway is constructed is negative only if there is a loss in amenity value . $\frac{\partial \ln n(x;d_H,v_H)}{\partial v_H} < 0 \Rightarrow \frac{\partial \ln z(x;d_F,v_F)}{\partial v_F} < 0$.*

This proposition follows directly from equation 2 and assumption 1. Given that net wages are weakly increasing everywhere with the addition of a freeway, the only way that density can decrease is due to a decline in the amenity value.

Proposition 2 *If the change in the amenity function is weakly increasing with respect to distance to the CBD, then density will increase more at distances farther from the CBD after a freeway is constructed, holding distance to the freeway constant. $\frac{\partial \ln z(x;d_H,v_H)}{\partial v_H \partial x} \geq 0 \Rightarrow \frac{\partial \ln n(x;d_F,v_F)}{\partial v_F \partial x} > 0$.*

Proposition 2 states that population will increase more in the suburbs than in neighborhoods close to the city, holding distance to the freeway constant. This will be true even if there is no disamenity from the freeway given that access benefits accrue more to distant locations. This is the standard result that follows from the monocentric model, and still holds true in this environment.

Proposition 3 *The change in density due to a freeway being constructed is increasing in distance to the freeway, d_F , only if the change in amenity is increasing with d_F . $\frac{\partial \ln n(x;d_F,v_F)}{\partial v_F \partial d_F} > 0 \Rightarrow \frac{\partial \ln z(x;d_F,v_F)}{\partial v_F \partial d_F} > 0$.*

From assumption 1, net wages increase relatively more near freeways after they are built, or $\frac{\partial \ln w(x;d_F,v_F)}{\partial v_H \partial d_F} \leq 0$. Thus if density decreases near freeways more than locations farther away, it must come from the change in the amenity function. In other words, a larger decline in density for locations close to a freeway relative to far away holding distance to the CBD constant, is evidence of a disamenity effect from the freeway. Note that this is a necessary condition but not sufficient. The change in density after a freeway is constructed may be positive or negative, even if there is a disamenity, and it will depend on the relative weight of the disamenity versus the reduction in commuting costs.

Additionally, the change in density close to a freeway will depend systematically on how close a location is to the CBD. This is formally stated in the following proposition which describes the interaction of distance to the freeway and distance to the CBD and the effect on density.

Proposition 4 *The slope of the change in density with respect to distance from the freeway is decreasing with distance to the CBD if the slope of the change in amenities with respect to distance from the freeway is decreasing with distance to the CBD, $\frac{\partial \ln z(x; d_F, v_F)}{\partial v_F \partial d_F \partial x} < 0 \implies \frac{\partial \ln n(x; d_F, v_F)}{\partial v_F \partial d_F \partial x} < 0$*

This proposition outlines a sufficient but not necessary condition on the amenity function. Even with no disamenity effect from the freeway, the change in the wage function would insure that the interaction between distance to the freeway and distance to the CBD would have a negative effect on the change in density after construction. If the disamenity effect from the freeway were relatively worse near the CBD, then this interaction would simply be more negative. More to the point, this proposition tells us that increases in population near freeways after construction does not rule out the existence of disamenities because we would expect increases in locations near the freeway but far away from the CBD.

In sum, this theory tells us what we would expect to observe after a freeway is built if in fact there are disamenities from freeways. First, for locations near the CBD and near a freeway, we would expect to see strict population decline after a freeway is built. This is due to the fact that locations near the CBD get no commuting benefits from the freeway, and instead only experience a disamenity. Second, for locations near the CBD we would expect that the decline in population would be less at locations further from the freeway. There is no benefit from being close to the freeway near the CBD, only disamenity, but the disamenity effect attenuates at locations further from the freeway. Third, for locations further from the CBD, proximity to the freeway becomes more beneficial, and locations near the freeway may actually see higher population increases relative to those further from the freeway. This would be true even without a disamenity effect from the freeway, and it suggests that there is an interaction between distance to the freeway and distance to the CBD that must be controlled for to properly identify the disamenity effect.

2.1 Sorting Effects of Freeways

Next, we want to consider how the construction of a freeway may affect of the sorting of different worker types with respect to distance to the CBD and distance to the freeway. It is worth noting that when a freeway is built, unless there is a disamenity effect, then locations near the freeway will be more desirable given that they will reduce commuting costs. If we assume that higher income

agents sort to more desirable neighborhoods, then we would see increased incomes near a freeway after it is constructed unless the disamenity effect dominates. However, sorting patterns can be somewhat more complicated. Therefore, in what follows, we will be precise about the changes in sorting after a freeway is constructed. Here we will discuss heterogeneity in skill-type, but the discussion applies to other worker characteristics as well.

To start, let us assume that workers are heterogeneous in both productivity and preferences. There are two types of workers, denoted $i = (H, L)$ corresponding to their skill level, who each receive a wage at the center of the city with $w_H > w_L$. In addition, these workers may have different preferences for neighborhood amenities γ_i or housing β_i , or the amenity functions and wage functions themselves, may vary by skill type.⁶

The sorting patterns will be determined by the relative bid rent at different locations for different worker types, which reflect the willingness of each type to pay for a given location in order to exactly achieve their reservation utility. The bid rent increasing in both the net wage and the amenity of a location and is given by

$$\ln q_i(x; d_F, v_F) = \ln C_q + \frac{1}{1 - \beta_i} (\ln w_i(x; d_F, v_F) + \gamma_i \ln z_i(x; d_F, v_F)), \quad (4)$$

where,

$$\ln C_q = \frac{1}{1 - \beta_i} ((1 - \beta_i) \ln (1 - \beta_i) + \beta_i \ln \beta_i - \ln \bar{u}_i). \quad (5)$$

For this simplified discussion we will forgo microfounding land allocation, and just assume that the allocation of land depends on the relative value of the bid rents for the different agents.⁷ Denote the fraction of land allocated to high-skilled workers in each location as $\theta_H(\ln q_H - \ln q_L)$, and assume that,

$$\frac{\partial \theta_H(\ln q_H - \ln q_L)}{\partial (\ln q_H - \ln q_L)} \geq 0 \quad (6)$$

such that the fraction of land allocated to high income workers increases with the ratio of the bid rent of high-skilled and low-skilled workers. Given that the bid rents are functions of the freeway speed, distance to the CBD, and distance to a freeway, we can rewrite the land use function as

⁶They will also have different reservation utilities, but this enters as a constant, and thus has no role in changes after a freeway is built.

⁷Land may be allocated to the highest bidder, or we could assume that there is a transformation of land services that leads to a continuous allocation of land between different types.

$\theta_H(\ln q_H - \ln q_L) = \theta_H(x; d_F, v_F)$. As $\theta_H(x; d_F, v_F)$ increases, the average income of a location will increase.

The goal here is then to explain how the ratio of bid rents for different skill types change after a freeway is built and hence how different skill types sort into different locations in the city. To do this, we maintain the same assumptions on the net wage function as before; net wages increase more near freeways, increase more further away from the CBD, and the benefit in reduced commuting costs of being near a newly constructed freeway is increasing in distance to the CBD.

The change in sorting patterns among skill types after a freeway is built will depend on the source of heterogeneity and its relationship to skill level. There are three main sources of potential heterogeneity, and we will consider each in isolation. The first is that expenditure shares on land may change with skill or income level. Let us assume that land expenditure shares decline with income such that $1 - \beta_H < 1 - \beta_L$.⁸ In this case, the bid rent for high-skilled workers will respond more to any change in either the net wage or amenities relative to low-skilled workers as can be seen from equation 4. This should lead unambiguously to sorting of high skilled workers into the suburbs, given that net wages will increase more in the suburbs. However, the sorting with respect to proximity to a freeway is ambiguous, given that the net wage increases near freeways, while the amenity may increase or decrease. If the change in net wages near freeways dominates, then we would expect to observe high-skilled workers sorting near freeways. If the disamenity effect dominates, the opposite would be true. For locations near the CBD, the effect from the change in amenity will drive the sorting, while at locations further from the CBD the change in net wages should be more prevalent.

The second source of heterogeneity can arise is from differences in tastes for neighborhood amenities.⁹ Let us assume that the importance of local amenities increases with income such that $\gamma_H > \gamma_L$.¹⁰ We will also assume, without loss of generality, that the amenity function $z_i(x; d_F, v_F)$ is the same across types. In this case, after a freeway is constructed, high-skilled workers will sort into neighborhoods where amenities have increased the most (or declined the least). Thus, if the

⁸The literature is mixed on the response of expenditure shares to income. See Davis and Ortalo-Magne (2011) and Albouy et al. (2014)

⁹For different types, some amenities or disamenities may be valued the same, for example, noise, parks, pollution, or ocean views. Other amenities may be valued differently, however, such as variety, average income of the neighborhood, or population density.

¹⁰Several papers have addressed differences of preferences for amenities among skill or income groups including, Lee and Lin (2015), Lee (2008), Handbury (2012), Brinkman (2016), and Diamond (2016).

amenity value of neighborhoods decline near freeways, we would expect high-skilled workers to sort away from freeways.

Finally, it might be the case that change in the net wage function $\ln w_i(x; d_F, v_F)$ itself varies by skill-type. This would arise if the change in commuting costs after a freeway is built are not proportional to income. For example, if there is some per mile monetary cost or a fixed cost to use the freeway, then building a freeway would be more beneficial for high income workers.¹¹ If we assume this to be true, then this would result in sorting of high income workers to locations further from the CBD and close to freeways. In addition, there would be an interaction effect in that the sorting of high-skilled workers to locations near freeways would be more prominent in locations further from the CBD.

In general, the effects on sorting are similar to the effects on density that were reviewed previously. If there is a disamenity effect from being located close to the freeway, then it will be more important for sorting in neighborhoods near the CBD. In suburban neighborhoods, the sorting patterns after freeway construction will depend more on the reduced commuting costs. The fact that there are potentially multiple sources of heterogeneity makes overall patterns ambiguous. We will use the empirical results to shed some light on the important sources of heterogeneity that lead to changes in sorting after freeway construction.

¹¹See LeRoy and Sonstelie (1983).

3 Data

- Population, income, etc. for consistent-boundary census tracts from Lee and Lin (2015).
- Metropolitan areas are CBSAs as defined in 2010.
- City centers identified using the 1982 Census of Retail Trade, following Fee and Hartley (2013)
- Limited access highway shapefiles from the National Highway Planning Network (2016), a GIS database containing line features representing highways in the United States. We use all segments designated as limited access.
- PR-511 database provides opening dates for each interstate highway segment, up until 1993. A digitized version of these data and a corresponding shapefile were provided by Nate Baum-Snow. We did some further cleaning of these data.
- Planned-route IV: We digitized the 1947 interstate highway plan, following Baum-Snow (2007). “National System of Interstate Highways selected by joint action of the several state highway departments as modified and approved by the administration, federal works agency, August 2, 1947,” Public Roads Administration, Federal Works Agency (1947). We also constructed an alternate version of this instrument by connecting all city pairs via shortest-path routes. City pairs were selected using any 2 cities connected by the 1947 plan without going through an identified intermediate third city.
- Historical-route IV: We used historical rail routes from Jeremy Atack. We digitized historical exploration routes from the National Atlas, following Duranton and Turner (2012).
- Planned intra-city Interstate routes are from the “General Location of National System of Interstate Highways” (1955), commonly known as the “Yellow Book.” These plans from 1955 were the first within-metropolitan area plans for the location and routing of highways.

4 The effects of freeways: disamenities vs. access

In this section, we turn to the data to examine the implications of the theory presented earlier in this paper. We primarily consider the long-run effects of highway construction in the U.S between 1950 and 2010. Specifically, we present evidence that after freeways were constructed 1) central cities experienced absolute declines in populations, 2) populations in outlying areas increased more than those close to the CBD, 3) in locations nearer the CBD, proximity to a new freeway is associated with larger population declines or smaller growth relative to locations further away, and 4) in areas close to the CBD, proximity to a freeway reduces population, while in areas far from the CBD, proximity to a freeway has a positive effect on population.

We start by presenting some descriptive patterns, focusing on a particular freeway in Chicago in addition to aggregate data from a selection of metro areas. Given that highway location is endogenous, we formally test the theory by using IV techniques to identify the causal effects of freeway construction. We then extend the analysis to consider the importance of access to other exogenous regional amenities, in particular oceans, and finally consider the effects of freeways on income sorting, where the predictions from the theory are less clear.

4.1 Descriptive patterns

Before formally examining the causal effects of freeway construction, we first present some descriptive evidence on how neighborhoods change after freeway construction. We start by looking specifically at the city of Chicago to help build intuition. Figure 1 shows the change in the natural log of density for census tracts in Chicago between 1950 and 2010. The highway network of Chicago is mostly radial, with several beltways. The radial highways converge on “the loop” which is the CBD of Chicago located on Lake Michigan and contains approximately half of the jobs in the City of Chicago, and around 17 percent of all jobs in the metropolitan area.

The first thing to note is that areas at the edge of the city gained significant population over the time period relative to neighborhoods near the CBD. This is consistent with standard predictions of a monocentric model, where travel times are reduced more in the suburbs. However, areas near the CBD experienced absolute population losses, which might indicate declines in neighborhood amenities. In addition, note that in locations near the CBD, there tends to be a particularly large

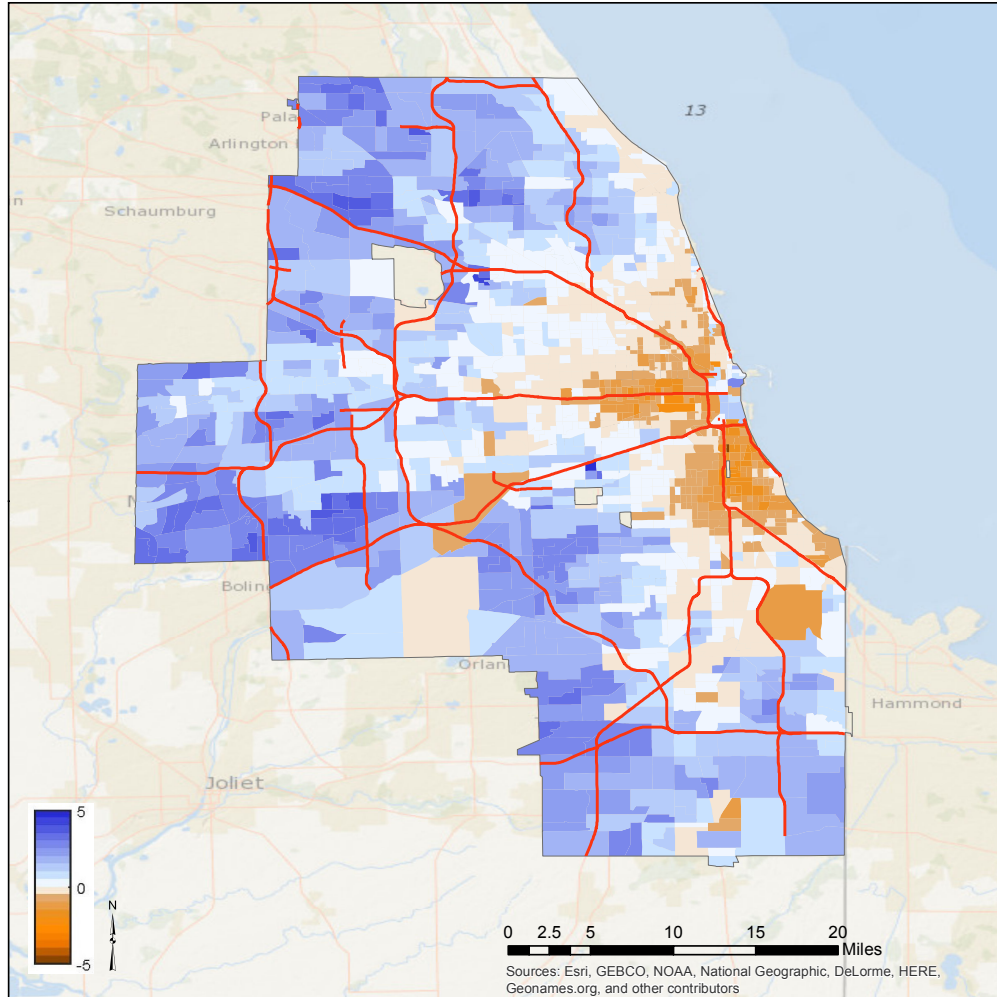


Figure 1: Change in consistent-boundary tract population, 1950–2010, Chicago metropolitan area

decline in population in neighborhoods close to freeways.

To further illustrate this pattern, Figure 2 zooms in on the I-290/I-88 corridor that runs west from downtown Chicago. Construction on I-290 and I-88 began in the 1950s and both segments were completed in the 1970s. Following the freeway away from downtown, it is clear that population gains clearly increase with distance to the CBD. In areas within 10 miles of the CBD, population gains are positively correlated with distance to the freeway. However, in locations more than 10 miles from the CBD the picture is less clear, with locations near the freeway potentially having larger gains than those further away.

Finally, Figure 3 shows these patterns for all census tracts in all metropolitan areas in our sample. For this exercise, the sample was separated into four bins by distance to the city center:

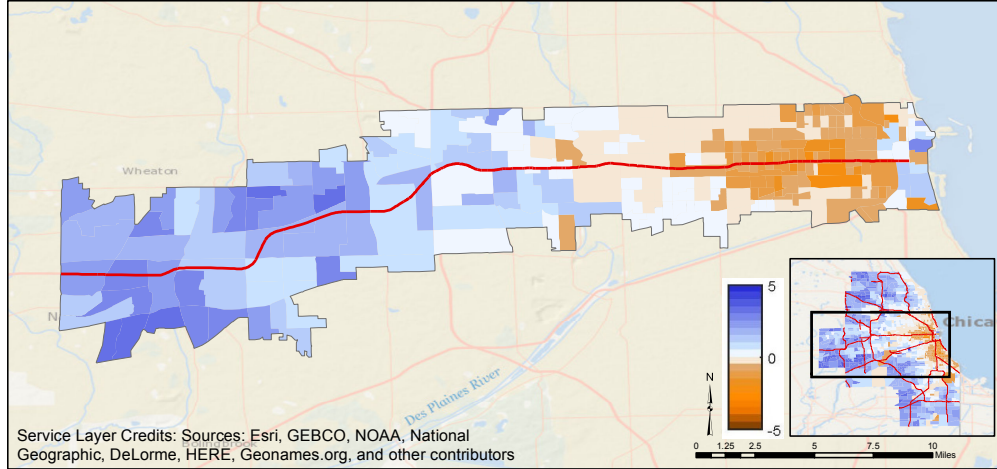


Figure 2: Change in consistent-boundary tract population, 1950–2010, I-290 / I-88 corridor

0–2.5 miles, 2.5–5 miles from the city center, 5–10 miles, and more than 10 miles. (Of the 64 metropolitan areas in our sample, 38 have tracts beyond 10 miles.) Each plot shows kernel-weighted local polynomial smooths of the 1950–2010 change in the natural logarithm of consistent-boundary tract population. Consistent-boundary tract changes in log population are centered around their metropolitan area means. Each smooth ends at the 99th percentile consistent-boundary tract by distance to the nearest freeway, so e.g., 99 percent of tracts within 2.5 miles of the city center are within 2.8 miles of a freeway. For neighborhoods within 5 miles from city centers, proximity to a freeway is negatively correlated with population growth, while for neighborhoods farther than 5 miles from city centers, proximity to a freeway appears positively correlated with population growth.

Overall, these patterns are consistent with the predictions of the theory. For locations near the CBD, there are very little access benefits from being close to a freeway, and therefore, the freeway acts as a net disamenity. However, for suburban locations, the access benefits of the freeway dominate, and proximity to a freeway can be desirable.

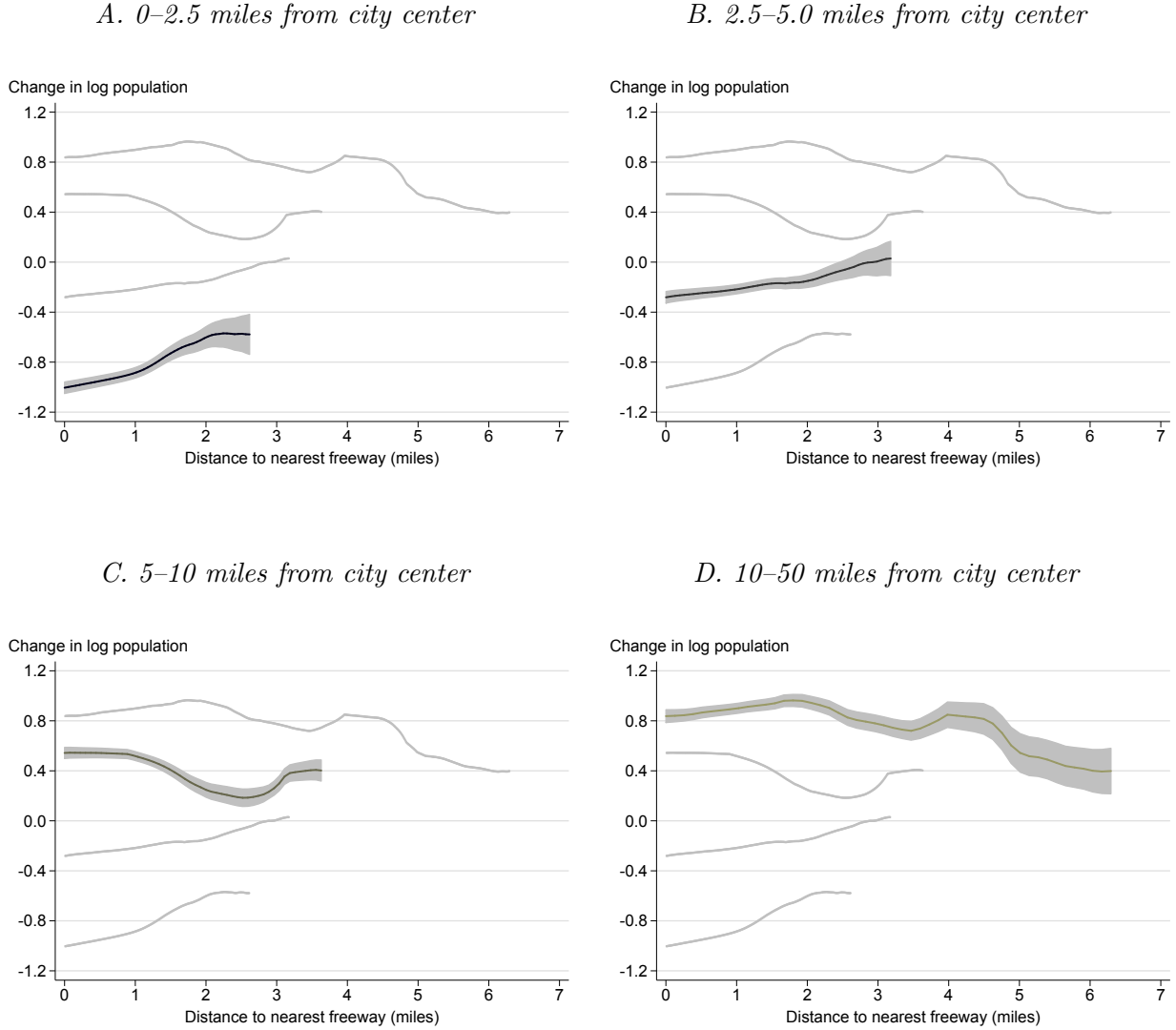


Figure 3: Change in consistent-boundary tract population, 1950–2010, by distance to city center and distance to the nearest freeway

These figures show kernel-weighted local polynomial smooths of the 1950–2010 change in the natural logarithm of consistent-boundary tract population. Consistent-boundary tract changes in log population are centered around their metropolitan area means. Smooths use Epanechnikov kernel with bandwidth 0.5 and local-mean smoothing. Shaded areas indicate 95 percent confidence intervals. Each smooth ends at the 99th percentile consistent-boundary tract by distance to the nearest freeway.

4.2 Estimation and Identification

Next we formally test the effects of adding a freeway to a city. To do so we will mostly consider the long-run changes to neighborhoods over the period from 1950 to 2010, corresponding to the primary era of highway construction in the U.S. Consider the following regression:

$$\Delta n_{g[m]} = \alpha_m + \beta_1 d_F + Z'_g \gamma + \epsilon_g \quad (7)$$

This is a “long-difference” regression. Here, $\Delta n_{g[m]}$ is the change in log population density between 1950 and 2010 for neighborhood g in metropolitan area m . Metropolitan area fixed-effects α_m ensure that identification comes from variation across neighborhoods, within metropolitan areas, in proximity to the realized highway network. d_F is distance from neighborhood centroid to nearest freeway. Z_g is a vector of other fixed and persistent neighborhood factors, such as proximity to water, slope, elevation, etc. We run this regression separately for subsamples conditioned on distance to the city center—i.e., neighborhoods within 2.5 miles of the city center, neighborhoods between 2.5 and 5 miles from the city center, neighborhoods between 5 and 10 miles from the city center, and neighborhoods more than 10 miles from the city center.

This flexible specification allows us to test whether the effects of freeway construction on neighborhoods vary by proximity to the city center. The key test of the disamenity effect comes from the coefficient on distance to the highway, d_F , as noted in Proposition 3.¹² For neighborhoods closest to the city center, β_1 will only be positive if there is measurable disamenity from being located near a highway. A positive coefficient means that holding all else equal, near the CBD locations further from the freeway experienced higher population growth. Note that this need not be true for suburban locations, given that the marginal effect of freeway proximity changes with distance to the CBD.

Of course, highways are not allocated randomly to neighborhoods, and a key challenge of this analysis is dealing with this selection bias. There are two possible selection margins. First, highways might be targeted to neighborhoods with greatest growth potential in order to maximize the benefits of public investment. On the other hand, highways might be routed through neighborhoods with

¹²A disamenity would also be consistent with a decline in population in the center of the city (Proposition 1) corresponding to negative MSA level fixed effects. We suppress the constant term given that a separate coefficient is estimated for each city, but on average neighborhoods in central cities near freeways lost population.

less growth potential, perhaps for political economy reasons. Duranton and Turner (2012) find evidence suggesting that the latter is relevant for understanding the allocation of highways across metropolitan areas—they find that slow-growing or shrinking cities were allocated more highways.

Our identification strategy follows the literature on causal identification of highway effects including research by Chandra and Thompson (2000), Baum-Snow (2007), Michaels (2008), and Duranton and Turner (2012). One important distinction between our work and previous work is a focus on neighborhood-level allocation of highways and outcomes as opposed to differences across metropolitan areas. Specifically, we will rely on differences in outcomes among neighborhoods within metropolitan areas as the important source of variation.

A survey by Redding and Turner (2015) classifies three types of instrumental variables: (i) planned-route, (ii) inconsequential-unit, and (iii) historical-route. We will use all three instruments in our analysis. The planned-route method, following Baum-Snow (2007), uses the 1947 highway plan that resulted from the Federal-Aid Highway Act of 1944 as an instrument for actual highway locations. The 1947 plan was designed to improve inter-city travel and national defense objectives. Thus, the plan is unlikely to be correlated with neighborhood characteristics. In fact, the planned routes were drawn at national, not regional or metropolitan, scales, so the location of planned highways was mostly determined by the number and orientation of nearby large metropolitan areas.

A variant of this instrument relies on the logic of the inconsequential units instrument. Based on the 1947 plan, we connect via shortest-path routes all city pairs connected by a planned highway without going through an intermediate third city. Because the 1947 plan was drawn at national resolution, the planned-route and inconsequential-unit IVs are highly correlated. Differences between the two instruments occur where a “curved” planned route is “straightened out” when we draw the shortest-path distance between two connected cities.

Finally, we use a historical routes IV following Duranton and Turner (2012). The identification in this case arises from the fact that historical transportation routes, exploration routes, railroads, etc., are unlikely to be correlated with current neighborhood characteristics. These routes are likely low-cost locations either due to topography (first nature) or for land assembly reasons (second nature). For this application, we use historical rail routes from Atack (2013), which contain all railroads in operation by 1898. One potential concern regarding the validity of this instrument is

that topography or railroads might have amenity value. We also use pre-1890 explorer routes from National Atlas (1970), following Duranton and Turner (2012).

4.3 Results

Table 1 shows the main results with the OLS and IV specifications in separate panels. Panel A shows weighted least-squares estimates, where individual tract observations are weighted by the inverse of the number of tracts in the metropolitan area. (These weights ensure that large metropolitan areas with many tracts have less influence over the results. Later, we show similar results without weights.) Each column is a separate regression, using tracts conditioned on distance to the city center identified by the column title. The coefficient estimates have the expected sign and are precisely estimated. The coefficient on miles to highway can be interpreted as the additional percentage growth in population for each additional mile a tract is located from the highway. For tracts closest to the city center, this effect is positive, meaning that tracts 1 mile from a freeway at the city center grew 24 percent more than those located next to the freeway. (A positive coefficient means that population declines are larger, or population increases are smaller, closer to freeways.) This is the key test of the theory. Additionally, this effect declines with distance to the city center. Looking across columns, the estimates decline, with tracts closest to the freeways increasing more in population compared with tracts farther from freeways. This is consistent with the idea that the relative importance of access versus neighborhood amenities is different in the suburbs versus the city. Panel B shows estimates adding controls for natural and historical factors: tract distance to the nearest river, lake, coastline, seaport, and 4 separate dummies for average tract slope.

Panels C, D, and E show the instrumental variables results. Panel C uses neighborhood distance to 1947 plan routes and shortest-path routes between 1947 plan cities as instruments. Panel D uses neighborhood distance to 1898 railroad and pre-1890 exploration routes as instruments. Panel E uses all instruments simultaneously. Again, all of the coefficients have the expected sign and nearly all are statistically significant. In terms of the point estimates, the IV estimates are larger than those obtained from the OLS exercise, suggesting the causal effect of freeways is larger (more negative) than what simple growth rates would suggest. This would imply that highways were generally allocated to neighborhoods that had high growth potential. Later, we discuss evidence why this

	(1) 0–2.5 miles	(2) 2.5–5 miles	(3) 5–10 miles	(4) 10–50 miles
<i>A. WLS estimates</i>				
Miles to nearest freeway	0.241 ^c (0.076)	0.118 ^c (0.034)	-0.156 ^b (0.075)	-0.072 (0.059)
R^2	0.026	0.011	0.019	0.008
Neighborhoods	2,312	3,482	5,561	5,173
Metropolitan areas	64	63	56	38
<i>B. WLS estimates with controls for natural and historical factors</i>				
Miles to nearest freeway	0.257 ^c (0.067)	0.110 ^c (0.033)	-0.187 ^b (0.072)	-0.033 (0.038)
<i>C. IV estimates using 1947 inter-city plan and great-circle routes</i>				
Miles to nearest freeway	1.751 ^c (0.342)	0.712 ^c (0.241)	0.377 (0.408)	0.029 (0.194)
Weak id (C-D Wald F)	53.4	61.9	61.6	105.1
Over id (Hansen J)	0.00	2.37	2.32	0.33
... p	0.99	0.12	0.13	0.56
<i>D. IV estimates using 1898 railroad and pre-1890 exploration routes</i>				
Miles to nearest freeway	0.994 ^c (0.268)	0.846 ^c (0.227)	0.979 ^a (0.548)	0.313 (0.240)
Weak id (C-D Wald F)	105.1	76.0	31.7	104.4
Over id (Hansen J)	0.37	2.59	0.65	0.78
... p	0.83	0.27	0.72	0.68
<i>E. IV estimates using all plan and historical route instruments</i>				
Miles to nearest freeway	1.149 ^c (0.252)	0.792 ^c (0.199)	0.602 ^a (0.363)	0.201 (0.176)
Weak id (C-D Wald F)	73.1	64.2	41.7	92.9
Over id (Hansen J)	5.87	5.30	2.86	1.95
... p	0.21	0.26	0.58	0.74

Table 1: Effects of freeways on 1950–2010 change in population

Each cell is an estimate from a separate fixed-effects regressions of the logarithm of the 1950–2010 change in consistent-tract population on distance to nearest highway in miles. All regressions include metropolitan area fixed effects. Estimated standard errors, robust to heteroskedasticity and clustering on metropolitan area, are in parentheses. ^a— $p < 0.10$, ^b— $p < 0.05$, ^c— $p < 0.01$.

might be the case. In short, the historical evidence and suggests that urban highways, particularly in city centers, were actually built along previously less-developed and less-dense “corridors” left behind by previous radial development patterns. These neighborhoods had higher growth potential compared with neighborhoods that did not receive freeways. Central neighborhoods that were allocated freeways along planned or historical routes suffered especially large population losses.

	(1)	(2)	(3)	(4)
	0–2.5 miles	2.5–5 miles	5–10 miles	10–50 miles
<i>A. IV estimates using all plan and historical route instruments</i>				
Miles to nearest freeway	1.149 ^c (0.252)	0.792 ^c (0.199)	0.602 ^a (0.363)	0.201 (0.176)
<i>B. With controls for 1950 tract characteristics</i>				
Miles to nearest freeway	0.878 ^c (0.280)	0.831 ^c (0.221)	0.706 ^a (0.374)	0.107 (0.146)
<i>C. Excluding New York and Los Angeles metropolitan areas</i>				
Miles to nearest freeway	1.106 ^c (0.251)	0.796 ^c (0.206)	0.583 (0.363)	0.179 (0.169)
<i>D. No weights</i>				
Miles to nearest freeway	1.023 ^c (0.248)	0.776 ^c (0.190)	1.340 ^c (0.428)	0.146 (0.253)
<i>E. By distance to coast, not city center (coastal metros only)</i>				
Miles to nearest freeway	1.296 ^c (0.272)	1.878 ^b (0.750)	0.390 (0.252)	0.365 (0.438)

Table 2: Effects of freeways on population — Robustness

Each cell is an estimate from a separate fixed-effects regressions of the logarithm of the 1950–2010 change in consistent-tract population on distance to nearest highway in miles. All regressions include metropolitan area fixed effects. Estimated standard errors, robust to heteroskedasticity and clustering on metropolitan area, are in parentheses. ^a— $p < 0.10$, ^b— $p < 0.05$, ^c— $p < 0.01$.

Table 2 shows other specifications to test the robustness of the results. Overall, the estimates are very stable and all are statically significant. The baseline IV results are shown in Panel A. Panel B adds a number of controls for 1950 tract characteristics, including race, educational attainment, income, and housing values and rents. In Panel C we exclude New York and Los Angeles from the sample. In Panel D we weight each tract equally. The point estimates suggest similar patterns: Larger population declines near freeways in city centers compared with suburban areas.

Up to this point, we have only considered the access benefits of highways for commuting to the CBD. However, this same analysis should apply to other regional level destinations. In particular we complete the same method using distance to a coastline as our measure of access.¹³ Note that coastlines potentially provide production benefits (i.e. they are spatially correlated with job centers) and consumption benefits (views, beaches, moderate climates). Either way, if these amenities act on a regional scale we would expect that locations far from the coast benefit more from proximity

¹³For this analysis we include great lakes in addition to oceans, and we drop MSAs that are not near a coast

to a highway, while locations near the coast would only experience a disamenity from the freeway.

The results are shown in Table 2, Panel E. The estimates in this case are very similar to those using distance to the CBD, and all are statistically significant. Also, we see the estimates using the IVs are larger than the OLS results, consistent with a negative selection effect for freeway location. Overall, this provides additional insight in the cost and benefits of highway construction in urban areas.

Next, we investigate the change in neighborhood population over time, accounting for the timing of interstate construction. In this exercise we regress change in population in each decade on distance to the CBD and distance to the highway on only highways that were currently completed. We use the same IV strategy as before. To do so we use the PR-511 data which has the date at which each interstate segment was open to traffic. Note that this data only includes designated interstate highways, and is thus a subset of the highway data used in previous regressions. In addition, these are 10-year changes, so the magnitudes of the coefficients are expected to be smaller. What is clear from this table is that the effects of highway construction were most pronounced between 1950 and 1980. After 1990, the effects are more modest, which corresponds with the decline in highway construction.

4.3.1 Sorting Effects

We consider the effects of freeways on the sorting of different types spatially in urban areas. To do so, we consider the relative change in income over the time period and how it varies with respect to freeway proximity and distance to the CBD. Our dependent variable in this case is the change in average household log income over the time period from 1950 to 2010. Recall from the theoretical predictions for income that sorting effects are ambiguous and depend on the source of heterogeneity across groups, as well as the form of the commuting technology. This is reflected in the results shown in Table 4 which are weaker than the results using population change.

Nonetheless, the results suggest that in general highway construction caused several changes in the sorting patterns of different income groups. There is weak evidence that higher income groups sorted away from freeways, and that this effect was larger in city centers compared with the suburbs.

These results are consistent with several sources of heterogeneity, and thus we cannot definitively

	(1) 0–2.5 miles	(2) 2.5–5 miles	(3) 5–10 miles	(4) 10–50 miles
<i>A. 1950–1960 (Total interstate miles: 10,400*)</i>				
Miles to nearest freeway	0.543 ^c (0.087)	0.473 ^c (0.122)	0.112 (0.153)	-0.059 (0.064)
<i>B. 1960–1970 (Total interstate miles: 31,500*)</i>				
Miles to nearest freeway	0.624 ^c (0.170)	0.182 ^a (0.103)	0.091 (0.116)	-0.147 ^a (0.076)
<i>C. 1970–1980 (Total interstate miles: 40,300*)</i>				
Miles to nearest freeway	0.116 ^b (0.059)	0.075 ^a (0.039)	0.193 ^b (0.087)	0.088 (0.055)
<i>D. 1980–1990 (Total interstate miles: 42,500*)</i>				
Miles to nearest freeway	0.018 (0.046)	0.069 ^b (0.034)	0.051 ^b (0.025)	0.063 ^b (0.031)
<i>E. 1990–2000 (Total interstate miles: 42,800*)</i>				
Miles to nearest freeway	-0.067 (0.042)	0.008 (0.027)	0.050 ^a (0.026)	0.056 ^a (0.030)
<i>F. 2000–2010 (Total interstate miles: 46,900†)</i>				
Miles to nearest freeway	-0.030 (0.043)	0.035 (0.058)	0.073 ^a (0.041)	0.049 (0.031)

Table 3: Effects of freeways on population — By decade

Each cell is an estimate from a separate fixed-effects regressions of the logarithm of the ten-year change in consistent-tract population on distance to nearest highway in miles. All regressions include metropolitan area fixed effects. Estimated standard errors, robust to heteroskedasticity and clustering on metropolitan area, are in parentheses. ^a— $p < 0.10$, ^b— $p < 0.05$, ^c— $p < 0.01$. *—Table HNG-12. †—Table HM-20.

attribute these results to specific differences between income groups. Recall from the previous discussion and Equation 4 that there are three important sources of heterogeneity: differences in expenditure shares, differences in amenity valuation, and differences in the effects of transportation costs. The changes observed would be consistent with decreased expenditure shares on housing for higher income groups (i.e. $1 - \beta_H < 1 - \beta_L$). As transportation costs decline, higher income groups benefit relatively more from moving to areas farther from the CBD. In addition, particularly near the CBD, this would lead to sorting of high income households away from the freeway. In suburban areas, the sorting with respect to proximity would be ambiguous, and the coefficients on the interaction term are consistent with this explanation.

However, the empirical results would also be consistent with other sources of heterogeneity. If amenity valuation changes by income, ($\gamma_H > \gamma_L$), then this would result in sorting away from

	(1) 0–2.5 miles	(2) 2.5–5 miles	(3) 5–10 miles	(4) 10–50 miles
<i>A. WLS estimates</i>				
Miles to nearest freeway	0.077 ^c (0.026)	0.008 (0.014)	0.046 ^c (0.016)	0.034 ^b (0.013)
<i>B. IV estimates using 1947 inter-city plan and great-circle routes</i>				
Miles to nearest freeway	0.971 ^b (0.484)	0.082 (0.120)	0.014 (0.086)	0.109 (0.084)
Weak id (C-D Wald F)	11.4	45.9	55.2	84.3
Over id (Hansen J)	0.01	0.19	1.55	0.08
... p	0.94	0.66	0.21	0.77
<i>C. IV estimates using 1898 railroad and pre-1890 exploration routes</i>				
Miles to nearest freeway	0.193 ^b (0.091)	0.143 ^b (0.060)	0.471 ^c (0.115)	0.130 ^a (0.075)
Weak id (C-D Wald F)	83.0	67.5	29.3	89.5
Over id (Hansen J)	3.05	4.79	1.03	3.15
... p	0.22	0.09	0.60	0.21
<i>D. IV estimates using all plan and historical route instruments</i>				
Miles to nearest freeway	0.233 ^c (0.088)	0.125 ^b (0.063)	0.216 ^c (0.069)	0.121 ^a (0.063)
Weak id (C-D Wald F)	51.4	55.6	38.4	78.7
Over id (Hansen J)	7.69	6.15	12.73	3.85
... p	0.10	0.19	0.01	0.43

Table 4: Effects of freeways on 1950–2010 change in income

Each cell is an estimate from a separate fixed-effects regressions of the logarithm of the 1950–2010 change in consistent-tract average household income on distance to nearest highway in miles. All regressions include metropolitan area fixed effects. Estimated standard errors, robust to heteroskedasticity and clustering on metropolitan area, are in parentheses. ^a— $p < 0.10$, ^b— $p < 0.05$, ^c— $p < 0.01$.

freeways everywhere. In addition, differences in relative benefits of highways through the net wage function $\ln w_i(x; d_F, v_F)$ itself, could lead to sorting of high income residents away from the CBD. This would happen in the presence of fixed or per mile commuting costs, that are not proportional to income.

While we cannot pin down the structural source of changes in sorting patterns, the results do suggest that highway construction has a relatively greater effect on the bid rent of high income groups both in terms of increased benefits of access and in decreased amenities near freeways. More generally, this result is consistent with the idea that high income workers will outbid low income worker for the “best” neighborhoods in terms of access and amenities, which aligns with

the mechanisms and analysis provided by Lee and Lin (2015).

4.4 Evidence on mechanisms from travel surveys

So far we have presented evidence consistent with freeway disamenities from neighborhood population and income changes. In this section, we provide supplemental evidence on mechanisms that might explain these results. This evidence relies on data constructed from archival travel surveys. Travel surveys, also known as origin-destination or trip-diary surveys, are household surveys that ask respondents to record the number of trips, purpose, mode choice, origin and destination, for a typical or reference day. Modern-day surveys of this type include the Census Transportation Planning Package from 1990 and 2000 and the National Household Travel Survey (2001).

These surveys actually have their origin in the early 20th century, as planning for interregional highways began (Levinson and Zofka, 2006). These surveys were conducted in hundreds of cities. Unfortunately, most of these surveys that predate the Interstate highway construction have been lost.

In this section, we rely on data from two studies, conducted in Detroit in 1953 and Chicago in 1956. These studies have a number of advantages. One, they predate the construction of the interstate highways. Two, they were among the first “modern” travel surveys, pioneering the use of statistical and survey methods used in modern surveys. Unfortunately, the Chicago household-level data are lost, so we rely instead on published aggregate statistics from various reports from the Chicago survey.

Jobs. An alternative interpretation of our results so far is that highways may be affecting residential location not through household utility but through firm productivity. That is, perhaps population declines near freeways in city centers is driven not by freeway disamenities, but by increased productivity of firms, which then outbid households for freeway locations. To evaluate this hypothesis, it would be useful to have data on long-run changes in establishment location or land prices between 1955 and today, at a finely disaggregated level (census tracts). Such data are not generally available. However, one can construct a crude measure of job locations from the travel survey data, by observing destinations for trips made for the purpose of going to work. The results for Chicago are shown in Table 5.

In Panels A and B, we repeat the WLS and IV regressions reported in Table 1 for Chicago tracts

	(1) 0–5 miles	(2) 5–10 miles	(3) 10–28 miles
<i>A. Population — OLS</i>			
Miles to nearest freeway	0.403 ^c (0.098)	0.140 ^c (0.035)	-0.114 ^c (0.040)
Neighborhoods	263	460	648
<i>B. Population — IV</i>			
Miles to nearest freeway	0.219 ^b (0.107)	0.322 ^c (0.059)	-1.037 ^c (0.209)
<i>C. Employment — WLS</i>			
Miles to nearest freeway	0.112 (0.257)	-0.035 (0.037)	-0.080 ^b (0.032)
<i>D. Employment — IV</i>			
Miles to nearest freeway	0.237 (0.277)	-0.162 ^c (0.056)	0.136 (0.150)

Table 5: Effects of freeways on population, income, and employment — Chicago

Each cell is an estimate from a separate regressions of the logarithm of the 1950–2010 change in consistent-tract population on distance to nearest highway in miles. Estimated standard errors, robust to heteroskedasticity and clustering on metropolitan area, are in parentheses. ^a— $p < 0.10$, ^b— $p < 0.05$, ^c— $p < 0.01$.

only. The results are similar to the entire sample (the closest 2 categories have been combined in this table due to the small number of observations and for presentation purposes). Panels C and D report regressions for identical regressions, except that the dependent variable is now the log change in jobs recorded in each tract. The estimated effects of freeways on jobs are imprecise, so it is hard to make definitive conclusions. However, it is notable that the point estimates suggest that jobs increase more farther from freeways in city centers, following the population results. We view this as tentative evidence that the changing geography of jobs is not a major factor in explaining our main results.

Barrier effects. It has long been speculated that transportation infrastructure might create barrier effects, that is, increases in the cost of travel *across* a highway. (In fact, following this logic, Oltmans Ananat (2011) constructs an instrument for racial segregation that uses historical rail lines.) A block-wide elevated train line in Center City Philadelphia was long known as the “Chinese Wall.” Of course, actual walls also block spatial spillovers (see Redding and Sturm, 2008, and Ahfeldt et al. 2015).

We analyze trip flows using the Detroit survey from 1953 and a follow-up survey conducted in 1994. A database of trips records the origin and destination latitudes and longitudes. We then measure the distance of the shortest-path route between these coordinates. To provide evidence on the barrier effects of highways, we compare the 1953 and 1994 share of trips at a given distance that cross a present-day freeway. In 1953, before the freeways were built, such trips would have been unaffected by the future freeway route. In 1994, decades after freeway construction, household trips would be affected along a number of margins. Obviously, trips would be longer, given faster travel speeds. However, conditioned on trip distance, if freeways serve as barriers, we might expect to see a larger number of trips at that distance avoid crossing a freeway. We also expect to see this effect at short distances. One, because barriers might be especially affect walking trips. Two, because for longer trips, the marginal cost of detours forced by fewer cross-freeway arterials might be lower.

Figure 4 shows the 1994 trip data as dashed lines. Note that trip density is so high as to make only trips on the periphery distinguishable. We also only analyze 1994 trips within the 1953 footprint of city, also shown. Figure 5 shows, by trip distance, the percent of trips made that cross at least one present-day freeway. Interestingly, in 1953, nearly 70% of short trips of less than 5km cross a present-day freeway. However, in 1994, only about 40% of trips of 5km cross a freeway. We view this as preliminary evidence that freeways potentially increase the cost of travel across a freeway.

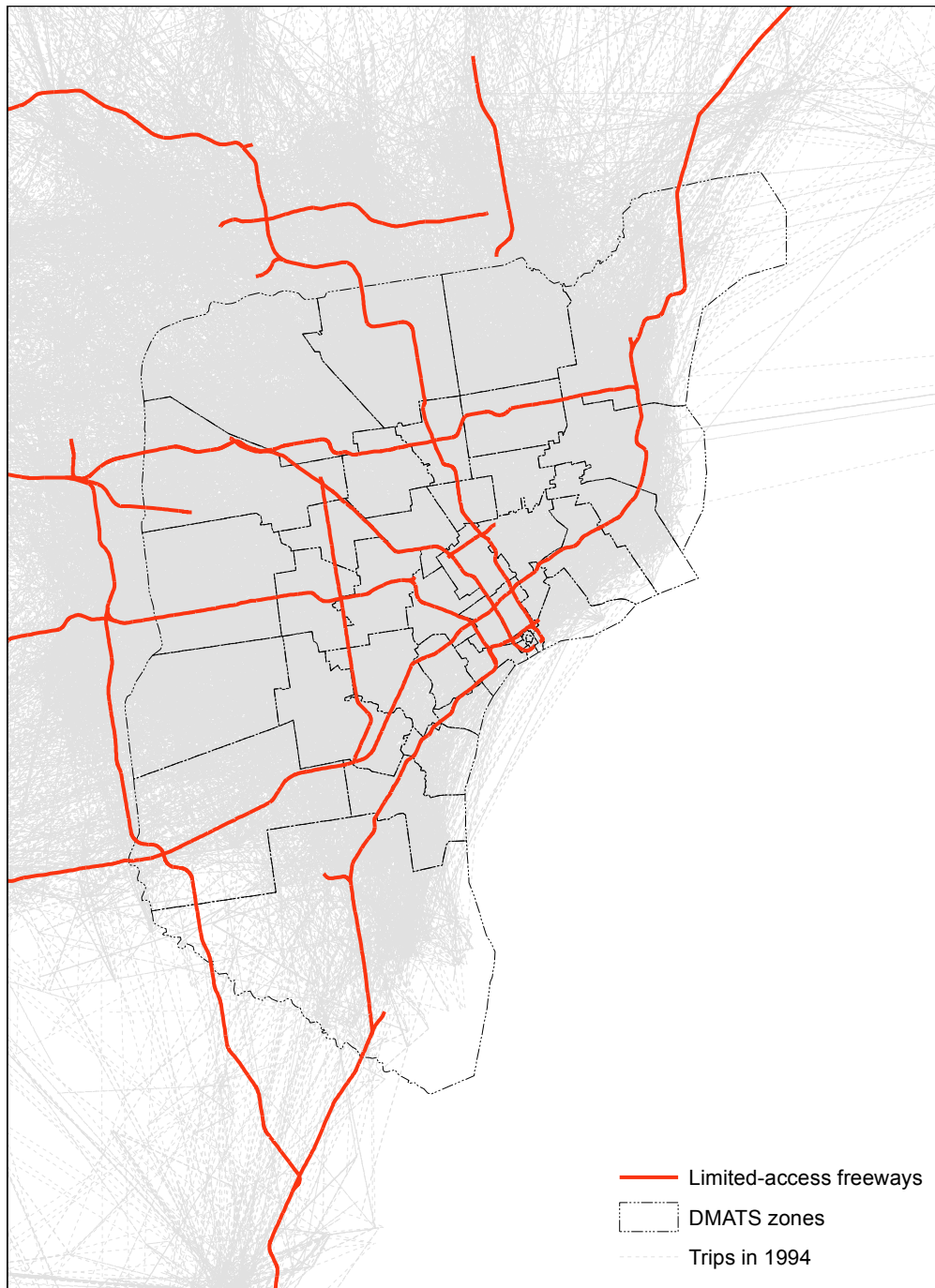


Figure 4: Map of Detroit area showing 1953 DMATS zone boundaries

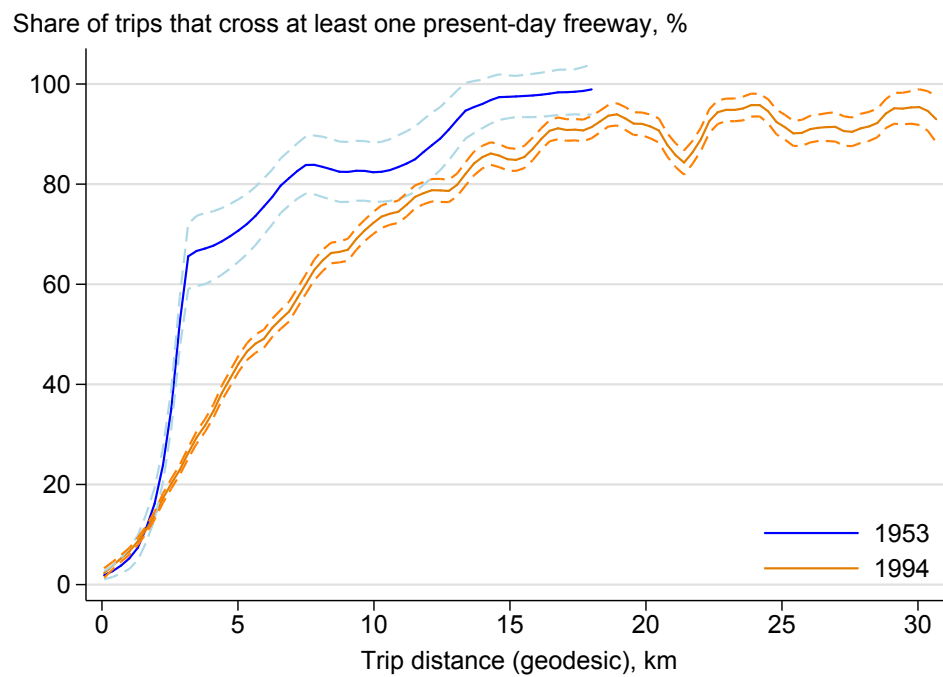


Figure 5: Number of person-trips by geodesic distance and present-day freeway crossings, Detroit 1953 vs. 1994

5 The freeway revolts and the changing allocation of freeways

5.1 Historical background

5.1.1 Highway planning before 1955

Congress began considering what would become the Interstate Highway System in the 1910s and 1920s. In this period, high-speed, limited-access roads were planned and financed by state and local agencies dominated by highway engineers. (The bulk of federal funding would not come until the 1956 highway act.) These builders did not anticipate negative amenity effects. Concept drawings by Le Corbusier and others in the 1920s and 1930s showed “broad highways penetrat[ing] central cities, slicing through phalanxes of skyscrapers” (DiMento and Ellis, 2013, p. 17). A 1924 plan for Detroit showed superhighways with a “‘parkway’ ambience [...] reinforced by groups of pedestrians ambling along only a few feet from the freeway, as though it were a Parisian boulevard” (p. 19). Through the 1930s, planners views of effects of automobiles were still immature. “[T]he meaning of the automobile—and of parkways—was quite different [...] from its later incarnations. [...] Even Lewis Mumford [...] viewed the automobile as a beneficent liberator of urban dwellers from the cramped confines of the industrial city” (p. 38).

Urban freeway planning in the 1940s and 1950s was still dominated by highway engineers at state highway departments and the federal Bureau of Public Roads (BPR), whose experience was almost entirely in building out the rural sections of the national highway network under the provisions of the Federal-Aid Highway Act of 1944. Rural highway building was less concerned with negative externalities and displacing existing factors. Instead, speed and capacity were the guiding concerns. “Between 1946 and 1956 [...] [i]nitial planning was begun on the interstate system, with state highway departments taking the lead and emphasizing traffic-carrying efficiency [...]” (p. 100). Few city officials (not even considering local residents) were involved in planning. “The planning and design professions stood outside the highway planning community [...] State highway departments consolidated their hold on the urban freeway planning process, eclipsing local planning and public works officials” (p. 100).

5.1.2 The “Yellow Book” plan of 1955

The mid-1950s marked a turning point in the development of the Interstate Highway System. In 1947, the BPR had mapped about 90 percent of National System of Interstate Highways authorized (but incompletely funded) by Congress in the Federal-Aid Highway Act of 1944 (this is the map used in Baum-Snow, 2007). This map showed rural routes that terminated outside metropolitan areas. In 1955, the remaining (urban) mileage was designated by the BPR in a series of maps contained in the *General Location of National System of Interstate Highways Including All Additional Routes at Urban Areas Designated in September 1955*, known as the “Yellow Book.” Unlike the 1947 plan, which described only routes *between* cities, the Yellow Book described the general routing of highways *within* each of 100 metropolitan areas. These routes were determined with the cooperation of State highway departments according to several criteria. Routes were favored that (1) penetrated the downtown core or (2) circumvented central cities via beltway; (3) used undeveloped land; (4) linked to other modes such as rail stations and ports; (5) followed forecasted demand and (6) topography and physical feature such as rivers; and (7) were compatible with existing land uses and (8) national defense (“Criteria for Selection of Interstate System Routes,” testimony by Commissioner of Public Roads C.D. Curtiss, April 15, 1955, in Weingroff, 2015).

The Federal-Aid Highway Act of 1956 authorized the 41,000 mile Interstate system to be built over 13 years (Weingroff, 1996). Importantly, the Act provided for 90 percent federal funding, lowering the last major barrier for mass construction of urban freeways. “The mass production of urban interstates would soon be under way [...] Between 1956 and 1970, urban freeway form concepts [...] became blueprints for actual construction” (DiMento and Ellis, p. 102). State highway departments, “believ[ing] they had to finish the entire 41,000 miles within the 13-year funding framework” (Weingroff, 2016), raced to complete their segments. State highway departments varied in their initial planning and construction. The AAHSO (1965) noted that

Not all Interstate routes were starting from the same point, in 1956. Some sections, indeed, were already completed, although mostly these were toll roads. Some others were in varied stages of development: a 2-lane highway needed expansion to 4 lanes; an expressway lacking full control of access or needing additional grade separations or lanes [...] Not all States were starting from the same point in 1956, either, for a variety

of reasons. A “shelf” of project plans was available in some States but not others. Some State highway departments were able to staff up to a job rapidly while others took much longer; many had previously done little or no right-of-way acquisition on their own; some had never before designed or built freeways on a large scale.

An important feature of this period is that, as of 1955, highway planners did not anticipate the breadth or intensity of community resistance to urban freeway plans. “[N]o one anticipated the urban battles ahead so no one thought ‘I better build my urban segments right away before anyone starts fighting them.’ Officials simply made choices about the priority of each segment for construction based on whatever factors they considered important” (Weingroff, 2016).

5.1.3 The spread of freeway revolts after 1955

In 1955, residents in the path of the Western Freeway in San Francisco organized to fight the proposed route (Dimento and Ellis, p. 137). Protests (“freeway revolts”) continued to spread to a large number of cities in the 1950s and 1960s. Although the most famous are in San Francisco and lower Manhattan (e.g., the LOMEX proposal that set Jane Jacobs against Robert Moses), Wikipedia notes over 200 controversial freeway proposals that experienced community protests, across 50 cities. Lowell K. Bridwell, an early federal administrator who was sympathetic to revolts, noted highway planners faced social and environmental “problems of a serious nature in at least 25 cities” in March 1968 (Mohl, 2008, p. 202). It’s worth noting that the widespread freeway revolts are *prima facie* evidence of the negative amenity effects of freeways.

In response to spreading freeway revolts, the policy and practice of highway planning began to change. According to Mohl (2004):

The timing, progress, and outcome of the emerging freeway revolt differed from city to city ... [I]n cities where the highway builders moved quickly in the late 1950s to build the urban interstates, the inner beltways and radials, opposition never materialized or was weakly expressed. [...] Where freeway construction was delayed into the 1960s, affected neighborhoods, institutions, and businesses had time to organize against the highwaymen. In some cases, freeway fighters successfully forced the adoption of alternative routes, and they even shut down some specific interstate projects permanently

(p. 675)

In addition, subsequent highway bills responded to the freeway revolts by making it more difficult for highway planners to override community opposition. For example, the 1958 highway act first required State highway planners to hold public hearings and consider economic effects in advance of construction. The 1962 highway act further required that highway projects be “carried out cooperatively” with local communities (DiMento and Ellis, 2013). Highway legislation in 1966 and 1968 created new environmental and historic-preservation hurdles for new highway construction. In addition, highways were now subject to the Department of Transportation, established in 1966 and opened in 1967. Its first Secretary, Alan S. Boyd, was sympathetic “to the public clamor over the damaging impact of interstates in urban neighborhoods” (Mohl 2004, p. 681). By 1967, “The freeway debates and protests of the late 1960s begin to erode formerly uncritical acceptance of urban freeways.” (DiMento and Ellis, 2013, p. 140). “Within a year of taking office at the DOT [in 1967], [Secretary of Transportation] Boyd had seemingly become the most effective national spokesman for the freeway revolt.” (Mohl 2004, p. 681).

5.2 The changing allocation of freeways

The freeway revolts and the increasing legislative requirements following the 1962 highway act combined to change the allocation of freeways to neighborhoods over time. As freeway planners did not expect the breadth and intensity of subsequent freeway revolts circa 1955, the choice of which projects to begin first was unrelated to the later intensity of community opposition. Further, in 1955, states highway departments varied in their readiness to implement the Interstate highway plan. Some had plans on the shelf, while others needed more time to perform right-of-way acquisition, design, and engineering activities. But because of the growing freeway revolts, interstates that were built earlier in the 13-year period authorized by the 1956 highway act were more likely to be completed along their initial planned routes.

We start with the 1955 Yellow Book to as a baseline to analyze the changing allocation of freeways. The Yellow Book plan has several advantages for this purpose. To summarize, it was the first official publication detailing Interstate routes within metropolitan areas. It covered 100 metropolitan areas. It was prepared and published just before the Federal Aid Highway Act of 1956,

which authorized 90 percent federal funding for the Interstate Highway System. It largely reflected highways planners' views, who were later surprised by the strength and breadth of freeway revolts. It predates the freeway revolts era; later plans (e.g., the 1960 I-266 "Three Sisters Bridge" plan) had more highways, but also reflected increased recognition of community protests. These later plans may have selected routes that were more sensitive to neighborhood concerns and unobserved factors.

5.2.1 Washington, D.C.

For Washington, D.C., we use information on programming dates per highway segment. "Programming" refers to initial engineering and design work for a highway segment. To our knowledge there is no comprehensive study of freeway planning, programming and revolts across many states and cities. Getting information on planning dates for unbuilt highways is especially difficult. However, there is pretty good information on highway planning from individual state and US DOT records, e.g., PR-511 data, for routes that were eventually built. In addition, for unbuilt highways, portions or stubs that *were* built may have planning dates from the PR-511 records. These stubs' planning dates can then be extrapolated to unbuilt segments. Also, there are many case studies of individual highway segments and cities on planning dates for segments that were eventually abandoned. (In the case of Washington, D.C., we rely on detailed histories on the web sites DCroads.net and Roads to the Future.)

We define a segment as a unique route number-county-intersecting route combination. Sub-county resolution is often unwieldy and unreliable. In addition, it is difficult to collect data on highway planning at the neighborhood level. Further, neighborhood-level highway construction outcomes are likely to be endogenous to neighborhood characteristics. In contrast, counties are heterogeneous and planning dates are less subject to neighborhood factors. Finally, intersecting routes are useful divisions because highways were often built in stages, with an intersecting route being a natural stopping point. Figure ?? shows these divisions in the 1955 Yellow Book plan. It also shows the program dates, measured to the best of our ability.

Programming dates are determined as follows. For segments of the Yellow Book plan that were eventually built and have valid PR-511 data, we use the latest date of right-of-way acquisition or PS&E development (plan, specification, and estimate) listed. For segments that were eventually

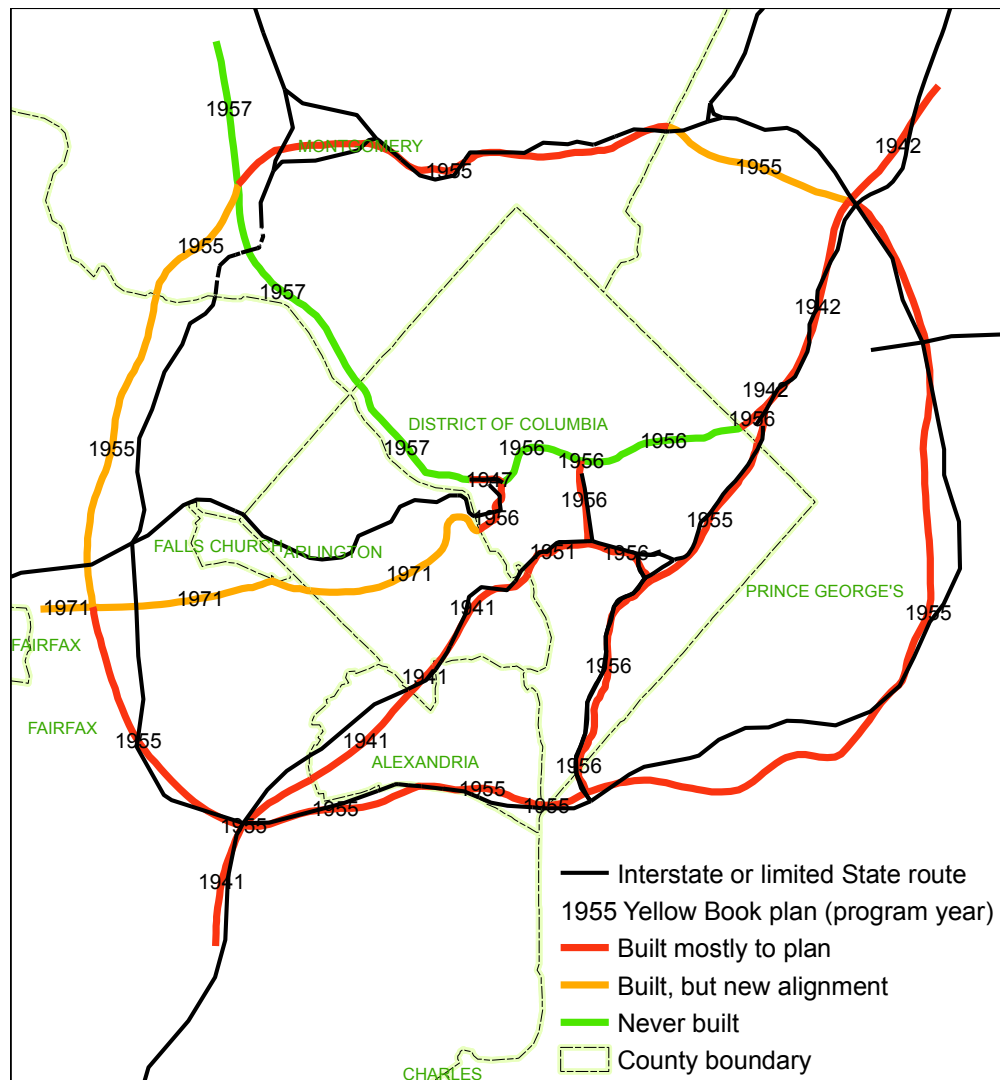


Figure 6: Map of Washington area showing Yellow Book plan and present-day freeways with approximate program year

built, this errs on the side of moving the program date later, towards the 1955 cutoff.

For segments of the Yellow Book plan that were eventually abandoned, what was the earliest year in which right-of-way acquisition, public hearing, surveying, engineering, etc. occurred? This errs on the side of moving the program date earlier.

A few features are of note. Programming for the Beltway began before the Interstate Highway Act was passed, and it was built largely to plan. Highway segments that were programmed later tended to deviate more from the original plan routes. The alignment for I-66, stretching west from DC to Fairfax, was significantly altered. This was in part due to its late programming date—initial work was not begun until well after the revolts. There was also intense citizen opposition in Arlington and Falls Church, which also contributed to the departure from initial plans. The freeway that was to run northwest from downtown DC through Georgetown along the Potomac was eventually canceled in the face of a freeway revolt. It’s notable that both of these routes went through affluent, predominantly white areas.

5.2.2 Nationwide

For the U.S. as a whole, we lack comprehensive programming dates. Instead we can use the PR-511 data, which records year open to traffic for routes that were eventually built. For each year of 1955, 1960, 1965, 1970, and 2016, we compute tract distance to the nearest segment planned or open to traffic by that year. Then, we regress miles to the nearest highway open to traffic that year on a variety of 1950 tract characteristics to illustrate the changing selection of urban neighborhoods for freeways over time.

Figure 7 shows the results of regressions on 1950 tract population density. The vertical axis measures the coefficient on 1950 tract population density, which is standardized within metropolitan areas. The coefficient can then be interpreted the change in miles from the nearest freeway associated with a one-standard deviation increase in 1950 tract population density. Panel A shows results for all tracts. Panel B shows results just for tracts within 2.5 miles from the city center. Though the estimates are imprecise, the pattern of results across the two panels and over time is interesting. First, in 2016, there is little correlation between 1950 tract population density and distance to freeways, overall. However, in city centers, this correlation is positive. That is, tracts that had high population densities near downtown were *less* likely to receive freeways.

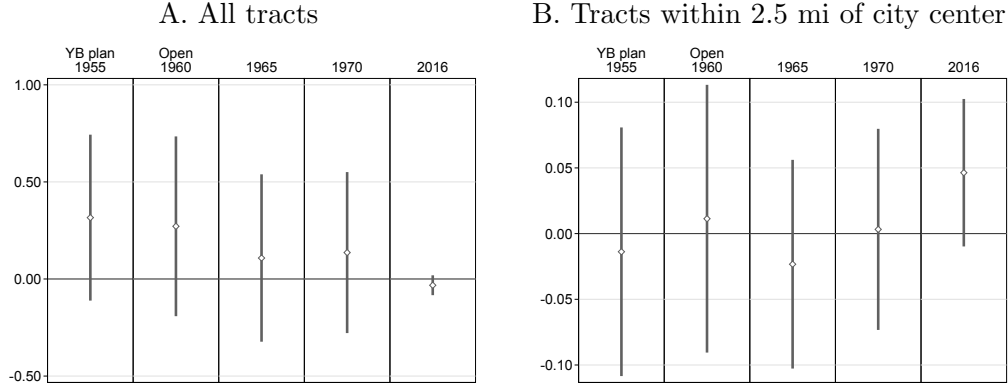


Figure 7: Selection of freeway routes over time by 1950 population density

Each panel reports estimates from five separate regressions. First column of each panel titled “Yellow Book” shows estimated coefficient and 95% confidence interval from fixed-effects regression of the distance in miles to the nearest Yellow Book plan route on 1950 population density. Standard errors clustered on metropolitan area. Subsequent columns show estimated coefficient from fixed-effects regressions of the distance in miles to the nearest freeway open to traffic by year indicated by column title on 1950 tract population density. Tract characteristics are standardized within 1950 metropolitan areas to mean 0, standard deviation 1. All regressions use observations of 15,161 consistent-boundary tracts in 52 metropolitan areas. A negative estimate indicates positive selection on that 1950 tract characteristic for freeway route (i.e., closer to freeways). Total mileage open to traffic at end of 1960: 10,400; 1965: 21,200; 1970: 31,500; 1999: 46,300. Average distance (standard deviation) in miles to nearest freeway: Yellow book plan—2.1 (2.9); Open by 1955—27.4 (84.8), Open by 1960—8.5 (26.2), Open by 1965—2.4 (2.6); Open by 1970—2.2 (2.6); Open by 1999—1.8 (2.4).

Interestingly, the yellow book plan shares this feature for all neighborhoods: Denser tracts in 1950 were less likely to receive freeways (they were further from freeways). This actually accords with some historical evidence. In 1957, the American Association of State highway Officials issued a new codification of standards for interstates in the so-called “Red Book.” It offered specific suggestions for the location of urban freeways:

Most cities have land areas outside the central core that lend themselves to the location of new highways. The improvement of radial highways in the past stimulated land development along them and often left wedges of relatively unused land between these ribbons of development. These undeveloped land areas may offer locations for radial routes (p. 89)

(Other criteria for route selection cited included blighted areas, adjacent to railroads or shore lines of rivers and lakes, and within or along parks or other large parcels owned by cities or institutions.) Thus the Red Book emphasized land assembly and acquisition costs as a guiding principle for freeway route selection. This advice appears to have been followed by the Yellow Book plan, though gradually later highway locations were less related to 1950 population density—

perhaps as a greater proportion of freeways were built in low-density outlying areas. However, in central cities, actually built highways followed the opposite trend: Over time, highways were less likely to be built in initially high-density neighborhoods. The fact that in central cities, highways were more likely to be built in initially less-developed areas, is consistent with the selection of neighborhoods on high growth potential seen in the larger IV estimates compared with WLS estimates earlier.

The influence of the Red Book can also be seen in the changing geography of highways according to shorelines and parks. Figure 8 shows that while the Yellow Book plan put highways far from coastlines, lakes, rivers, and parks, over time, actually-built freeways tended to be closer to these natural features.

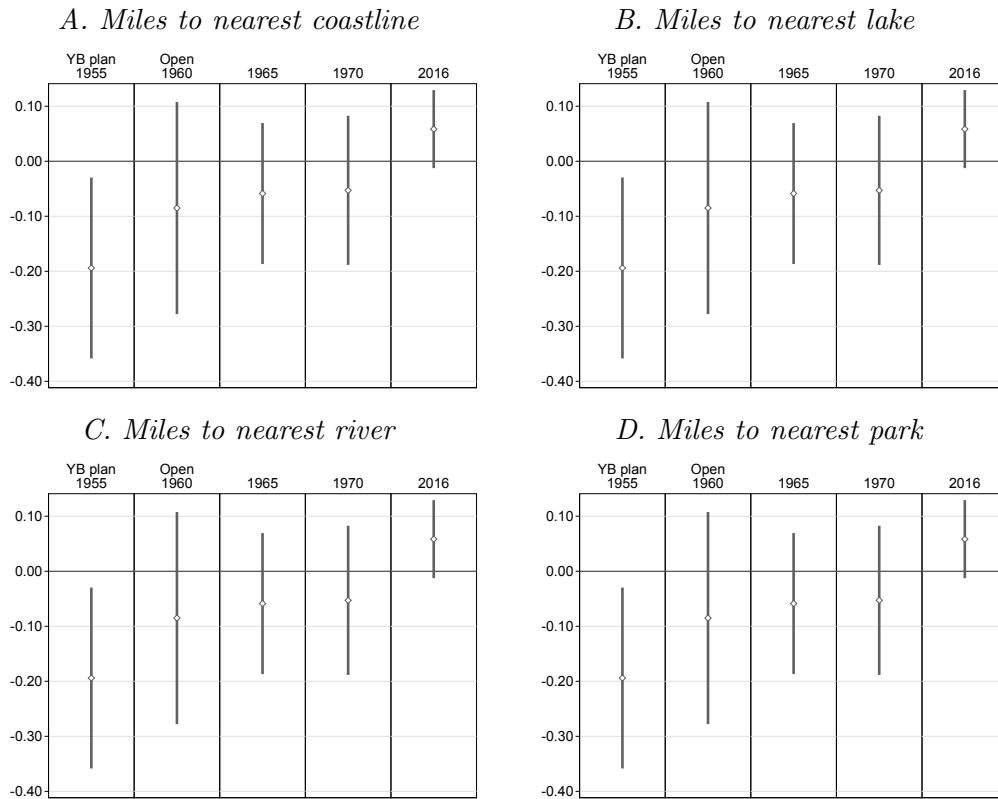


Figure 8: Selection of freeway routes over time by natural factors

Finally, Figure 9 shows the changing correlation of actually-built freeways with a number of 1950 tract characteristics. Compared with the Yellow Book plan, neighborhoods selected for freeways had in 1950 a higher share of African Americans; fewer college graduates, and lower incomes, house

values and rents.

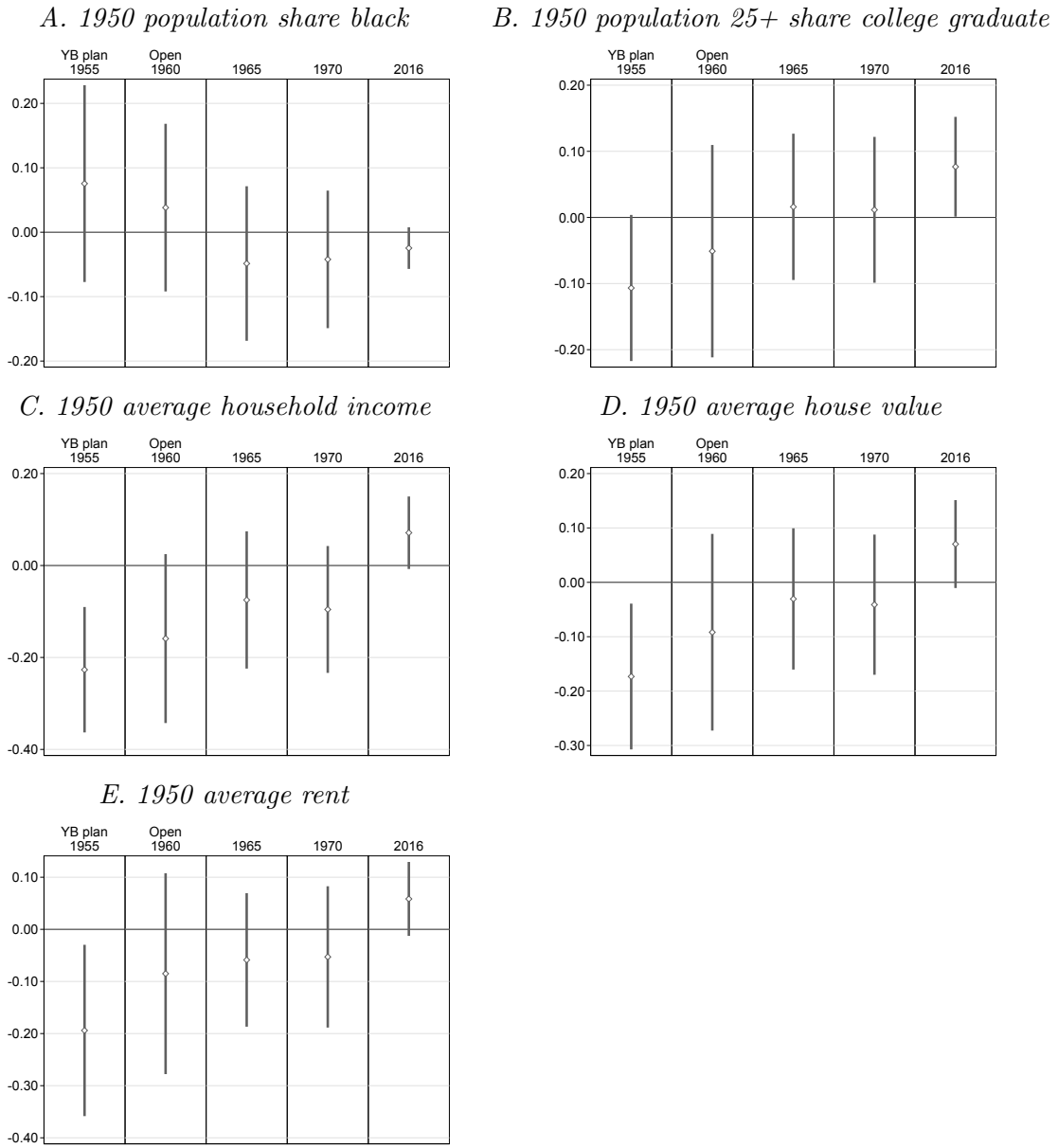


Figure 9: Selection of freeway routes over time by 1950 neighborhood characteristics

6 A Quantitative Model of Urban Highways

In this section, we develop a quantitative model of highways in urban areas, which builds on the work of Ahfedlt, Redding, Sturm, and Wolfe (2015). The key departure is that we explicitly model a disamenity effect from highways for nearby neighborhoods.

6.1 Geography

There are J locations in the city, each with land area L_j . Land may be used for residential or production purposes. There is a cost of traveling between locations, d_{jk} , that depends on the transportation network, T , such that $d_{jk} = e^{\kappa\tau_{ij}}$, where τ_{ij} is the travel time between two locations. The transportation network is complex and consists of freeways and surface streets. The city is embedded within a larger economy, and workers are free to leave the city, although they cannot commute into or out of the city for work. Therefore, the population of workers, N , is endogenously determined by the outside reservation utility, $\bar{U}$, which is the same for all workers.

6.2 Workers

Workers have increasing preferences over consumption, c , land, l , and some neighborhood-specific amenity, z_j .¹⁴ In addition, each individual worker, n , is endowed with one unit of labor, which they supply inelastically, and has an idiosyncratic preference for a given commute between home location j and work location k , $\nu_{jk,n}$. The idiosyncratic component is not revealed until the worker moves to the city, thus the expected utility is equal to the reservation utility. **Utility** is given by,

$$U_{jk,n}(c, l) = \nu_{jk,n} B_j \left(\frac{c}{\beta} \right)^\beta \left(\frac{l}{1-\beta} \right)^{1-\beta}.$$

The idiosyncratic component is drawn from a type II extreme value distribution defined by,

$$F(\nu_{jk,n}) = e^{-r_j s_k \nu_{jk,n}^{-\varepsilon}}$$

where r_j and s_k determine the average utility of working in location k and living in location j respectively.¹⁵ Workers earn a wage that is dependent on where they work, w_k . The workers' budget constraint is then given by,

¹⁴We assume direct consumption of land, but could include a housing/building production function. Cobb-Douglas should imply a direct relationship between land rents and property rents.

¹⁵ s_k can be modeled in an isomorphic way as a location-specific productivity.

$$\frac{w_j}{d_{jk}} = lq_j + c,$$

where q_j is the price of land. It can be shown, that **indirect utility** is then given by

$$u_{jk,n}(c, l) = \nu_{jk,n} \frac{w_k}{d_{jk}} B_j \ln q_j^{(\beta-1)}$$

Land consumption by commute pair is given by:

$$l_{jk} = \frac{w_k}{q_j d_{jk}} (1 - \beta)$$

The probability that a worker will live in location j and commute to k is given by:

$$\pi_{jk} = \frac{r_j s_k (d_{jk} q_j^{1-\beta})^{-\varepsilon} (B_j w_k)^\varepsilon}{\sum_{j'=1}^J \sum_{k'=1}^J r_{j'} s_{k'} (d_{j'k'}^{1-\beta})^{-\varepsilon} (B_{j'} w_{k'})^\varepsilon}$$

The probability that a worker will commute to location k , conditional on living in j , is given by:

$$\pi_{jk|j} = \frac{s_k \left(\frac{w_j}{d_{jk}} \right)^\varepsilon}{\sum_{k'=1}^J s_{k'} \left(\frac{w_{j'}}{d_{jk'}} \right)^\varepsilon}$$

This implies the **commuting market clearing** condition:

$$N_{Wk} = \frac{s_k \left(\frac{w_j}{d_{jk}} \right)^\varepsilon}{\sum_{k'=1}^J s_{k'} \left(\frac{w_{j'}}{d_{jk'}} \right)^\varepsilon} N_{Rj}$$

Where N_{Wk} represents the measure of workers working in location k , and N_{Rj} represents the measure of workers residing in location j . Population mobility requires that the expected utility is equal to the reservation utility. Formally:

$$E[u] = \Gamma\left(\frac{\varepsilon-1}{\varepsilon}\right) \left[\sum_{j'=1}^J \sum_{k'=1}^J r_{j'} s_{k'} (d_{j'k'}^{1-\beta})^{-\varepsilon} (B_{j'} w_{k'})^\varepsilon \right]^{1/\varepsilon} = \bar{U}$$

where Γ is the Gamma function. **Total residential land consumption** in a location is calculated by summing the land demand for all workers in a location.

$$L_{Hj} = (1 - \beta) \frac{N_{Hj}}{q_j} \sum_{k=1}^J \pi_{jk|j} \frac{w_k}{d_{jk}}$$

6.2.1 The Amenity Function

The amenity function may be endogenous and depend on proximity to a highway, and is given by,

$$B_j = b_j g(d_H) \left(\sum_{j'=1}^J e^{-\rho\tau_{jj'}} \left(\frac{N_{Wj'}}{L_{j'}} \right) \right)^\gamma,$$

where b_j is the exogenous component, and $g(d_H)$ is the disamenity resulting from proximity to a highway. For now we will assume that the disamenity is a simple function of distance to the highway, and does not depend on endogenous variables. We assume the disamenity takes the following form.¹⁶

$$g(d_H) = 1 - b_H e^{-\eta d_H}$$

where b_H is the scale effect, and η describes the attenuation of the disamenity across space.

6.3 Production

There is a single final good that is costlessly traded, produced under perfect competition and has the following constant returns production function in each location.

$$Y_j = A_j L_{Wj}^{1-\alpha} N_{Wj}^\alpha$$

where A_j is total factor productivity, L_{Wj} , is total land used for production in each location, and N_{Wj} is total employment in each location. We assume productivity is partially exogenous and partially endogenous, and given by the following,¹⁷

$$A_j = a_j x_j^\eta$$

where a_j is the exogenous productivity of a location, and x_j , is a production externality that arises from clustering of economic activity, and is given by,

$$x_j = \sum_{j'=1}^J e^{-\delta\tau_{jj'}} \left(\frac{N_{Wj'}}{L_{j'}} \right).$$

Total commercial land use in each location is given by the following relationship.

$$L_{Wj} = N_{Wj} \frac{(1-\alpha)}{\alpha} \frac{w_j}{q_j}$$

¹⁶This is isomorphic to a cost that decays exponentially with distance to the highway. See Nelson (1982) for an example in the literature.

¹⁷For now, we assume there is no productivity disadvantage of locating near a highway.

6.4 Land Market Clearing

The land market clearing condition is the following.

$$L_{Wj} + L_{Hk} = L_j$$

Define θ_j to be the fraction of land used for production such that $\theta_j L_j = L_{Wj}$ and $(1 - \theta_j)L_j = L_{Hk}$.

6.5 Solution Algorithm

First note that certain terms are isomorphic in equilibrium, and thus it is not necessary to solve for the quantities separately.¹⁸ Specifically, we can define the following in order to simplify the equilibrium solution.

$$\tilde{w}_k = w_k s_k^{1/\varepsilon}$$

$$\tilde{A}_k = A_k s_k^{\alpha/\varepsilon}$$

$$\tilde{B}_j = B_j r_j^{1/\varepsilon}$$

6.5.1 Solution Algorithm with no Spillovers

We observe land area and travel times $\{L_j, d_{ij}\}$. We know values for the models parameters $\{\alpha, \beta, \varepsilon\}$ and location fundamentals, $\{\tilde{A}_k, \tilde{B}_j\}$. To solve for equilibrium, we start with a guess of rents, wages, and land use, $\{q_j^0, \tilde{w}_k^0\}$. We use these to calculate new variables iteratively, using the equations below.

1. fraction of workers who chose each commuting pair.

$$\pi_{jk}^1 = \frac{\left(d_{jk}(q_j^0)^{1-\beta}\right)^{-\varepsilon} (\tilde{B}_j \tilde{w}_k^0)^\varepsilon}{\sum_{j'=1}^J \sum_{k'=1}^J \left(d_{j'k'}(q_{j'}^0)^{1-\beta}\right)^{-\varepsilon} (\tilde{B}_{j'} \tilde{w}_{k'}^0)^\varepsilon}$$

2. fraction of workers who chose a commute conditional on residential location

¹⁸These could theoretically be identified with other moments, but are necessary for the analysis here. See Ahlfeldt, Redding, Sturm, and Wolf (2015) for details.

$$\pi_{jk|j}^1 = \frac{\left(\frac{\tilde{w}_j^0}{d_{jk}}\right)^\varepsilon}{\sum_{k'=1}^J \left(\frac{\tilde{w}_{j'}^0}{d_{jk'}}\right)^\varepsilon}$$

3. Residential Population

$$\begin{aligned} N_{Hjk}^1 &= \pi_{jk}^1 N \\ N_{Hj}^1 &= \sum_{k=1}^J N_{Hjk}^1 \\ N_{Hj}^1 &= \sum_{k=1}^J \pi_{jk}^1 N \end{aligned}$$

4. Employment

$$N_{Wj}^1 = \sum_{k=1}^J \pi_{jk}^1 N$$

5. Residential Land Use

$$\begin{aligned} L_{Hjk} &= (1 - \beta) \frac{N_{Hjk}^1}{q_j^0} \frac{\tilde{w}_k^0}{d_{jk}} \\ L_{Hj} &= \sum_{k=1}^J L_{Hjk} \\ L_{Hj} &= (1 - \beta) \frac{N_{Hj}^1}{q_j^0} \sum_{k=1}^J \pi_{jk|j}^1 \frac{\tilde{w}_k^0}{d_{jk}} \end{aligned}$$

6. Commercial Land Use

$$L_{Wj} = N_{Wj}^1 \frac{(1-\alpha)}{\alpha} \frac{w_j^0}{q_j^0}$$

7. Land Use Function

$$\theta_j^1 = \frac{L_{Wj}}{L_{Wj} + L_{Hj}}$$

8. Production

$$Y_j^1 = \tilde{A}_j \left(N_{Wj}^1\right)^\alpha \left(\theta_j^1 L_j\right)^{1-\alpha}$$

9. Wage is the marginal product of labor

$$\tilde{w}_j^1 = \frac{\alpha Y_j^1}{N_{Wj}^1}$$

10. Rent is the marginal product of land.

$$q_j^1 = \frac{(1-\alpha)Y_j^1}{\theta_j^1 L_j}$$

11. (For the open city model only) Expected utility must equal reservation utility.

$$E[u] = \Gamma\left(\frac{\varepsilon-1}{\varepsilon}\right) \left[\sum_{j'=1}^J \sum_{k'=1}^J \tilde{B}_{j'}^\varepsilon \tilde{w}_{k'}^\varepsilon \left(d_{j'k'} q_{j'}^{1-\beta}\right)^{-\varepsilon} \right]^{1/\varepsilon} = \bar{U}$$

where Γ is the Gamma function.

6.5.2 Solving with spillovers

Solving for the case of endogenous productivity and amenities requires adding the equations that describe the externalities. It also requires guessing an initial distribution of population and employment.

$$A_k = \tilde{a}_k \left(\sum_{k'=1}^J e^{-\delta\tau_{kk'}} \left(\frac{N_{Wk}}{L_k} \right) \right)^\eta$$

$$B_j = \tilde{b}_j g(d_H) \left(\sum_{j'=1}^J e^{-\rho\tau_{jj'}} \left(\frac{N_{Wj'}}{L_{j'}} \right) \right)^\gamma$$

7 Simulations

This section illustrates some of the features of the model and the predictions of the theory. In particular, we simulate the effects of adding a highway to a city, considering both the case where there are only access benefits through reduced transportation costs and the case where there are also residential disamenity effects. The model is roughly calibrated to match reasonable features of a real city, but here we only want to emphasize the qualitative effects of highways, and not take the quantitative results too seriously.

In this simulation we consider a city where initially there are only surface streets that run both parallel and perpendicular to the x-axis everywhere in the city. There is an exogenous productivity, such that production is concentrated in the center of the city. The first panel in Figure 10 shows the equilibrium distribution of population before the highway is built. In this case, population is

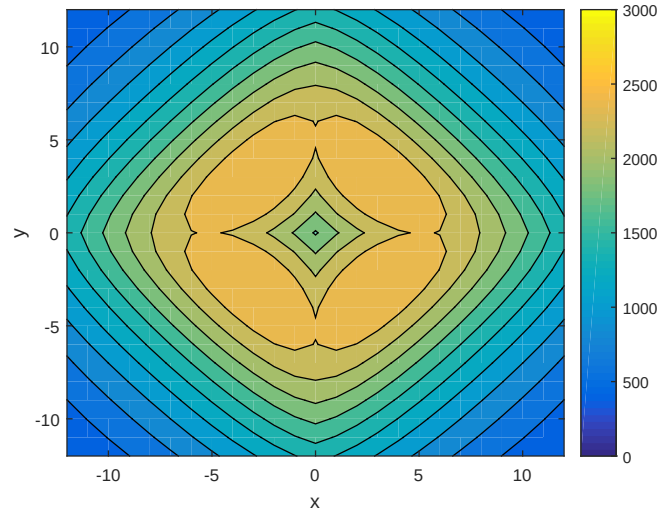
distributed symmetrically around the center of the city, first increasing from the city center, reflecting the increase in residential land use before declining in the outskirts of the city.

The second panel of Figure 10, shows the effects of adding a highway along the x-axis, without including the disamenity effects of the highway. The result is that population spreads out along the highway. The first panel in Figure 11 shows the log change in population for this case. First note that population increases are larger further from the city center and close to the highway, reflecting the increased access benefits provided by the highway. In addition, even for locations near the city center, proximity to a highway is associated with population increases; i.e. holding distance to the city center constant, population increases are larger for locations near the highway.

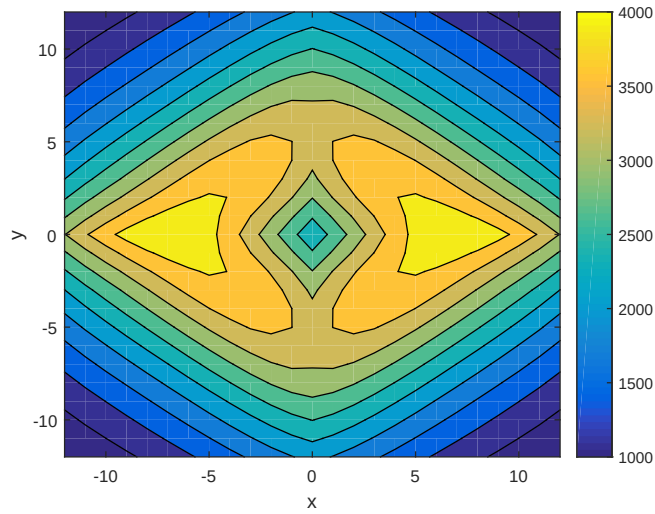
However, when the disamenity effects are included the picture changes. This is shown in the second panel of Figure 11. In this case, it can be seen that near the city center, locations near the highway experience a population loss. This is due to the fact that the highway provides few access benefits in these locations, but only disamenity effects. In locations further from the city center, however, the access benefits dominate, and proximity to a highway is still associated with larger population gains.

8 Conclusions

To come.

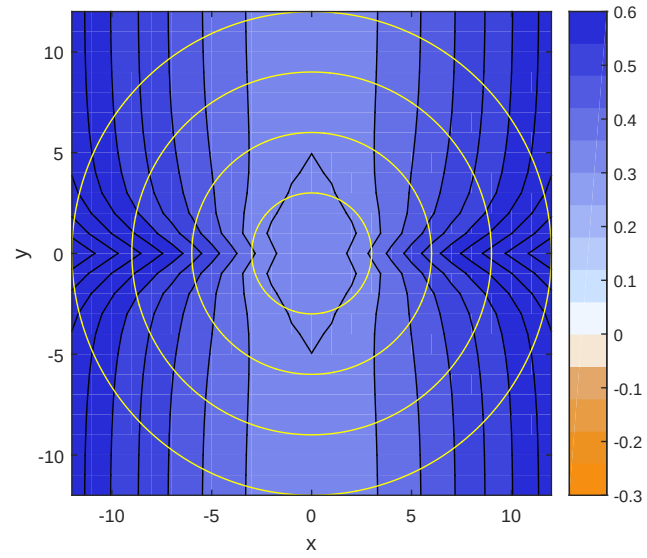


(a) population density before highway

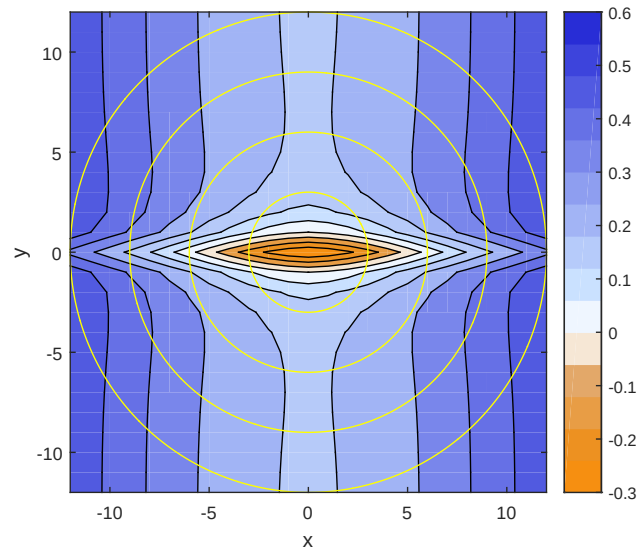


(b) population density after highway

Figure 10: Simulation of population density before and after a highway - No disamenity effects



(a) change without disamenity



(b) change with disamenity

Figure 11: Simulation of the change in log population density after a highway is built.

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