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We estimate the effects of interstate highways on the growth of U.S. cities between 1983 and 2003. We find that a 10% increase in a city's initial stock of highways causes about a 1·5% increase in its employment over this 20 year period. To estimate a structural model of urban growth and transportation, we rely on an instrumental variables estimation that uses a 1947 plan of the interstate highway system, an 1898 map of railroads, and maps of the early explorations of the U.S. as instruments for 1983 highways.

Key words: Urban growth, Transportation, Interstate highways, Instrumental variables

JEL Codes: L91, N70, R11, R49

1. INTRODUCTION

We investigate the role of interstate highways in the growth of U.S. cities. Our investigation is in three parts. In the first, we develop a simple structural model describing the joint evolution of highways and employment in cities. In the second, we develop an instrumental variables strategy that allows us to identify key parameters of our structural model. We are also able to provide out of sample evidence for the validity of our estimates and for the central assumptions of our model. In the third, we use our estimates to assess counterfactual transportation policies.

We find that a 10% increase in a city's stock of (interstate) highways causes about a 1·5% increase in its employment over 20 years and that an additional kilometre of highway allocated to a city at random is associated with a larger increase in employment or population than is a road assigned to a city by the prevailing political process. Our results also suggest that too many new highways were built between 1983 and 2003.

These findings are important for three reasons. First, transportation generally, and infrastructure in particular are large segments of the economy. The median U.S. household devotes about 18% of its income to road transportation while all levels of government together spend another 200 billion dollars annually. Overall, the value of capital stock associated with road transportation in the U.S. tops 5 trillion dollars (United States Bureau of Transportation Statistics, 2007, 2010). Given the magnitude of transportation expenditures, it is important that the impact of these expenditures on economic growth be carefully evaluated and not assessed on the basis of the claims of advocacy groups. Our analysis provides a basis for assessing whether these resources are well allocated.

Our results also provide useful guidance to policy makers charged with planning cities. Since changes in a city's transportation infrastructure cause changes to the city's employment, new transportation infrastructure causes complementary changes in the demand for public utilities and schools. Our results provide a basis for estimating the magnitude of such changes.

Finally, this research is important to furthering our understanding of how cities operate and grow. Transportation costs are among the most fundamental quantities in theoretical models

1407

of cities. Our model and associated parameter estimates provide a basis for a more complete understanding of the role of transportation costs in shaping cities.

To conduct our investigation, we first develop a simple dynamic model of the relationship between transportation infrastructure and urban growth. This model implies a relationship between a city's employment growth, its initial level of employment, and its supply of transportation infrastructure. It also implies that the transportation infrastructure of a city depends on its past levels of employment, its initial level of transportation infrastructure, and the suitability of its geography for building roads.

Our primary identification problem is the simultaneous determination of urban growth and transportation infrastructure. While one hopes that cities with high predicted employment and population growth receive new transportation infrastructure, we fear that such infrastructure is allocated to places with poor prospects. The resolution of this problem requires finding suitable instruments for transportation infrastructure. Our analysis suggests that such instruments should reflect either a city's level of transportation infrastructure at some time long ago or the suitability of its geography for building roads (keeping in mind that we also require the instruments to be uncorrelated with the residuals in our regressions).

To implement such an instrumental variables estimation, we gather data on U.S. metropolitan statistical areas (MSAs). These data describe interstate highways, decennial population levels since 1920, and the physical geography of cities. We also consider three instruments for the road infrastructure. The first follows Baum-Snow (2007) and Michaels (2008) and is based on the 1947 plan of the interstate highway system. We derive our second instrument from a map of the U.S. railroad network at the end of the 19th century. Our third instrument is based on maps of routes of major expeditions of exploration of the U.S. from 1518 to 1850.

This research contributes to several strands of literature. First, it adds to the work on the determinants of urban growth. Despite the central role of internal transportation in theoretical models of cities, the empirical literature has mostly ignored urban transportation. It has instead emphasized dynamic agglomeration effects (Glaeser *et al.*, 1992; Henderson, Kuncoro and Turner, 1995), the presence of human capital (Glaeser and Saiz, 2004), and climate and other amenities (Rappaport, 2007; Carlino and Saiz, 2008). We believe that this neglect of transportation results from a lack of data about urban transportation infrastructure, a lack of clear predictions regarding the effect of the level of transportation infrastructure on subsequent city growth, and the difficulty of dealing with the simultaneous determination of employment or population growth and transportation infrastructure in cities—the three main innovations of this paper.

Taking the advice of Lucas (1988) seriously, it may be in cities that economic growth is best studied. Hence, this research is also related to the large cross-country growth literature precipitated by Barro's (1991) work. As made clear below, our estimations resemble cross-country growth regressions. However, cross-country regressions are afflicted by fundamental data and country heterogeneity problems that are much less important in the context of metropolitan areas within a country. Furthermore, growth regressions are plagued by endogeneity problems that are often extremely hard to deal with in a cross-country setting (Durlauf, Johnson and Temple, 2005). Looking at cities within countries offers more hope of finding solutions to these identification problems.

There is a substantial empirical literature that investigates various aspects of theoretical urban models. Much of it is concerned with variation in land use and land prices within cities, an issue not directly related to our work. Only a small a number of papers look at the relationship between transportation costs or infrastructure and the spatial distribution of population. In what is probably the most closely related paper to our own, Baum-Snow (2007) uses instrumental variables estimation to investigate the effect of the interstate highway system on suburbanization. Put differently, Baum-Snow (2007) is concerned with the effects of transportation infrastructure

on the distribution of population *within* cities while we look at the distribution of employment *across* cities, a complementary inquiry.

Finally, our work is also related to the large literature dealing with the effects of infrastructure investment. By showing that more transport intensive industries tend to benefit more from state-level road investment, Fernald (1999) provides the most convincing evidence about the productivity effects of road investment, although his approach does not completely resolve the simultaneity of road provision and productivity growth. Gramlich (1994) summarizes and critiques this line of research. More recent work has moved away from the macro-economic approach used in the 1980's and 1990's towards an explicit modelling of sub-national units such as cities or states (Haughwout, 2002). It also shifted its focus away from hard to measure variables such as productivity and developed models with predictions concerning the composition of economic activity and the distribution of population (Chandra and Thompson, 2000; Michaels, 2008). Finally, it has attempted to tackle the fundamental simultaneity problems that plagued earlier work by either relying on plausibly exogenous developments such as the gradual expansion of the U.S. interstate system (Chandra and Thompson, 2000; Michaels, 2008).

2. THEORY AND ESTIMATION

We begin with a simple model of how employment and roads evolve in a system of cities before turning to the main issues that arise when attempting to estimate it.

2.1. *The model*

By driving down travel costs, extra roads increase the attractiveness of a city, which brings new residents. In turn, the stock of roads depends on employment: higher levels of use increase depreciation and affect funding. This basic intuition suggests that we require two main equations to describe the evolution of a city's stock of employment and roads. The first must describe the growth of employment as a function of roads and other characteristics. The second must describe the evolution of the stock of roads in cities.

For a given city, A indexes the quality of amenities in the city, C is the consumption of a numéraire composite good, X is the distance travelled, and L is the consumption of land. To ease exposition, we think of housing capital as being part of the consumption of numéraire. The budget constraint for a representative agent in our city is $w = C + pX + qL$, where w is earnings, p is the cost of driving, and q is the price of land. The utility function for such a representative resident is

$$U = \frac{AC^{1-\alpha-\beta}X^{\alpha}L^{\beta}}{\alpha^{\alpha}\beta^{\beta}(1-\alpha-\beta)^{1-\alpha-\beta}}. \tag{1}$$

Solving the resident's problem yields demand functions; $C = (1-\alpha-\beta)w$, $X = \alpha w/p$, and $L = \beta w/q$. Inserting these expressions into equation (1) gives the indirect utility function

$$V = \frac{Aw}{p^{\alpha}q^{\beta}}. \tag{2}$$

While intuitive, this specification is novel. It provides a parsimonious description of the allocation of four goods: amenities that are not paid for directly, land, transportation, and the composite numéraire.[1] Unlike traditional "monocentric" approaches, our specification does not

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1. We are aware that "travel distance" is not always a final good but an intermediate consumption produced with the numéraire and time to allow residents to go to work, to shop for other consumption goods, and to enjoy their leisure. It would be easy but cumbersome (and restrictive) to introduce a time constraint and treat distance as an intermediate

impose a particular (and restrictive) geography for cities. Traditional approaches also focus almost exclusively on commuting, which represents less than 20% of all trips with privately owned vehicles in the U.S. (Small and Verhoef, 2007). This said, Appendix A shows that the specification we derive below also arises naturally in the context of a monocentric model. A more extensive discussion of the monocentric city model in this context is available in Duranton and Puga (2012).

One of the main characteristics of roads is that they are congestible and in most cases unpriced (Small and Verhoef, 2007). Therefore, we should expect the cost of driving to increase with total kilometres travelled and to decrease with the provision of roadway for a given level of travel. To describe this cost structure, we suppose that the cost of travel per unit of distance is given by

$$p = R^{-\delta}(NX)^{\delta}, \tag{3}$$

where R is the roadway, N is city employment, and NX is aggregate vehicle travel in the city. Equation (3) assumes constant returns to scale: doubling roads and travel leaves costs unchanged. This assumption of constant returns in the provision of vehicle travel receives strong support from a large transportation literature (see Small and Verhoef, 2007 for a discussion of the evidence). Note that equation (3) is an inverse supply equation.

To close the model, it remains to specify the land market. Following standard theoretical models, we assume that the supply of land is limited not by its availability but rather by the willingness of residents to live far from the centre of the city. That is, the "supply" of land for urban use is limited not by the price of land but rather by the willingness of residents to drive. To capture this intuition in a simple way, we suppose that the supply of land to the city is given by

$$L = bX^{\phi}, \tag{4}$$

where we can normalize b to unity without loss of generality by choice of units. Clearly, we could also write the land supply as depending on the price of travel. Our dual formulation is essentially equivalent and, as we will see, is based on quantities that are more easily observed.

Production in the city is subject to agglomeration economies. In particular, individual earnings in a city of size 1 are $\underline{w}$ and increase with employment according to

$$w = \underline{w}N^{\sigma} \tag{5}$$

for $\sigma > 0$. We postpone a detailed discussion of agglomeration economies but note that their existence and magnitude are well established (Rosenthal and Strange, 2004; Melo, Graham and Noland, 2009; Puga, 2010).

Between 1980 and 2000, non-MSA population in the U.S. grew by 14% while the percentage of foreign born Americans increased from 6% to more than 11%. Thus, during our study period, cities draw immigrants from a large and growing pool of people in rural areas of the U.S. and have increasing access to people from abroad. To describe this situation, we suppose that all workers in the countryside receive utility $\underline{U}$ and that cities draw their new workers from this rural pool. This is the standard "open city" assumption. In our application, it implies that we may look at changes in one city while holding other cities fixed (rather than treating all cities as part of an interconnected system). This allows us to treat the city as the unit of observation in our empirical work and in our welfare analysis. Section 4 provides further evidence to support this assumption.

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good in the production of leisure or in the consumption of the numéraire good. We also limit our model to one mode of transportation: privately owned vehicles. It represents nonetheless a vast majority of trips, including more than 90% of the commutes (United States Bureau of Transportation Statistics, 2007).

Equalization of utility between residents and non-residents, together with equilibrium in land and travel markets, implies that the equilibrium employment of a city can be written as a function of R

$$N^*(R) = \left[\underline{U}^{\delta+1} \left(\frac{\beta \underline{w}}{b} \right)^{\beta(\delta+1)} (\alpha \underline{w})^{\alpha\delta-\phi\beta} R^{-\delta(\alpha+\phi\beta)} \right]^{\frac{-1}{\alpha\delta(\sigma+1)-\phi\beta(\sigma-\delta)-\sigma(\delta+1)}}, \qquad (6)$$

where $N^*(R)$ describes a deterministic steady state. Consistent with the fact that employment levels adjust to changes in local conditions, and more specifically, that the rate of adjustment depends on how far "out of steady state" is a city, we describe the adjustment of a city's employment by

$$N_{t+1} = N_t^{*\lambda} N_t^{1-\lambda} \qquad (7)$$

for $\lambda \in (0, 1)$. It is easy to check that N_t^* is a steady state of this equation and that the rate of convergence increases as λ approaches unity. Together, equations (6) and (7) imply

$$N_{t+1} = E_t R_t^a N_t^{1-\lambda}, \qquad (8)$$

where

$$a \equiv \frac{\lambda\delta(\alpha+\phi\beta)}{\alpha\delta(\sigma+1)-\phi\beta(\sigma-\delta)-\sigma(\delta+1)}, \qquad (9)$$

and E_t is all terms that multiply R in equation (6).

A comment is required. Frictionless labour markets are a common feature of simple growth models. However, the migration of workers to cities is both costly and, since the housing stock needs to adjust, subject to crowding. As a result, we expect a sticky labour adjustment process. Equation (7) provides a reduced form description of this process. An alternative approach would allow workers to choose their city as a result of an intertemporal optimizing process subject to migration costs and congestion in the migration process. In fact, for the two-region case, Baldwin (2001) shows that these micro-foundations can lead to a reduced form like equation (7). Two facts lead us to prefer our reduced form model of migration. First, our understanding of local labour markets is still too incomplete to provide much help in understanding the precise determinants of migration decisions (Moretti, 2011). Second, the extant literature on migration typically proceeds by estimating a reduced form equation like equation (7) and using these estimates to infer migration costs. Given our focus, this would add little to what we do.

Taking logs for any city i and denoting $r = \ln(R)$ and $n = \ln(N)$, expression (8) implies that

$$n_{i\,t+1} - n_{it} = ar_{it} - \lambda n_{it} + e_i + \varepsilon_{1it}, \qquad (10)$$

where e_i is a city effect depending on its amenities and its stock of land and ε_{1it} is a random disturbance term.

We note that this equation is a natural reduced-form urban growth regression describing city employment growth as a function of initial employment, initial stock of roads, and other city characteristics that enter e_i. The main parameter of interest is a. Aside from its structural interpretation in equation (9), a describes the rate at which city employment responds to road provision.

During our study period, the U.S. federal government pays for about 90% of the costs of the interstate highway system using earmarked funds from the federal gas tax (which are also used to fund public transportation) and from general revenue. Federal highway funds are allocated to states based on planned projects and a complicated formula that depends upon mileage, population, the legal drinking age, and maximum speed limit among others (United States Bureau of Transportation Statistics, 2007).

Consistent with this institutional setting, we assume that the stock of roads R_{t+1} at time $t+1$ depends on the stock of roads in the preceding period, R_t and on last period's employment N_t. Finally, roads depend on fixed city characteristics and may be subject to random shocks, either from natural events or from randomness in the appropriations process, so that there is both a fixed city specific, m_i and a random component, ε_{2it}. Formally, we assume that

$$R_{it+1} = e^{m_i + \varepsilon_{2it}} R_t^{1-\theta} N_t^{\eta}, \tag{11}$$

where we expect $\theta, \eta \in (0, 1)$. Taking logs, expression (11) becomes

$$r_{it+1} - r_{it} = -\theta r_{it} + \eta n_{it} + m_i + +\varepsilon_{2it}. \tag{12}$$

This specification has commonsense implications. All else equal, a city with a larger employment today will have more transportation infrastructure tomorrow. A city with more transportation infrastructure today will have more transportation infrastructure tomorrow. Transportation infrastructure depreciates. Finally, transportation infrastructure depends on some fixed city characteristics and may be subject to random shocks, either from natural events or from randomness in the appropriations process. In addition, this specification is flexible enough to allow the data to tell us what drives the road allocation process.[2]

2.2. Estimation

Equations (10) and (12) provide a coherent theoretical description of the evolution of employment and roads in cities. We now turn our attention to estimating these equations.

We face a number of inference problems. First, data limitations preclude meaningful estimates of the fixed effects e_i and m_i. Instead, we approximate these fixed effects as a function of observable city characteristics, denoted x_i, but postpone a detailed description of these variables.

Second, we suspect that roads are not assigned to cities at random, and in particular, that r_{it} is correlated with ε_{1it}, in equation (10). In particular, we hope that new roads are assigned to cities realizing a positive employment shock but fear that they are given to cities realizing a negative employment shock. In both cases, reverse causation would be at work. In addition, and formally related to the first problem, some omitted variable may be correlated with the initial level of roads and cause subsequent employment growth. We are also concerned that in equation (12), r_{it} may be correlated with ε_{2it}. This might occur if some unobserved city characteristic, for example, geography or industrial composition, leads to more roads at the beginning of our study period and a greater allocation of new roads after. We also worry about classical measurement error in equation (12). In some of the cities, we observe roads that may have just opened, while in others road openings may be imminent. In these cases, the "true" stock of roads relevant to our study period will be mismeasured.

We exploit exogenous variation in three instrumental variables to resolve these endogeneity problems. Denote our vector of instrumental variables z_i. To exploit these variables, we describe our data with a system of three equations, the two structural equations corresponding

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2. It is tempting to specify a model of road provision that would allocate roads on the basis of an explicitly specified dynamic optimizing process to mimic the way capital is usually allocated in growth models. Such a model would, however, be difficult to reconcile with the funding mechanism just described and with well-documented evidence of political interference in transportation projects (*e.g.* Knight, 2004). Our simple specification allows us to focus attention on the identification of the causal effect of employment and existing highways on the allocation of new highways. We can then use the results of our estimation to assess the efficiency of this allocation process for new roads.

to equations (10) and (12), and a reduced form equation describing the initial level of roads. Formally, we have

$$n_{it+1} - n_{it} = A_1 + ar_{it} + \lambda n_{it} + c_1 x_i + \varepsilon_{1it}, \tag{13}$$

$$r_{it+1} - r_{it} = A_2 + \theta r_{it} + \eta n_{it} + c_2 x_i + \varepsilon_{2it}, \tag{14}$$

$$r_{it} = A_3 + c_3 n_{it} + c_4 x_i + c_5 z_i + \varepsilon_{3it}. \tag{15}$$

This system is identified only if the instruments z_i satisfy,

$$c_5 \neq 0, \tag{16}$$

$$\text{Cov}(z, \varepsilon_1) = 0, \tag{17}$$

$$\text{Cov}(z, \varepsilon_2) = 0. \tag{18}$$

Condition (16) is a relevance condition. It requires that, conditional on control variables, the instruments predict the endogenous dependent variable. Conditions (17) and (18) are exogeneity conditions or exclusion restrictions. They require that the instruments affect the dependent variables only through their affect on roads.

We include exactly the same explanatory variables in both the structural equations. This is a minor simplifying assumption with two useful consequences. First, there is no efficiency gain from estimating the system jointly (*e.g.* with 3SLS) rather than separately estimating the two pairs of equations (13) and (15) and (14) and (15). Second, the relevance condition (16) is appropriate and we need not investigate more complicated joint-relevance conditions like those discussed in Arellano, Hansen and Sentana (2012). This would not be the case if the structural equations did not include the same list of explanatory variables or if we had additional cross-equation restrictions.

3. DATA

Our unit of observation is a U.S. (Consolidated) MSA within the continental U.S. constructed from 1999 boundaries. MSAs are defined as a collection of counties. Our main variables are described in Appendix B, while Table 1 reports summary statistics. Appendix B also provides further details about the data presented in this section.

TABLE 1
Summary statistics for our main variables

	Mean	Standard deviation
1983 Employment ('000)	250·5	588·4
2003 Employment ('000)	410·7	861·9
1983–2003 Annual employment growth (%)	2·8	1·2
1983 Interstate highways (km)	243·4	297·0
2003 Interstate highways (km)	255·2	309·4
1983 Interstate highways per 10,000 population (km)	6·4	6·8
2003 Interstate highways per 10,000 population (km)	5·1	4·0
Planned 1947 highways (km)	117·6	128·1
1898 Railroads (km)	286·1	298·2
1528–1850 Exploration route index	3031·9	4270·7

Note: Averages are across all 227 MSAs.

Our study period begins in 1983, the date of the earliest available electronic inventory of interstate highways, and ends in 2003, just after the 2000 census. In a typical estimation of our employment growth equation (13), we predict MSA employment growth between 1983 and 2003 as a function of 1980–1983 MSA characteristics. In a typical estimation of our road growth equation (14), we predict MSA growth in interstate highway kilometres between 1983 and 2003 as a function of 1980–1983 MSA characteristics.

We use data from the County Business Patterns (CBPs) to construct the dependent variable for most of our employment growth regressions, change in log employment between 1983 and 2003, $\Delta_{03,83} \ln \text{Emp} = \ln \text{Emp}_{03} - \ln \text{Emp}_{83}$. We also use employment levels for 1983 as a control.

We use data from Highway Performance and Monitoring System (HPMS) "Universe" data to construct the dependent variable for road growth regressions, change in log kilometres of interstate highways between 1983 and 2003, $\Delta_{03,83} \ln \text{Int. Hwy km} = \ln \text{Int. Hwy km}_{03} - \ln \text{Int. Hwy km}_{83}$. We also use the 1983 level of interstate highway kilometres, our explanatory variable of interest.

We use the natural logarithms of MSA population levels in decennial years between 1920 and 1970 and a number of variables describing the physical geography of MSAs as controls. In light of the finding in Burchfield *et al.* (2006) that the availability of groundwater is an important determinant of the spatial structure of MSAs, we use the share of each MSA's land that overlays an aquifer. Since terrain may impact both economic growth and the costs and effects of transportation infrastructure, we use MSA elevation range and an index of terrain ruggedness. Since climate may affect both employment growth and the costs of transportation infrastructure, we control for heating and cooling degree days. In some regressions, we also use indicator variables for each of the nine census divisions and a variety of sociodemographic characteristics from the 1980 census as additional control variables.

Finally, in robustness checks, we sometimes use population growth instead of employment growth, use an alternative measure of initial roads from a 1980 U.S. Geological Survey (USGS) digital road map, use a lane weighted measure of interstate highways, and examine employment growth over subperiods.

3.1. *1947 plan of the interstate highway system*

Our first instrument derives from the 1947 plan of the interstate highway system. After some early planning by the bureau of public roads in 1921, President Franklin D. Roosevelt took an interest in a national highway system and in 1937 began planning such a system. Subsequently, a National Interregional Highway committee recommended a plan for the national highway system. This plan considered a strategic highway network suggested by the War Department, the location of military establishments, interregional traffic demand, and the distribution of population and economic activity at that time. In turn, this plan informed the 1944 Federal Aid Highway Act, which led to the 1947 highway plan shown in Figure 1. Substantive funding for the interstate highway system arrived with the Federal Aid Highway and Highway Revenue Acts of 1956. By 1980, the federal interstate highway system was substantially complete.

To construct our 1947 planned highways instrument, we create a digital image of the 1947 highway plan from its paper record (United States House of Representatives, 1947) and convert this image to a digital map. We then calculate kilometres of 1947 planned interstate highway in each MSA.

Since many of the highways planned in 1947 were ultimately built, this instrument should be relevant. The correlation between log 1983 interstate highway kilometres and log 1947 planned highway kilometres is 0·62. In Table C1 of Appendix C, we present the results of first-stage

FIGURE 1
1947 U.S. interstate highway plan

estimates of equation (15) and show that this instrument predicts the initial level of roads in 1983 conditional on the controls we use in estimates of the structural equations (13) and (14). We repeat these results for the other two instruments described below. While exact critical values for weak instrument tests vary with specification and econometric technique, the relevant first-stage statistics for our instruments are large enough that our instruments are unlikely to be weak. Thus, our instruments satisfy the relevance condition (16).

Condition (17) requires that our instruments affect the growth of city employment only through their effect on the initial stock of roads. The 1947 plan was first drawn to *connect by routes as direct as practicable the principal metropolitan areas, cities and industrial centres, to serve the national defense, and to connect suitable border points with routes of continental importance in the Dominion of Canada and the Republic of Mexico* (United States Federal Works Agency, Public Roads Administration, 1947 cited in Michaels, 2008). Importantly, the mandate for the highway plan makes no mention of transportation within cities or future development. In particular, it does not require planners to anticipate employment growth.[3] Historical evidence confirms that the 1947 highway plan was, in fact, drawn to this mandate (see Mertz, undated and Mertz and Ritter, undated as well as other sources cited in Chandra and Thompson,

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3. The fact that the interstate highway system quickly diverged from the 1947 plan is consistent with this mandated myopia: the 1947 plan was amended and extended from about 37,000 miles to 41,000 before it was funded in 1956, and additional miles were subsequently added. Some of these additional highways were surely built to accommodate population growth that was not foreseen by the 1947 plan.

2000; Baum-Snow, 2007; and Michaels, 2008). Further evidence that the 1947 highway plan was drawn in accordance with its mandate is obtained directly from the data. In a regression of log 1947 kilometres of planned highway on log 1950 population, the coefficient on planned highways is almost exactly one. Adding controls for geography and past population growth from the 1920s, 1930s, and 1940s does not change this result, and pre-1950 population coefficients do not approach conventional levels of statistical significance. Thus, we conclude that the 1947 plan was drawn, as stipulated by its mandate, to connect major population centres and satisfy the needs of inter-city trade and national defense as of the mid-1940's. In sum, the 1947 highway plan predicts roads in 1983 but should not predict employment growth between 1983 and 2003.

Note that equation (17) requires orthogonality of the dependent variable and the instruments conditional on control variables not unconditional orthogonality. This is an important distinction. Cities that receive more roads in the 1947 plan tend to be larger than cities that receive less. Since we observe that large cities grow more slowly than small cities, 1947 highway planned highway kilometres predicts employment growth directly as well operating indirectly through its ability to predict 1983 interstate highway kilometres. Thus the exogeneity of this instrument hinges on having an appropriate set of controls, historical population variables in particular. This is consistent with our finding below that results for the over-identification tests sometimes fail when we do not control for historical population levels.

Condition (18) requires that, conditional on controls, our instruments affect road growth only through their affect on initial roads. Thus, to the extent that measured highway kilometres does not reflect functional highway kilometres, that is, classical measurement error, we require only that the "error" with which our 1947 highway plan measures the true stock of highways is independent of the error with which the HPMS measures true roads. This seems plausible.

Alternatively, if initial roads and change in roads both depend on some omitted variable, "suitability for roads" then we should be concerned that the 1947 Highway plan variable, which itself describes an alternative road network, is also partly determined by this unobserved trait. With this said, we expect that any omitted variable that determines our initial road measure, changes in roads, and our instruments will likely reflect either the physical geography or the industrial composition of a city. If such an omitted variable is important to our estimations, we should find that observed measures of physical geography and industrial composition are important. In our estimations, we include these types of variables as controls and find no evidence that they affect our results.

3.2. *1898 railroad routes*

Our second instrument is based on the map of major railroad lines from about 1898 (Gray, 1898) shown in Figure 2. We convert this image to a digital map and calculate kilometres of 1898 railroad contained in each MSA.

Building both railroad tracks and automobile roads requires levelling and grading a roadbed. Hence, an old railroad track is likely to become a modern road because old railroads may be converted to automobile roads without the expense of levelling and grading. Second, railroad builders and road builders are interested in finding straight level routes from one place to another. Thus, the prevalence of old railroads in an MSA is an indicator of the difficulty of finding straight level routes through the local terrain. The ability of the 1898 railroad network to predict the modern highway network is demonstrated by the 0·53 correlation between log 1983 interstate highways kilometres and log 1898 railroad kilometres, and in representative first-stage results reported in Appendix C.

FIGURE 2
Gray's map of 1898 railroads

The *a priori* case for thinking that 1898 railroad kilometres satisfy exogeneity condition (17) rests on the length of time since these railroads were built and the fundamental changes in the nature of the economy in the intervening years. The rail network was built, for the most part, during and immediately after the civil war, and during the industrial revolution. At the peak of railroad construction, around 1890, the U.S. population was 55 million, with 9 million employed in agriculture or nearly 16% of the population (United States Bureau of Statistics, 1899, p. 3, 10). By 1980, the population of the U.S. was about 220 million with only about 3·5 million or 1·6% employed in agriculture (United States Bureau of the Census, 1981, p. 7, 406). Thus, while the country was building the 1898 railroad network, the economy was much smaller and more agricultural than it was in 1980 and was in the midst of a technological revolution and a civil war, both long completed by 1980.

Furthermore, the rail network was constructed by private companies who were looking to make a profit from railroad operations in the not too distant future (Fogel, 1964; Fishlow, 1965). It is difficult to imagine how a rail network built for profit during the civil war and the industrial revolution could affect economic growth in cities 100 years later save through its effect on roads. As for the highway plan, the same important qualifying comment applies: instrument validity requires that rail routes need only be uncorrelated with the dependent variable conditional on the control variables.

The argument that log 1898 rail kilometres satisfies the second exogeneity condition, that is, affects road growth only through its affect on initial roads, is the same as for the 1947 highway plan.

3.3. *Routes of major expeditions of exploration 1528–1850*

Our third instrument is based on exploration routes in early U.S. history. The National Atlas of the United States of America (1970) describes the routes of major expeditions of exploration
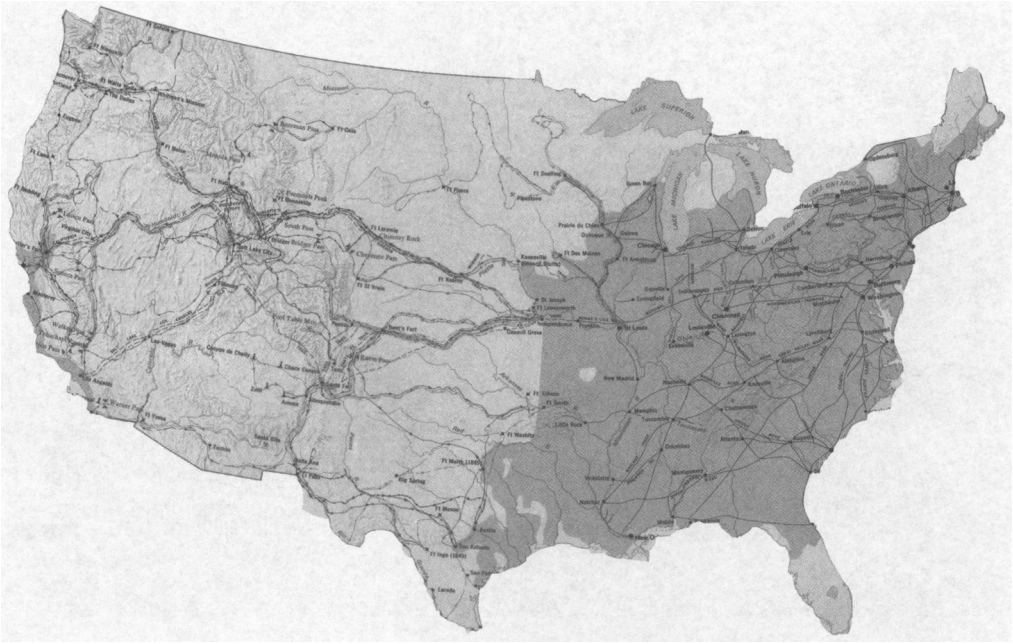
FIGURE 3

Map showing the routes of major expeditions of exploration between 1835 and 1850

that occurred during each of five time periods: 1528–1675, 1675–1800, 1800–1820, 1820–1835, and 1835–1850. We digitize each map and count 1 km by 1 km pixels crossed by an exploration route in each MSA. We then compute our index by summing those counts across all maps. Following this procedure, routes used throughout the 1528–1850 period receive a higher weight than those used for a shorter period of time. We also count minor variants of any route because the existence of such variants reflects the intensity with which the route is used. The 1835–1850 map is displayed in Figure 3.

Exploration routes result from a search for an easy way to get from one place to another on foot, horseback, or wagon. Since a good route for a man, horse or wagon will likely be a good route for a car, exploration routes will often be good routes for contemporary interstate highways. The ability of the exploration routes variable to predict the modern highway network is demonstrated by the 0·43 correlation between the log of the exploration routes index an 1983 interstate highways kilometres and in representative first-stage results reported in Appendix C.

Our maps of exploration routes describe major expeditions of exploration ranging over three centuries; from those of the early Spanish explorers Hernando de Soto and Álvar Núñez Cabeza de Vaca, who explored the American South and Southwest in the mid-16th century, to the great French explorer, Robert de LaSalle, who explored the Mississippi and the Great Lakes region in the late 17th century, to the famous Lewis and Clark expedition of 1804 and to Frémont's explorations of the West in the mid-1800's. The motivations for these expeditions were as varied as the explorers and times in which they lived from the search for gold and the establishment of fur trading territories to finding emigration routes to Oregon or the expansion of the U.S. territory towards the Pacific Ocean. Our argument for the exogeneity of these routes rests on the improbability of these explorers choosing routes that were systematically related to anything that affects the economic growth of cities at the end of the 20th century, save the suitability of a place for roads.

4. RESULTS

4.1. *Ordinary Least Squares (OLS) results*

We first estimate structural equations (13) and (14) by ordinary least squares (OLS). These OLS estimates provide valid estimates of our econometric model only if unobserved determinants of initial roads are uncorrelated with unobserved determinants of changes in roads and employment. Since this condition probably does not hold, our OLS results should be regarded as primarily descriptive.

Panel A of Table 2 presents OLS regressions, predicting the change in log MSA employment from 1983 to 2003 as a function of the log of 1983 interstate highway kilometres, the log of 1983 employment, and other controls. Column 1 includes only initial employment and initial highway kilometres as controls. As expected, large cities grow more slowly and cities with more roads grow more quickly. Columns 2 and 3 add controls for decennial population levels and physical geography to the specification in column 1. We note that past population levels are strong controls and that once these variables are included, other controls are typically insignificant. While the coefficient on roads decreases only slightly, the coefficient on initial employment changes dramatically. This reflects collinearity of 1983 employment and historical population levels. Column 4 adds squares of our physical geography variables and some interactions between them. Column 5 adds five socioeconomic characteristics for 1980: share of poor, share of adults with at least some college education, log mean income, a segregation index, and share of manufacturing employment. Column 6 further adds census division indicators. This extensive set of controls reduces the coefficient on initial roads.

TABLE 2
Growth of employment and roads as a function of initial roads, OLS estimates

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: Employment or population growth								
$\ln(\text{Int. Hwy km}_{83})$	0.073***	0.074***	0.061***	0.060***	0.042***	0.030**		0.056***
	(0.017)	(0.013)	(0.014)	(0.014)	(0.014)	(0.015)		(0.014)
$\ln(\text{Emp}_{83})$	−0.086***	−0.24	−0.26	−0.26	−0.26	−0.25	−0.27	0.26***
	(0.020)	(0.19)	(0.19)	(0.19)	(0.22)	(0.23)	(0.19)	(0.077)
$\ln(\text{USGS maj. roads}_{80})$							0.17***	
							(0.030)	
R^2	0.11	0.43	0.47	0.48	0.53	0.59	0.46	0.64
Panel B: Road growth								
$\ln(\text{Int. Hwy km}_{83})$	−0.52***	−0.53***	−0.54***	−0.55***	−0.56***	−0.54***		
	(0.10)	(0.10)	(0.11)	(0.11)	(0.10)	(0.089)		
$\ln(\text{Emp}_{83})$	0.34***	0.31**	0.29**	0.28**	0.19*	0.12	0.25*	
	(0.067)	(0.12)	(0.12)	(0.12)	(0.11)	(0.098)	(0.15)	
$\ln(\text{USGS maj. roads}_{80})$							−0.22	
							(0.14)	
R^2	0.54	0.55	0.56	0.57	0.59	0.63	0.06	
$\{\ln(\text{Pop}_t)\}_{t \in \{20,...,70\}}$	N	Y	Y	Y	Y	Y	Y	Y
Physical geography	N	N	Y	Ext.	Ext.	Ext.	N	N
Socioeconomic controls	N	N	N	N	Y	Y	N	N
Census divisions	N	N	N	N	N	Y	N	N

Notes: 227 observations for each regression. All regressions include a constant. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%. Panel A: dependent variable is $\Delta_{03,83} \ln \text{Emp}$ in columns 1–7 and $\Delta_{00,80} \log \text{Pop}$ in column 8. Panel B: dependent variable is $\Delta_{03,83} \log$ Interstate Highway kilometres.

In column 7, we repeat column 3 but measure initial roads with log 1980 USGS major roads kilometres. This leads to a somewhat larger estimated coefficient for roads than in the corresponding coefficient in column 3. We suspect that this reflects the process by which roads are selected into the 1980 USGS map. In column 8, we also duplicate the regression of column 3 but use the change in log population from 1980 to 2000 as our dependent variable. Using this alternative dependent variable leads to a slightly lower coefficient on initial roads than we see in column 3.

Despite differences across specifications, the OLS elasticity of city employment relative to initial roads remains low, between 0·03 and 0·17. If we restrict attention to regressions predicting change in employment as a function of initial interstate highway, the range of estimates is just 0·03 to 0·07.

Panel B of Table 2 is similar to panel A, except that the dependent variable is change in log interstate highway kilometres from 1983 to 2003 rather than change in log employment (or population). Where panel A presents estimates of equation (13), panel B presents estimates of equation (14).

In column 1 of Table 2 panel B, we include only two regressors, the log of kilometres of 1983 interstate highways and the log of 1983 employment. As expected, growth in log interstate highway kilometres increases with 1983 employment, but this increase is far from proportional. There is also strong mean reversion in road provision. The coefficient on initial roads is −0·52. In columns 2–6, we gradually add more controls. The coefficient on 1983 interstate highways remains stable across these specifications and is estimated quite accurately. The coefficient on log 1983 employment is positive and statistically different from zero in almost all specifications except for column 6. Given the high correlation between 1983 employment and historical employment levels, it is not surprising that the coefficient on log 1983 employment is less stable across specifications than is the coefficient on log 1983 interstate highway kilometres. In column 7, we repeat the estimation of column 3 but use log 1980 USGS major road kilometres as our measure of initial roads. Reassuringly, the point estimate for this coefficient is also negative, though unsurprisingly, it has less explanatory power than does log 1983 interstate highway kilometres. Column 8 of panel A uses an alternative measure of city growth as a robustness check. Data limitations preclude a similar exercise for changes in roads so that panel B has no regression corresponding to column 8 of panel A.

4.2. *Main IV results*

Table 3 presents our main results. Since it provides more reliable point estimates and test statistics with weak instruments than two-stage least squares (TSLS), we use limited information maximum likelihood (LIML) to separately estimate the two structural equations for change in employment and change in roads, with the initial stock of roads treated as endogenous. In all regressions, we use all three of our instruments, 1947 planned interstate highway kilometres, 1898 kilometres of railroads, and our index of 1528–1850 exploration routes. The format of the table is similar to Table 2. In panel A, the dependent variable is a measure of city growth, change in log employment from 1983 to 2003 for columns 1–7, and change in log population from 1980 to 2000 for column 8. In panel B, the dependent variable is the change in log interstate highway kilometres from 1983 to 2003. In all columns but 7, we use log 1983 interstate highway kilometres to measure initial roads. As a robustness check, column 7 uses log 1980 USGS major road kilometres to measure initial roads. The control variables used in each column of Table 3 match the corresponding column of Table 2.

In column 1 of panel A, we estimate the effect of log 1983 interstate highway kilometres and log 1983 employment on the change on log employment from 1983 to 2003. The coefficient

TABLE 3

Growth of employment and roads as a function of initial roads, IV

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: Employment or population growth								
ln(Int. Hwy km$_{83}$)	0·13**	0·15***	0·15***	0·16***	0·13**	0·096*		0·13***
	(0·056)	(0·037)	(0·043)	(0·047)	(0·054)	(0·053)		(0·030)
ln(Emp$_{83}$)	−0·11***	−0·26	−0·27	−0·27	−0·27	−0·28	−0·30	0·24***
	(0·037)	(0·19)	(0·19)	(0·19)	(0·21)	(0·21)	(0·19)	(0·075)
ln(USGS maj. roads$_{80}$)							0·29***	
							(0·084)	
Over-id p value	0·04	0·96	0·93	0·59	0·65	0·59	0·18	0·47
Panel B: Road growth								
ln(Int. Hwy km$_{83}$)	−0·27***	−0·28***	−0·26***	−0·26***	−0·28***	−0·25**		
	(0·086)	(0·093)	(0·099)	(0·097)	(0·10)	(0·10)		
ln(Emp$_{83}$)	0·21***	0·25**	0·26**	0·26**	0·14	0·017	0·34**	
	(0·050)	(0·11)	(0·11)	(0·12)	(0·091)	(0·099)	(0·17)	
ln(USGS maj. roads$_{80}$)							−0·53**	
							(0·23)	
Over-id p value	0·42	0·41	0·54	0·57	0·72	0·96	0·47	
{ln(Pop$_t$)}$_{t∈\{20,...,70\}}$	N	Y	Y	Y	Y	Y	Y	Y
Physical geography	N	N	Y	Ext.	Ext.	Ext.	N	N
Socioeconomic controls	N	N	N	N	Y	Y	N	N
Census divisions	N	N	N	N	N	Y	N	N
First-stage statistic	17·0	13·3	11·8	13·9	11·3	9·7	11·9	13·3

Notes: 227 observations for each regression. All regressions include a constant. Robust standard errors in parentheses.
*, **, ***: significant at 10%, 5%, 1%. Panel A: dependent variable is $\Delta_{03,83}$ ln Emp in columns 1–7 and $\Delta_{00,80}$ ln Pop in column 8. Panel B: dependent variable is $\Delta_{03,83}$ ln Interstate Highway kilometres. All regressions use 1947 planned highway kilometres, 1898 kilometres of railroads, and index of 1528–1850 exploration routes as instruments.

on 1983 interstate highway kilometres is 0·13. In column 2, we add historical population levels as controls, and in column 3, we also control for physical geography. In both columns, the coefficient on initial roads is 0·15 and is −0·26 and −0·27 for initial employment levels. Columns 4–6 add more control variables to the specification of column 3. The coefficient estimates for initial roads and employment are remarkably stable across the first six columns of panel A. Because of collinearity between 1983 employment and historical population, the effect of initial employment on change in employment is not statistically distinguishable from zero, except in column 1 where we do not include historical population levels as controls. In column 7, we use log 1980 USGS major road kilometres to measure initial roads. As for the OLS results, we find a somewhat larger coefficient. In column 8, we use the same specification as in column 3 but use change in log population from 1980 to 2000 as our dependent variable. The resulting coefficient on initial roads is not statistically different from estimates in columns 1–6.

Table 3 panel A also reports the *p* values for an over-identification test (Hansen's *J* statistic). For our preferred specification in column 3, the *p* value of this statistic is 0·93, so that we easily fail to reject our over-identifying restriction. In fact, in all columns of the table, except for column 1, we easily fail to reject our over-identifying restriction. Recall that the over-id test is a test of *joint*-exogeneity. In particular, instruments can pass this test if they are all endogenous and the

bias that this endogeneity induces is of similar sign and magnitude. Given different rationales for the exogeneity of the planned highway network, the 1898 rail network, and early exploration routes, this sort of endogeneity seems unlikely.

In column 1, our test of over-identifying restrictions marginally fails. This suggests that, consistent with our intuition, highway planners in 1947 and railroad builders in the 19th century did choose routes on the basis of factors like contemporaneous population that affect 1983–2003 employment growth independently of roads. It follows that our instruments are probably not exogenous when we do not control for historical population levels.

To sum up, our preferred estimate in column 2 gives a value of 0·15 for the parameter a in equation (10). This value implies that 10% more interstate highway kilometres in 1983 leads to 1·5% more employment after 20 years.

Panel B presents results describing the effect of the initial level of interstate highway on its subsequent provision. This panel duplicates panel A but uses changes in log interstate highway kilometres from 1983 to 2003 as the dependent variable rather than changes in log employment. In columns 1–6, the coefficient on log 1983 interstate highway kilometres is extremely stable, between −0·25 and −0·28, is estimated precisely, and is statistically different from zero. The coefficient for log of initial employment is also fairly stable across specifications and is statistically different from zero except when we use the very extensive sets of controls in columns 5 and 6. In column 7, we measure the initial stock of roads with log 1980 USGS major road kilometres. While the point estimate for the coefficient for this variable is larger in magnitude than the coefficient for log 1983 interstate highway variable kilometres, it is not different at standard levels of confidence.

Given that the first stage for regressions in panel B is the same as for panel A, the first-stage statistics are the same and hence pass weak instrument tests. We also always easily fail to reject our over-identifying restrictions.

Our preferred estimate in column 3 gives a value of 0·27 for the parameter θ in equation (12). This value implies that 10% more interstate highway kilometres in 1983 leads to 2·7% less growth in the provision of roads over the subsequent 20 years. Put differently, a standard deviation of 1983 interstate highways corresponds to a negative standard deviation in road growth over the following 20 years.

In Appendix D, we verify the robustness of the results presented in Table 3. Table D1 repeats the estimations of Table 3 using Generalised Method of Moments (GMM) estimation. The GMM estimations are practically indistinguishable from the LIML estimations. Table D2 demonstrates that our main results do not vary when we use subsets of our three instruments. Table D3 shows that our results do not vary if we measure changes in employment over sub-periods of our study period, if we split our sample into large and small cities, or if we recalculate our instruments on the basis the developed area of MSAs as described in Appendix B.

4.3. Discussion

Table 3 suggests that a 10% increase in an MSA's stock of interstate highways in 1983 causes the MSA's employment to increase by about 1·5% over the course of the following 20 years. Since the standard deviation of log 1983 interstate highways is 0·98, using our preferred estimate from Table 3 panel A, a one standard deviation increase in the log of 1983 interstate highway kilometres causes a 15% increase in employment over the following 20 years. This is slightly less than two-thirds of the standard deviation of the MSA employment growth rate during our study period. Thus, the effects of roads on urban growth are large in absolute terms.

The effects of roads on urban growth are also large relative to the three widely accepted drivers of recent urban growth in the U.S.: good weather, human capital, and dynamic

externalities. According to the findings of Glaeser and Saiz (2004) for U.S. MSAs between 1970 and 2000, one standard deviation in the proportion of university graduates at the beginning of a decade is associated with a quarter of a standard deviation of population growth. In his analysis of the effects of climate for U.S. counties since 1970, Rappaport (2007) finds that one standard deviation increases in January and July temperature are associated with, respectively, an increase of 0·6 standard deviation of population growth and a decrease of 0·2 of the same quantity. A direct comparison with the findings of Glaeser *et al.* (1992) on dynamic externalities is more difficult but a standard deviation of their measures of dynamic externalities is never associated with more than a fifth of a standard deviation of employment growth for industries in cities. In sum, that a standard deviation in roads per worker causes nearly two-thirds of a standard deviation in employment growth suggests that roads and infrastructure are important drivers of urban growth.

Our results also highlight two important aspects of the provision of new interstate highways: strong mean reversion and a small effect of initial MSA employment. These two results are consistent with core features of the policy for funding transportation infrastructure in the U.S. This policy tends to equalize spending *per capita* across different types of areas. Because roads are more expensive to build in larger MSAs (Ng and Small, 2008), large cities get fewer new roads *per capita* and the provision of interstate highways then falls behind urban growth.

4.4. *Explaining the differences between OLS and IV*

Column 2 of Table 3 gives our preferred estimate of the effect of initial roads on employment growth. At 0·15, this LIML IV estimate is more than twice as large as the corresponding OLS estimate of 0·06 from Table 2. More generally, the LIML IV estimates of the effects of initial roads on employment growth are dramatically larger than the similar OLS estimates.

Larger LIML IV than OLS coefficient estimates for endogenous initial roads may be due to classical measurement error. If so, then the larger LIML IV than OLS coefficient estimate for the effect of log of 1980 USGS major road kilometres on employment growth is probably also due to measurement error. However, for both road measures, OLS coefficient estimates increase by about a factor of two in LIML IV. This means that the effect of measurement error on coefficient estimates is about the same for both variables. Given the different nature of the two measures of roads, this seems improbable. Furthermore, if classical measurement error were behind the LIML IV versus OLS difference, we should see a similar difference in regressions that predict growth of roads. In fact, for these regressions, we see the opposite pattern.

Another explanation for larger LIML IV than OLS coefficient estimates is a negative correlation between properly measured log 1983 interstate highway kilometres and the error term in equation (13). This could be due to either missing variables or reverse causation. One possible missing variable is "good consumption amenities", which could be associated with faster employment growth during 1983–2003 and with fewer interstate highways in 1983. While past population and geography are powerful controls, the possibility remains that the difference between our LIML IV and OLS estimates could be explained by such a missing variable.

Turning to reverse causation, it may be that conditional on controls, cities that experience negative shocks to employment, also on average experience positive shocks to their stock of roads. While our data do not allow us to test this hypothesis directly, we are able to look at the relationship between changes in city employment and changes in employment in road construction—a precursor of new roads.

To investigate the proposition that roads are given to cities experiencing negative growth shocks, we use detailed employment data from the CBP to calculate the share of an MSA's

TABLE 4
Employment in road construction and population growth, OLS

Dependent variable	Share emp. road const.				Δ share emp. road const.			
	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
$\Delta_{00,80}\ln$ Pop	−0·27	−0·37*	−0·43	−0·45*	−0·35**	−0·36*	−0·41*	−0·40*
	(0·24)	(0·21)	(0·27)	(0·26)	(0·16)	(0·18)	(0·24)	(0·24)
Physical geography	Y	Y	Y	Y	Y	Y	Y	Y
Census divisions	N	Y	Y	Y	N	Y	Y	Y
$\{\ln(\text{Pop}_t)\}_{80}$	Y	Y	Y	Y	Y	Y	Y	Y
$\{\ln(\text{Pop}_t)\}_{t\in\{20,...,70\}}$	N	N	Y	Y	Y	Y	Y	Y
Share emp. building construction	N	N	N	Y	N	N	N	Y
R^2	0·31	0·46	0·49	0·53	0·12	0·15	0·17	0·18

Notes: 227 observations for each regression. All regressions include a constant. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%. In columns 1–4, the dependent variable is the log share of employment in road construction during the 1980s and 1990s. In columns 5–8, we use the difference in log share of employment between the 1990's and 1980's.

population that is employed in building roads during the 1977–1997 period.[4] We then check whether this employment share is negatively correlated with contemporaneous population growth in the MSA. Column 1 of Table 4 presents the results of a regression of the log share of MSA employment in road construction on the change in log population from 1980 to 2000, controlling for physical geography and 1980 population. The partial correlation between population growth and employment in road construction is negative but insignificant. Column 2 adds census division dummies and the coefficient on population growth is now significant. In column 3, we add historical population, and in column 4, we also control for the share of employment in other construction. These results are consistent with the observed difference between our OLS and IV results in Table 3: MSAs experiencing negative population shocks have larger road building sectors.

In columns 5–8, we repeat the same four regressions as in columns 1–4 but use the change in the log share of employment in road construction. The results are more consistent. They show that MSAs experiencing negative population shocks have growing road building sectors. Overall, these results suggest that the political economy of road provision is such that MSA's with slower conditional growth are assigned more roads.

In summary, our IV estimates of the effects of roads on employment growth are larger than the corresponding OLS estimates. If our instruments are valid, then this requires that, conditional on controls, roads are allocated to slow growing cities. Table 4 supports this implication: conditional on controls, there is more employment in road construction in slow-growing cities. Thus, Table 4 provides out of sample evidence confirming the validity of our instruments.

4.5. *Comparison with the long-run effects of rail*

In column 3 of Table 3 panel A, the coefficient on log 1983 employment is −0·15. As a check on the reasonableness of this number, we can compare it with the longrun railroad elasticity of city population. In Table E1 in Appendix E, we report regressions that predict the change

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4. Our measure of employment in road building is based on SIC 16, "heavy construction contractors". Because of the change from SIC to NAIC after 1997, we prefer to use the 1977–1997 period.

in MSA population between 1920 and 2000, that is, the 80 year rate of population growth, as a function of the MSA's stock of 1898 railroads. After we control for initial population and physical geography, we find that the long-run population growth elasticity of 1898 rail is around 0·30. While a comparison of the long-run effect of rail and the long-run effect of 1983 interstate highways is a bit strained, the relevant elasticities are close.

4.6. *The roles of internal transportation versus market access*

Our analysis so far implicitly assumes that changes to an MSA's roads affect employment by changing the cost of driving within this MSA. However, it is possible that changes to the road network affect an MSA's employment by improving its access to markets (*i.e.* by reducing transportation costs of accessing markets outside the MSA).

The hypothesis that roads affect employment through market access has two implications. First that an MSA's employment increases with improvements to its own roads. Second that an MSA's employment increases with improvements in the road network of its trading partners because such improvements also reduce the cost of accessing markets. By checking whether changes to roads in neighbouring MSAs affect employment in the subject MSA, we can test whether roads affect an MSA's employment by reducing the costs of travelling within the MSA or by improving market access.

We calculate two measures of neighbouring MSAs' stocks of roads. First, for each MSA, we identify the largest MSA which is between 150 and 500 kilometres away, that is, too far to commute but still within a day's drive. For each such neighbouring MSA, we calculate two measures of roads. The first is simply the log kilometres of 1983 interstate highways. The second is a "gravity" based measure

$$\text{Neighbour gravity} = \frac{\text{Neighbour population} \times \text{Neighbour Interstate Highway km}}{\text{Distance to neighbour}}.$$

In Table E2 in Appendix E, we present regressions that test for the role of network effects by including these two measures of roads in a regression (like that of column 2 of Table 3), predicting change in employment as a function of initial roads. While we cannot prove a negative statement, these results are consistent with our premise that the changes in road infrastructure affect city employment growth by affecting driving within the city not by affecting market access. This conclusion is consistent with Duranton, Morrow and Turner (2011) who find that a city's road network does not affect the total value of inter-city trade, although it does affect the composition of this trade.

5. USING OUR MODEL

We now recover the structural parameters of our model and use them to conduct a number of policy experiments.

5.1. *Recovering the structural parameters*

Our model has nine structural parameters: α (share of transportation in expenditure), β (share of land in expenditure), δ (elasticity of unit transportation costs to road provision), λ (employment adjustment), η (elasticity of current roads to past employment), θ (road adjustment), σ (agglomeration economies), ϕ (land supply elasticity), and $\underline{w}$ (rural wage). Using our estimates and others from the literature, we now assign values to each of these variables.

From our estimation of equation (13), we obtain a (a function of α, β, δ, λ, and σ) and λ. For a, our preferred value is $\hat{a} = 0·15$ as obtained from our favourite specification in column 2

of Table 3. For λ, the strong collinearity between log 1980 population and log 1983 employment makes its estimation sensitive to the inclusion of the population controls. We retain $\hat{\lambda} = 0\cdot11$ from column 1 of Table 3, a specification that does not control for population.

From our estimation of equation (14), we obtain η and θ. For η, our preferred value is $\hat{\eta} = 0\cdot25$ from column 2 of Table D1. For θ, the same estimation yields $\hat{\theta} = 0\cdot28$. Despite the strong collinearity between log 1980 population and log 1983 employment, the coefficient on initial employment is virtually the same as in column 1 of the same table, where we do not control for historical population levels.

The parameter α is the share of transportation in expenditure. According to the United States Bureau of Transportation Statistics (2007), U.S. households devoted slightly above 13% of their income on average (and 18% for the median) to transportation, 95% of which is associated with buying, maintaining, and operating a private vehicle. This suggests $0\cdot13$ as an estimate for α.

The parameter β is the share of land in expenditure, and our estimate for this parameter is $\hat{\beta} = 0\cdot032$. We calculate our estimate for this parameter from estimates of the share of housing in consumption and the share of land in housing production. The details of this calculation are given in Appendix F. In the same appendix, we also estimate ϕ to be $0\cdot70$.

The parameter δ is the elasticity of unit transportation costs to road provision. Duranton and Turner (2009) provide direct estimates of δ by estimating the MSA mean cost of driving (as measured by inverse speed) as a function of interstate lane kilometres. Their preferred estimate is $\hat{\delta} = 0\cdot06$.[5] Alternatively, using the first-order condition for utility maximization with respect to driving distance and inserting it into expression (3) implies that equilibrium driving is

$$X = R^{\frac{\delta}{1+\delta}} N^{-\frac{\delta}{1+\delta}} (\alpha w)^{\frac{1}{1+\delta}}. \tag{19}$$

This exact expression is estimated in Duranton and Turner (2011). For roads and population, they find coefficients that are equal but opposite in sign as predicted by equation (19). Depending on the particular measure of driving that they use, their results yield a value of δ between $0\cdot05$ and $0\cdot10$. Although this procedure is less direct and less precise, it yields results consistent with our preferred value of $0\cdot06$.

To approximate $\underline{w}$, the reservation wage in a city of size one, we use the 1980 *Statistical Abstract of the United States* to find national average hourly wage and hours worked in 1979. This gives us mean weekly earnings of 212\$. Multiplying by weeks per year, adjusting to 2007 dollars and rounding up to the nearest thousand, we have \$32,000 per year.

A large literature estimates σ. Rosenthal and Strange (2004) survey earlier estimates and conclude that the range for σ is between $0\cdot04$ and $0\cdot08$. More recent estimates that deal with a series of econometric problems find somewhat lower values. Davis, Fisher and Whited (2009) find a value of $0\cdot02$ for σ in the U.S. Glaeser and Resseger (2010) suggest a value of $0\cdot04$ or less. These estimates are consistent with recent estimates obtained in other countries (*e.g.* Combes *et al.*, 2010 for France). Our preferred value of $0\cdot03$ is central in the range of these estimates.

5.2. Policy experiment: road building

We now compare status quo and alternative highway policies. A transportation policy is a sequence describing the provision of roads in each period from 0 to T, $(R_t)_{t=0}^{T}$. Our estimates of equation (14) describe the realized equilibrium transportation policy. Equation (13) describes the evolution of employment, $(N_t)_{t=0}^{T}$, associated with this policy. To assess the optimality of

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5. Page 23, Table C1, column 4.

observed policy, we compare it with alternative policies. An alternative policy is an alternative sequence of roads, $(\tilde{R}_t)_{t=0}^T$. It generates an alternative sequence of employment, $(\tilde{N}_t)_{t=0}^T$.

Our model consists of two classes of agents, city residents, whose preferences we have described, and an implicit class of absentee landlords who own land in the city. For a representative resident, let V_t and $\tilde{V}_t$ denote utility at t (as defined in equation (2)) under the status quo and alternative policies. For a resident, the change in welfare only involves the difference between these two quantities. We monetize this change using the standard notion of equivalent variation, which we denote EV_t. In Appendix G, we establish that under the assumptions of Section 2, equivalent variation for our representative agent is

$$EV_t = \underline{w}N^\sigma \left[\left(\frac{\tilde{R}_t}{R_t} \right)^{\frac{\delta(\alpha+\beta\phi)}{\delta+1}} \left(\frac{N_t}{\tilde{N}_t} \right)^{\frac{\alpha\delta(\sigma+1)+(\beta-1)\sigma(\delta+1)-\beta\phi(\sigma-\delta)}{\delta+1}} - 1 \right]. \tag{20}$$

Let π_t and $\tilde{\pi}_t$ denote *per capita* land rents under the status quo and alternative transportation policy, and $\Delta\pi_t = \tilde{\pi}_t - \pi_t$ the *per capita* change in land rents. Appendix G shows that

$$\Delta\pi_t = \beta\underline{w}[\tilde{N}_t^\sigma - N_t^\sigma]. \tag{21}$$

The change in welfare on a *per capita* basis caused by the change from the status quo to the alternative policy for period t is the sum of EV_t and $\Delta\pi_t$. Note that we use average welfare rather than total welfare. This relieves us of some accounting when employment levels change. It is equal to

$$\Delta\Omega_t = EV_t + \Delta\pi_t. \tag{22}$$

The total change in welfare is the corresponding discounted sum,

$$\Sigma_{t=0}^T \rho^t \Delta\Omega_t. \tag{23}$$

Our simulations take 1983 as their initial date and 2083 as their terminal date, so that T varies from 0 to 99. We take the annual social discount rate to be 5%. After 100 years, the discount factor is about 1/130 so there is no reason to expect that longer simulations will arrive at qualitatively different conclusions. Our estimations describe changes over a 20 year period and thus our estimates of equations (13) and (14) predict the path of roads and employment at 20 year intervals. We construct annual predictions by linear interpolation of the 20 year values given by the model.

It remains to assess the costs of a change in transportation policy. According to the Congressional Budget Office, the average kilometre of interstate completed after 1970 came at a cost of nearly 21 million of 2007 dollars. Ng and Small (2008) arrive at generally higher estimates for interstate highways in metropolitan areas. In particular for 2006, they find that the total cost of an extra lane kilometre of interstate is: m$3.64 for MSAs with a population less than 200,000; m$5.34 for MSAs with a population between 200,000 and 1 million; and m$11·96 for MSAs with a population greater than 1 million. Multiplying by about 4·69 lanes for an average lane kilometre of 1983 MSA interstate in our sample gives construction costs per interstate kilometre of: m$17·07 per kilometres for MSAs with a population less than 200,000; m$25·04 per kilometres for MSAs with a population between 200,000 and 1 million; and m$56·09 per kilometres for MSAs with a population greater than 1 million. In what follows, we maintain the Ng and Small (2008) classification of "small", "intermediate", and "large" MSAs.

Around 136 billion dollars per year are spent on maintaining the federal road system (United States Bureau of Transportation Statistics, 2007). The interstate highway system accounts for

about one quarter of all passenger miles on this system. If we suppose that about one quarter of all maintenance dollars are also directed to the 75,000 kilometres of interstate highways, maintenance of these roads is about 450,000 dollars per kilometres annually. This is probably an understatement since highways within MSAs are more intensively used and thus require more maintenance. Taking a cost of capital of 5% per year, we have total cost per interstate kilometre per year of: m$1·30 for MSAs with a population less than 200,000; m$1·70 for MSAs with a population between 200,000 and 1 million; and m$3·25 for MSAs with a population greater than 1 million. Letting p_R denote the cost of a kilometre of interstate in a given city, the annual *per capita* cost of changing from transportation policy $(R_t)_{t=0}^T$ to $(\tilde{R}_t)_{t=0}^T$ is $p_R(\tilde{R}_t - R_t)/N_t$.

Putting together the calculation of changes in welfare and changes in cost, we have that the alternative transportation plan, $(\tilde{R}_t)_{t=0}^T$, is socially preferred to the status quo, $(R_t)_{t=0}^T$, if and only if the following expression is positive:

$$\Sigma_{t=0}^T \rho^t (\Delta\Omega_t - p_R(\tilde{R}_t - R_t)/N_t) > 0, \tag{24}$$

where $\Delta\Omega_t$ is given by (22).

We use equation (24) to compare the status quo transportation policy with three alternatives. The status quo transportation policy is given by the observed level of interstate highways in 1983 and evolves over time according to equation (14) using our preferred estimates of θ and η. Under the status quo transportation policy, we use 1983 employment and have it evolve according to equation (13) using our preferred estimates of a and λ.

Our three counterfactuals all involve a one-time increase in highway provision after which highway provision and employment are determined by the same structural parameters as determine highway provision and employment under the status quo. That is, our counterfactual policies describe "stimulus" policies that build more highways in the short run but leave unchanged the institutions for allocating highways over the long run.

Under alternative policy 1, we adjust the status quo policy by increasing the initial 1983 stock of highways by 4·8% in each of the 227 MSAs in our sample. From Table 1, this is the sample mean increase in roads over 1983–2003. In words, alternative policy 1 moves highway construction forward 20 years and assigns new highway kilometres on the basis of the initial stock of roads. Under alternative policy 2, we calculate the discount present value of policy 1 and allocate these funds across MSAs on the basis of their 1983 share of aggregate MSA employment.[6] Alternative policy 3 is qualitatively the same as policy 2 but only assigns new 1983 highways to MSAs that have fewer kilometres of interstate per employee than the median MSA. Thus, policy 1 assigns new roads on the basis of the stock of existing roads, policy 2 assigns new roads on the basis of initial employment, and policy 3 directs new roads to cities where roads are relatively scarce. We note that these policy experiments refer explicitly to expansions of the highway network. The nature of our data and analysis does not allow us to do more than speculate about the effects of the depreciation or maintenance of the highway network.

Table 5 describes the effects of these policies. The top panel describes the average effects of different transportation policies over our whole sample of MSAs. The subsequent three panels provide the corresponding statistics for small, medium and large MSAs, where this classification is based on the 1980 population and the size categories defined earlier. The four columns of the panel refer to the status quo policy and the three alternative transportation policies.

Within each panel of Table 5, the top row gives the predicted average annual percentage growth rate of an average MSA between 1983 and 2083. Under the status quo transportation

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6. This cost is $\Sigma_{t=0}^{99} \rho^t (\tilde{R}_0 - R_0)$. This is the 100 year discounted present value of the new roads. It is not quite equal to the full cost of the policy because it does not account for induced changes to road construction or depreciation after the initial period since we assume no change in the policy regime.

TABLE 5

Effects of three hypothetical highway construction policies

	Status quo	Policy 1	Policy 2	Policy 3
Total MSAs				
% annual growth in employment	1·78	·1·79	1·80	1·80
$\Sigma \rho^t \Delta \pi$	—	5·26	9·76	10·51
$\Sigma \rho^t EV$	—	432·22	803·92	866·45
$\Sigma \rho^t p_R(\tilde{R} - R)$	—	1366·71	1517·59	1558·94
Net Δ welfare	—	−929·23	−703·92	−681·98
Small MSAs				
% annual growth in employment	1·91	1·92	1·92	1·92
$\Sigma \rho^t \Delta \pi$	—	4·84	5·84	4·09
$\Sigma \rho^t EV$	—	396·98	480·37	336·86
$\Sigma \rho^t p_R(\tilde{R} - R)$	—	1981·07	1486·35	619·57
Net Δ welfare	—	−1579·25	−1000·14	−278·61
Medium MSAs				
% annual growth in employment	1·85	1·86	1·87	1·87
$\Sigma \rho^t \Delta \pi$	—	5·04	6·70	6·41
$\Sigma \rho^t EV$	—	413·79	550·36	526·67
$\Sigma \rho^t p_R(\tilde{R} - R)$	—	1385·57	1468·02	1195·51
Net Δ welfare	—	−966·74	−910·96	−662·43
Large MSAs				
% annual growth in employment	1·74	1·76	1·77	1·77
$\Sigma \rho^t \Delta \pi$	—	5·38	11·22	12·59
$\Sigma \rho^t EV$	—	442·11	925·27	1037·84
$\Sigma \rho^t p_R(\tilde{R} - R)$	—	1303·78	1538·39	1776·31
Net Δ welfare	—	−856·29	−601·90	−725·88

Notes: Small MSAs have 1980 populations less than 200,000. Intermediate MSAs have 1980 populations above 200,000 but less than 1,000,000. Large MSAs have 1980 populations above 1,000,000. All quantities are 2007 dollars per MSA employee.

policy described in column 1, employment in an average city grew by about 1·8% per year over 100 years. We also note that large cities are predicted to grow more slowly than small cities by about one-fifth of a percentage point per year. These predictions follow from the fact that small cities in our sample typically have more highways *per capita* than large and are allocated more new highways than large cities.

Comparing across policies, we can see that an immediate 4·8% increase in highway mileage has very small effect on the growth rate of cities. This is easy to understand. Over a 20 year period, this 4·8% increase in highway mileage implies an increase in employment of 0·7%. On an annual basis, this corresponds to an extra growth of 0·03% points. That policies 1, 2, and 3 lead to the same overall growth rate suggests that, regardless of the details of the road building policy, we should expect only a small impact on the growth rate of employment.

Changes in land rent are reported in the second row of each panel of Table 5. We see that small predicted effects on the growth of employment translate into tiny increases in *per capita* land rent. The 4·8% increase in the provision of highways considered in policy 1 implies an increase in employment of 0·7% 20 years later. Given modest agglomeration effects of 3·0%, this small increase in employment only implies a tiny earnings effect of 0·02% point. For a city where average annual earning are $40,000, the gain would thus be of about $8·6 per annum. Then, it is also the case that residents devote a small fraction of their expenditure to land. With

our 3·2% share of expenditure on land, a 4·8% increase in highway mileage means only an extra 28 cents spent annually on land after 20 years. Hence, it is unsurprising that our simulations indicate tiny increases for the 100 year net present value of land rent per resident. Policies 2 and 3 yield marginally higher increases in land rents by either allocating funds more evenly on a *per capita* basis across cities or to cities with fewer roads.

The third row of every panel of Table 5 reports results for the increase in individual utility as measured by the equivalent variation. The effects are much higher than for land rents but still modest. For the 100 year net present value of the increase in equivalent variation relative to the status quo, the numbers are close to $400 for policy 1. Again, to understand these magnitudes, it is useful to focus on the effect after 20 years. As made clear in Appendix D, the equilibrium cost of driving depends on roads elevated to the power $-\delta/(1+\delta)$ (≈ -0.057) and population. Neglecting the small increase in the cost of driving caused by rising population, policy 1 that allocates 4·8% more highways to all cities leads to a decrease in driving costs of 0·27%. In a city, where average annual earnings are $40,000, residents spent 13% of this amount on driving, that is, $5200. A 0·27% decline in driving costs is equivalent to a monetary gain of $14 per year. By allocating new roads to places where they are relatively scarcer, policies 2 and 3 lead to bigger increases in the equivalent variation, particularly in large MSAs.

The fourth row of every panel of Table 5 reports results for the 100 year net present value of the cost of new highways. Policy 1 involves an extra cost of around $1350 relative to the status quo. To understand this magnitude, consider an MSA with a mean highway mileage in 1983 of 243·4 kilometres. Policy 1 involves building 11·7 extra kilometres of highways in that MSA. If that MSA also has a mean 1980 population which is below 1 million but above 200,000, the annual cost of these roads is about $20 million. With a mean number of workers in 1983 of 250,500, the annual cost per worker is about $80.[7] We can also see that policies 2 and 3, which tend to allocate the new highways to larger cities, are more costly.

Finally, the fifth row of every panel of Table 5 reports the sum of all the terms in the welfare calculation, the two gains in land rent and utility minus the cost of highways. All policies in all types of MSAs yield a negative number between about $300 and about $1600. In light of the numbers given above, this conclusion is unsurprising. Gains in land rents are trivially small. The value of utility gains (mostly from driving) is small. The cost of building highways is much higher. As a result, costs exceed benefits. We note that our policy experiments only looks at a "blanket" increases in highway provision. This does not mean that providing more lanes to reduce a particular bottleneck is never worthwhile.

While the costs estimates we use for highways are imperfect, it is difficult to imagine the result of *ex post* engineering studies to be wrong by a factor of three or five. It is also difficult to imagine that the land rent effects could be raised by three orders of magnitude. Even we were to multiply the effect of roads on employment by a factor of three (to reach an elasticity of employment to roads of 0·45 over 20 years instead of 0·15), multiply the share of land in consumption by a factor of five (to reach 16% instead of 3·2%), and multiply agglomeration economies by three (to reach 0·09 instead of 0·03), the 20 year effect on rents would jump from 28 cents to more than $12 but still falling short of an annual cost of highways of $80 despite taking implausibly high values for all the main parameters.

This leaves us only one possibility: making the utility gains from more interstate highway kilometres much higher. Going back to the calculation above, it may be possible to argue that

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7. The net present value of $80 per year is greater than the cost of $1366 estimated for policy 1. This is because the immediate increase in roadway is in part offset by a decrease in highway expansion at later dates. This is taken into account by our simulations but not by the simple calculation given here.

resources devoted to driving are higher than 13% of $40,000 per year. One can significantly increase this amount by valuing 2 hours a day spent in a car at $10 an hour, a figure corresponding to half the hourly wage associated with 2000 hours of work and $40,000 of earnings annually. Then to reach an equivalent variation of $80 per year for the 4·8% increase in highways considered here, we would need to elasticity of driving costs relative to the roadway δ to be 0·16 instead of the figure we use of 0.06. Whether road building can achieve such large reductions in the cost of driving is very much in doubt.

To summarize, marginal extensions to the Interstate highway system fail to provide welfare gains primarily because they result in such small decreases in the price of travel. As argued above, the elasticity of the cost of driving with respect to roads is $\frac{-\delta}{1+\delta} \approx -0\cdot057$. Thus, a 1% increase in the stock of roads results in a 0·057% decrease in the time cost of travel. A typical worker spends about 13% of their 40,000$ income on travel or about $5200. Therefore, holding everything else constant a 1% increase in the stock of highways is worth about 0·00057 × $5200 or slightly less than $3 to this worker. Since the annualized cost of a 1% increase in the stock of roads is about $16, an increase in the road network can only be welfare improving if indirect effects on congestion and on land and labour markets are much larger than the direct effects. The substance of the results in this section is that these indirect effects are tiny.

6. CONCLUSION

Public expenditure on roads in the U.S. exceeds 200 billion dollars annually. In order to conduct this massive resource allocation wisely, we must understand the implication of these investments for the evolution of cities over the course of generations.

Up until now, however, this question has escaped rigorous analysis. This reflects the difficulty of assembling data that measure roads, the absence of a theoretical model relating infrastructure to growth, and the difficulty of finding suitable instruments to correct for the endogeneity of infrastructure provision. This paper addresses all three of these issues to estimate the effect of roads on cities.

Over a 20 year period, we find that the major road elasticity of city employment is 15%. There are several reasons to believe this estimate is accurate. Our instrumental variables estimation strategy is consistent with a simple model of urban growth. There are plausible *a priori* arguments for the exogeneity of our instruments. Our three instruments each yield the same elasticity estimate. Our estimate is robust to changes of specification and estimation strategy. Our estimate of the road elasticity of employment growth is consistent with a crude estimate of the long-run effect of rail infrastructure on population growth. Finally, we provide out-of-sample verification for the difference between the OLS and IV results.

Our findings are important because they help to inform us about how cities evolve and grow, because they provide a sounder empirical basis for workhorse theoretical models of cities, and because they provide guidance to policy makers who must plan highway construction and complementary public infrastructure.

Our results also shed light on the process by which roads are allocated to cities. In particular, they indicate that roads are allocated to cities, in part, in response to negative population shocks. This suggests that road construction may be a substitute for social assistance and that roads are built where land and labour are cheap rather than in the places where they are most needed. It is unlikely that this is an optimal use of infrastructure dollars. Indeed, the structural model underlying our estimating equations allows us to analyse the social benefits of alternative transportation policies. This analysis suggests continuing to expand the interstate highway system at the 1983–2003 rate probably involves building more highways than is socially optimal.

APPENDIX A: ALTERNATIVE FOUNDATIONS FOR EQUATION (10)

We here present an alternative derivation of our estimating equation (10) based on the conventional monocentric city model.

A city consists of a segment of the real line with its centre at zero. Each location in the city is described by its displacement from the centre, x. All production in the city takes place at $x = 0$. All agents in the city choose a location x and commute to the city centre where they earn wage w. The unit cost of commuting is p. All agents consume one unit of land at rental price $r(x)$, and spend their income, net of rent and commuting, on a numéraire good c. Agents derive utility from consumption according to an increasing concave utility function u and have reservation utility $\underline{u}$.

Thus, with free migration, we must have

$$u(w - px - r(x)) = \underline{u}, \tag{A.1}$$

or, inverting u

$$w - px - r(x) = k, \tag{A.2}$$

for $k = u^{-1}(\underline{u})$. Thus, we have that $r(x) = w - px - k$ for any occupied location in the city.

Land outside of the city is employed in agriculture and generates reservation land rent $\underline{r}$. Thus, at the boundary of the city $\bar{x}$, we must have $\underline{r} = w - p\bar{x} - k$. Since agents consume one unit of land, this condition also determines equilibrium city population

$$N = \frac{2}{p}(w - \underline{r} - k). \tag{A.3}$$

If, as in equation (3), we allow unit transportation to be a function of a city's stock of roads and population, $p(N, R)$, then the equation above implicitly defines an equilibrium population level corresponding to the one used in the body of the paper, equation (6).

We can then use the same logic used in the body of the paper to derive the estimating equation (10) from equation (6).

To ease exposition, we here deliberately abstract from a number of important details: agglomeration effects, the production of housing, endogenous lot size, and the details of the transportation cost function. These features may be incorporated into the basic monocentric city model described here at some cost in complexity (see Duranton and Puga, 2012 for further details). The specification given in the text, and on which our analysis is based, reflects many of these details in a parsimonious way, although it is less specific about how, exactly, all these different processes interact.

APPENDIX B: DATA

Consistent MSA definitions

MSAs are defined as aggregations of counties. We use the 1999 definition. Our variables either come from maps that we overlay with a map of 1999 counties or county-level data. Construction of our employment, population, and road series requires tracking changes in county boundaries over time.

Employment and population data

To measure employment, we use the County Business Patterns data from the U.S. Census Bureau from 1977 to 2003. Since MSAs are defined as aggregations of counties, these data allow us to construct measures of total MSA employment for 1983, 1993, and 2003. We also construct measures of manufacturing employment in 1983 and pay close attention to employment in one particular sector, road construction (SIC 16), to provide out-of-sample corroboration of our main result. For population, we use all decennial censuses back to 1920, the earliest year for which we can construct population numbers for MSAs.

Road infrastructure and driving

To measure each MSA's stock of highways and traffic, we use the U.S. HPMS Universe data for 1983, 1993, and 2003. These data are described extensively in Duranton and Turner (2011) and references therein, including United States Department of Transportation, Federal Highway Administration (2005a). The U.S. Federal Highway Administration collects these data in cooperation with many sub-national government agencies on behalf of the federal government for planning purposes and to apportion federal highway money.

We use a county identifier to match every segment of interstate highway to an MSA and calculate kilometres of interstate highways within each MSA. In some regressions, we also use the information about the number of lanes to build an alternative measure of roads.

Within the most densely populated parts of MSAs (urbanized areas), interstates represent about 1·5% of all road kilometres and 24% of vehicle kilometres travelled (United States Department of Transportation, Federal Highway Administration, 2005b). As an alternative measure of road infrastructure, we also use the USGS 1980 digital line graph. In addition, we use measures of driving from Duranton and Turner (2011).

MSA characteristics

The five measures of physical geography described in the main text come from Burchfield *et al.* (2006). Our measures for the share of poor, the share of adults with at least a college degree, log mean income, and our index of segregation all derive from the 1980 census. We also use a measure of land development from Overman, Puga and Turner (2008). Finally, distances between cities are measured from centroid to centroid, where centroids are calculated on the basis of impermeable surface coverage using data from Burchfield *et al.* (2006).

APPENDIX C: FIRST-STAGE RESULTS

Column 1 of Table C1 presents regressions of the log of 1983 interstate highways kilometres on our three instruments and the log of 1983 employment. Column 2 adds controls for decadal population levels from 1920 through 1970 and corresponds to our preferred regression in column 2 of Table 3. Column 3 augments the regression of column 2 with further controls for physical geography, census divisions, and socioeconomic characteristics of MSAs. Columns 4, 5, and 6 reproduce the regression in column 2 but uses only a single instrumental variable.

The coefficients on planned interstates, railroads, and early exploration routes in Table C1 are almost always highly significant with the expected positive sign and their magnitudes are stable despite dramatic changes in the controls. While the table does not report coefficients for the controls, we find that population or employment controls tend to be significant, physical geography variables are sometimes significant, while census division indicators and socioeconomic variables are usually insignificant.

Table C1 also reports partial F-statistics for our instruments. Column 2 corresponds to the first stage of our preferred IV estimate below and has an F-statistic of 13·3. From Tables 1–4 in Stock and Yogo (2005), we see that this regression passes the size tests in the context of LIML estimation and the relative bias test in the context of TSLS estimation (since LIML has no relative bias test). Other regressions that use the 1947 highway plan, 1898 railroads, and early exploration routes in columns 1 and 3–6, have F-statistics that are near or above the critical values for the relevant weak instruments tests.

TABLE C1
First stage: dependent variable: ln(Interstate Highway km_{83})

	[1]	[2]	[3]	[4]	[5]	[6]
ln(Planned Interstate Hwy)	0·19***	0·17***	0·13***	0·24***		
	(0·042)	(0·042)	(0·040)	(0·043)		
ln(Railroad routes)	0·083	0·14*	0·13*		0·32***	
	(0·059)	(0·084)	(0·073)		(0·083)	
ln(Exploration routes)	0·051***	0·055**	0·025			0·097***
	(0·019)	(0·021)	(0·024)			(0·027)
ln(Emp$_{83}$)	Y	Y	Y	Y	Y	Y
$\{\ln(Pop_t)\}_{t \in \{20,...,70\}}$	N	Y	Y	Y	Y	Y
Physical geography	N	N	Y	N	N	N
Census divisions	N	N	Y	N	N	N
Socioeconomic controls	N	N	Y	N	N	N
R^2	0·54	0·55	0·65	0·53	0·48	0·47
First-stage statistic	17·0	13·3	8·3	30·0	15·0	13·4

Notes: 227 observations for each regression. All regressions include a constant. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%. Controls as in Table 1.

APPENDIX D: ROBUSTNESS TESTS FOR TABLE 3

In Table D1, we replicate our main IV results of Table 3 using a GMM estimator rather than LIML. The resulting coefficient estimates are very close to those presented in the main text.

In Table D2, we show that the estimates reported in Table 3 are robust to our choice of instruments. Column 1 replicates our preferred regression from column 2 of Table 3. In each of columns 2–7, we replicate this regression using a different subset of our three instrumental variables. Column 2 only uses the 1947 planned highway measure as an instrument. Columns 3 and 4 only use the 1898 railroad routes and 1528–1850 exploration routes, respectively. Columns 5–7 use all possible pairs of these three instruments. All these specifications produce estimates of the coefficient of 1983 interstate highways on employment growth that are equal to or statistically indistinguishable from 0·15.

In Table D3, we check that the results reported in Table 3 are robust to minor changes in variable and sample definition. The dependent variable in column 1 of Table D3 is the change in log employment between 1993 and 1983 (as opposed to 2003 and 1983). The regression is otherwise identical to our preferred specification form column 2 of Table 3. The dependent variable in column 2 is the change in log employment between 1993 and 2003. In this column, we retain our preferred specification but change the years for the employment and population controls as appropriate. In column 3, we duplicate the regression of column 2 but use kilometres of interstate highways for 1993 instead of 1983. In these three columns, we find the coefficients on roads to be between 0·063 and 0·098 over one decade. This is consistent with a coefficient of 0·15 over two decades in our preferred specification. Given that the correlation between 1993 and 1983 highways is high at 0·93, it is difficult to interpret these results further. In column 5, we duplicate our preferred regression but measure our instruments over the developable part of MSAs instead of their entire areas by imposing a 20

TABLE D1
Growth of employment and roads as a function of initial roads, GMM IV

	[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]
Panel A: Employment or population growth								
$\ln(\text{Int. Hwy km}_{83})$	0·15***	0·16***	0·15***	0·16***	0·12**	0·093*		0·12***
	(0·047)	(0·037)	(0·042)	(0·044)	(0·049)	(0·049)		(0·029)
$\ln(\text{Emp}_{83})$	−0·14***	−0·26	−0·26	−0·24	−0·25	−0·25	−0·37**	0·25***
	(0·032)	(0·18)	(0·18)	(0·18)	(0·21)	(0·21)	(0·18)	(0·074)
$\ln(\text{USGS maj. roads}_{80})$							0·29***	
							(0·066)	
Over-id p value	0·04	0·96	0·93	0·59	0·65	0·59	0·18	0·47
Panel B: Road growth								
$\ln(\text{Int. Hwy km}_{83})$	−0·21***	−0·25***	−0·24***	−0·24***	−0·27***	−0·24**		
	(0·059)	(0·082)	(0·088)	(0·090)	(0·98)	(0·98)		
$\ln(\text{Emp}_{83})$	0·19***	0·25**	0·26**	0·25**	0·14	0·012	0·28*	
	(0·042)	(0·11)	(0·11)	(0·11)	(0·091)	(0·094)	(0·16)	
$\ln(\text{USGS maj. roads}_{80})$							−0·42**	
							(0·20)	
Over-id p value	0·41	0·41	0·54	0·57	0·72	0·96	0·47	
$\{\ln(\text{Pop}_t)\}_{t\in\{20,\ldots,70\}}$	N	Y	Y	Y	Y	Y	Y	Y
Physical geography	N	N	Y	Ext.	Ext.	Ext.	N	N
Socioeconomic controls	N	N	N	N	Y	Y	N	N
Census divisions	N	N	N	N	N	Y	N	N
First-stage statistic	17·0	13·3	11·8	13·9	11·3	9·7	11·9	13·3

Notes: 227 observations for each regression. All regressions include a constant. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%. Panel A: dependent variable is $\Delta_{03,83}\ln$ Emp in columns 1–7 and $\Delta_{00,80}\ln$ Pop in column 8. Panel B: dependent variable is $\Delta_{03,83}\ln$ Interstate Highway kilometres. All regressions use 1947 planned highway kilometres, 1898 kilometres of railroads, and index of 1528–1850 exploration routes as instruments.

TABLE D2
Growth of employment and roads as a function of initial roads, robustness to instruments

	[1]	[2]	[3]	[4]	[5]	[6]	[7]
Panel A: Employment growth. Dependent variable: $\Delta_{03,83}$ ln Employment							
ln(Int. Hwy km$_{83}$)	0·15***	0·15***	0·15**	0·17***	0·15***	0·16***	0·16***
	(0·037)	(0·038)	(0·062)	(0·057)	(0·039)	(0·037)	(0·047)
ln(Emp$_{83}$)	−0·26	−0·26	−0·25	−0·26	−0·26	−0·26	−0·26
	(0·19)	(0·19)	(0·19)	(0·19)	(0·19)	(0·19)	(0·19)
Over-id test p value	0·96	·	·	·	0·92	0·77	0·79
Panel B: Road growth. Dependent variable: $\Delta_{03,83}$ ln Interstate Highway km							
ln(Int. Hwy km$_{83}$)	−0·28***	−0·28***	−0·21*	−0·41***	−0·26***	−0·30***	−0·28***
	(0·093)	(0·099)	(0·11)	(0·12)	(0·089)	(0·10)	(0·096)
ln(Emp$_{83}$)	0·25**	0·25**	0·24**	0·28**	0·25**	0·26**	0·25**
	(0·11)	(0·11)	(0·11)	(0·11)	(0·11)	(0·11)	(0·11)
Over-id test p value	0·41	·	·	·	0·56	0·21	0·22
Instruments used							
ln(Planned Interstate Hwy.)	Y	Y	N	N	Y	Y	N
ln(Railroad routes)	Y	N	Y	N	Y	N	Y
ln(Exploration routes)	Y	N	N	Y	N	Y	Y
First-stage statistic	13·3	30·0	15·0	13·4	15·8	18·2	14·4

Notes: 227 observations for each regression. All regressions are LIML IV and include a constant and controls for log 1983 employment and log population for all decades between 1920 and 1970. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%.

TABLE D3
City growth and initial roads, further robustness tests

	$\Delta_{93,83}$ ln Emp [1]	$\Delta_{03,93}$ ln Emp [2]	$\Delta_{03,93}$ ln Emp [3]	$\Delta_{03,83}$ ln Emp [4]	$\Delta_{03,83}$ ln Emp (>0.3m) [5]	$\Delta_{03,83}$ ln Emp (≤0.3m) [6]
ln(Int. Hwy km$_{83}$)	0·063***	0·078***		0·15***	0·12***	0·16***
	(0·020)	(0·030)		(0·039)	(0·029)	(0·059)
ln(Int. Hwy km$_{93}$)			0·098[a]			
			(0·037)			
First-stage statistic	13·3	12·3	15·0	11·4	13·3	5·93
Over-id test p value	0·78	0·63	0·56	0·90	0·91	0·96
Observations	227	227	227	227	107	120

Notes: All regression are LIML IV with robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%. In all columns but four instruments are MSA values of early exploration routes, 1898 railroads, and 1947 highways. In column 4, instrument values are calculated for the developable area of each MSA. Columns 1 and 4–6 include a constant, controls for decennial population growth from 1920 to 1970 and 1983 employment. Columns 2 and 3 include a constant, controls for decennial population from 1920 to 1980 and 1993 employment, others include controls for decennial population from 1920 to 1970 and 1983 employment.

kilometre buffer around developed areas as in Burchfield *et al.* (2006). The results are unchanged. We also replicate (but do not report) the regressions in reported in Table 3 using a lane weighted measure of interstate highways. The results are statistically undistinguishable from those using a simple measure of road kilometres.

Finally in columns 7 and 8 of Table D3, we split our sample of cities at a population threshold of 300,000, roughly the median population size, and repeat our preferred regression for each subsample separately. The coefficient on roads is the same for both subsamples and are consistent with estimates based on the whole sample.

APPENDIX E: LONG-RUN EFFECT OF RAILROADS AND NETWORK EFFECTS

In each of the four regressions of Table E1, the dependent variable is the change in log population between 1920 and 2000, that is, the 80 year rate of population growth. In column 1, we predict this long-run rate of population growth as a function of the log of 1898 railroad routes and the log population in 1920, the earliest date for which we have population data. In column 2, we add controls for physical geography. In column 3, we control for physical geography and census divisions. In column 4, we add extended controls for physical geography. These regressions indicate that the long-run population growth elasticity of 1898 rail is around 0·30, provided we control for physical geography.[8]

Table E2 presents results consistent with a lack of road network effect on employment growth. Column 1 augments our preferred OLS regression of column 2 of Table 2 with the log of kilometres of interstate highways for each MSA's neighbour. Column 2 repeats this regression but uses our gravity measure of roads for the neighbour MSA. In both cases, the coefficient on neighbour roads is negative, while the coefficient on own MSA roads is the same as in column 2 of Table 2. In columns 3 and 4, we use the same two road network measures to augment our preferred IV specification from column 2 of Table 3. Again, the coefficient on roads for the neighbour MSA is negative while that on the own MSA roads is unchanged. In columns 5 and 6, we repeat the same exercise but also instrument the neighbour's stock of interstate highways. Our instrumental variables estimation mirror for neighbour MSA roads what we do for subject MSA roads. The coefficients on neighbour roads are still negative while the coefficient on own MSA roads remains close to that of our preferred LIML IV regression. Finally, in columns 7 and 8, we add extended controls for physical geography, census division, and socioeconomic characteristics of MSAs. The coefficients on roads for the neighbouring MSA are again not distinguishable from zero.

TABLE E1

Long-run effects of rail on population growth

	$\Delta_{00,20}$ ln Pop			
	[1]	[2]	[3]	[4]
ln(1898 railroad routes)	0·56***	0·34***	0·30***	0·32***
	(0·15)	(0·088)	(0·11)	(0·12)
ln(Pop$_{1920}$)	−0·39***	−0·18***	−0·13*	−0·17**
	(0·099)	(0·062)	(0·067)	(0·073)
Physical geography	N	Y	Y	Ext.
Census divisions	N	N	Y	Y
R^2	0·14	0·65	0·72	0·76
Observations	112	112	112	112

Notes: All OLS regressions including a constant. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%.

8. Since small cities in 1920 will be counted as MSAs in 1999 only if they grow to at least 50,000 people, including cities that are small in 1920 over-samples small fast-growing cities. As a crude way of correcting for this problem, the regressions of Table E1 are based on the 112 MSAs with 1920 population of more than 100,000. Such cities could experience large increases or decreases of population and still be counted as MSAs in 1999. We experimented with 1920 population thresholds of 50,000 and found a slightly lower coefficient around 0·25 or 150,000 found a higher coefficient around 0·35.

TABLE E2
Employment growth rate 1983–2003 and network effects

	[1] OLS	[2] OLS	[3] LIML	[4] LIML	[5] LIML	[6] LIML	[7] LIML	[8] LIML
			Dependent variable: $\Delta_{03,83} \ln$ Emp					
$\ln$(Int. Hwy km_{83})	0.066***	0.062***	0.14***	0.13***	0.13***	0.13***	0.096**	0.091**
	(0.013)	(0.013)	(0.036)	(0.036)	(0.035)	(0.035)	(0.047)	(0.045)
$\ln$(Neighbour Int. Hwy_{83})	−0.056**		−0.043**		−0.053**		−0.034	
	(0.022)		(0.020)		(0.022)		(0.032)	
$\ln$(Neighbour gravity$_{83}$)		−0.028***		−0.021**		−0.023**		−0.018
		(0.0097)		(0.0092)		(0.0099)		(0.015)
$\ln(\text{Emp}_{83})$	−0.26	−0.27	−0.27	−0.27	−0.28	−0.27	−0.29	−0.29
	(0.19)	(0.19)	(0.19)	(0.19)	(0.19)	(0.19)	(0.22)	(0.22)
$\{\ln(\text{Pop}_t)\}_{t \in \{20,\ldots,70\}}$	Y	Y	Y	Y	Y	Y	Y	Y
Physical geography	N	N	N	N	N	N	Y	Y
Socioeconomic controls	N	N	N	N	N	N	Y	Y
Census divisions	N	N	N	N	N	N	Y	Y
Instruments used								
3 IV for own city hwy.			Y	Y	Y	Y	Y	Y
3 IV for neighbour hwy.			N	N	Y	Y	Y	Y
First-stage statistic			12·3	11·0	7·63	7·28	4·70	4·71
Over-id test p value			0.91	0.94	0.78	0.55	0.88	0.91

Notes: 227 observations for each regression. All regressions include a constant. Robust standard errors in parentheses. *, **, ***: significant at 10%, 5%, 1%. In columns 3–8 kilometres of MSA, 1983 interstate highways are instrumented by early exploration routes, 1898 railroads, and 1947 highways. In columns 5–8, 1983 measures of neighbour roads are instrumented by the corresponding 3 instruments for the neighbour city.

APPENDIX F: CALCULATION OF $\hat{\beta}$ AND $\hat{\phi}$

Assuming that housing capital and land enter the production function of housing in Cobb–Douglas fashion and using our Cobb–Douglas utility function, β is the product of the share of land in housing and the share of housing in household expenditure.

A recent and detailed study by Davis and Ortalo-Magné (2011) sets the share of housing in expenditure to 0·24. Turning to the share of land in housing, note that the first-order condition for profit maximization in housing development with respect to land implies that the user cost of land r^L is such that $r^L L = \phi H$, where ϕ is the share of land in housing production and H is the value of housing. The second first-order condition implies that the user cost of capital r^K is such that $r^K K = (1 - \phi)H$. These two first-order conditions imply

$$\frac{\phi}{1-\phi} = \frac{r^L L}{r^K K}. \tag{F.1}$$

Then, we know from Davis and Heathcote (2007) that the value of land accounts for about a third of the value of housing. That is, $L/K \approx 0.5$. Because housing capital depreciates, we think of the user cost of capital as being equal to the interest rate plus the rate of housing depreciation. Taking values of 5% for the interest and 1·5% for housing capital depreciation as in Davis and Heathcote (2005) yields $r^K = 0.065$. Land, unlike capital does not generally depreciate. Instead, according to Davis and Heathcote (2007), it appreciates by about 3% per year. That suggests a user cost of land $r^L = 0.05 - 0.03 = 0.02$. Inserting these numbers into equation (F.1) yields $\phi = 0.13$. We note that this value for the share of land in housing is consistent with an estimate of 0·106 from the U.S. Census Bureau reported by Davis and Heathcote (2007). Combining this estimate of 0·13 for the share of land in housing with 0·24 for the share of housing in expenditure yields a value $\hat{\beta} = 0.032$.

We are aware that taking a lower rate of depreciation of housing capital, a lower rates of appreciation for land, or a higher share of housing in expenditure would all lead to a higher value for β. In turn, the benefits from road investments turn out to be linear in β in a welfare analysis.

Next, we calculate ϕ by regressing the developed area in each MSA on MSA total driving. We measure total developed area in an MSA in 1992 using the same data on which the analysis of Overman, Puga and Turner (2008) is based. We measure total driving using three measures of total MSA driving used in Duranton and Turner (2011) and described in their Table D2: Mean Vehicle kilometre per person, Distance to work, and Total HPMS vehicle-kilometres travelled. The first two of these variables are based on the 1995 National Household Transportation Survey and measure total driving by recording changes in vehicle odometer reading over the course of a year or the distance driven to work on an typical day. The third measure of driving is based on the same source as we use to describe roads in this paper and measures the total driving on interstate highways within the MSA for 1993.

In the regression $\ln(\text{area}) = b + \phi \ln(\text{total driving}) + \varepsilon$, we estimate ϕ to be about 0·70 for each of our three measures of driving.

APPENDIX G: SUPPLEMENTAL WELFARE CALCULATIONS

We here derive equations (20) and (21). If x refers to a quantity under the status quo policy, then $\tilde{x}$ denotes the corresponding quantity under the alternative transportation policy.

Let $e(p, q, V)$ denote the expenditure function, the minimum expenditure to attain utility V given prices p and q. From the definition of equivalent variation, the monetary value of the utility change $V(\tilde{p}, \tilde{q}, \tilde{w}) - V(p, q, w)$ is $EV = e(p, q, \tilde{V}) - w$, where $\tilde{V}$ is a shorthand for $V(\tilde{p}, \tilde{q}, \tilde{w})$.

Recalling equation (1), we solve

$$\min C + pX + qL \tag{G.1}$$

$$\text{s.t. } U(C, X, L) = U_0 \tag{G.2}$$

to obtain the Hicksian demand functions for land, consumption, and travel:

$$X(p, q, U_0) = \frac{\alpha U_0 q^\beta}{A p^{1-\alpha}}, \quad C(p, q, U_0) = \frac{(1 - \alpha - \beta) U_0 q^\beta}{A p^{-\alpha}}, \quad L(p, q, U_0) = \frac{\beta U_0 q^{\beta - 1}}{A p^{-\alpha}}. \tag{G.3}$$

Using these Hicksian demand functions, it is straightforward to calculate that

$$e(p, q, U_0) = \frac{p^\alpha q^\beta}{A} U_0. \tag{G.4}$$

In turn, this gives us $EV = \frac{p^\alpha q^\beta}{A} \tilde{V} - w$. Substituting the indirect utility function (2) into this allows us to write the equivalent variation entirely in terms of the various prices

$$EV = \frac{p^\alpha q^\beta}{\tilde{p}^\alpha \tilde{q}^\beta} \tilde{w} - w. \tag{G.5}$$

Using the demand equation for X in equation (G.3) together with the inverse supply for travel equation (3) and the agglomeration equation (5), we can solve for the equilibrium value of p as a function of roads and employment

$$p = (\alpha \underline{w} N^{\sigma + 1} / R)^{\frac{\delta}{\delta + 1}}. \tag{G.6}$$

Similarly, using the demand equation for L in equation (G.3), together with the inverse supply for land equation (4) and the agglomeration equation (5) allows us to find the equilibrium value of q as a function of roads and employment

$$q = \left(\frac{\beta \underline{w}}{b}\right) (\alpha \underline{w})^{\frac{-\phi \delta}{\delta + 1}} R^{\frac{-\phi \delta}{\delta + 1}} N^{\sigma + \frac{-\phi(\sigma - \delta)}{\delta + 1}}. \tag{G.7}$$

Substituting the expressions (G.7) and (G.6) and the corresponding expressions for $\tilde{q}$ and $\tilde{p}$ into equation (G.5), we obtain equation (20) in the text.

To derive equation (21) note that the total land rent is simply price times quantity, $q \times L$. Using the demand equation for land, we know that at the equilibrium, each household's expenditure on land is βw. Using the agglomeration rule (equation (5)), we have that $qL = \beta \underline{w} N^\sigma$. Using this expression, we calculate equation (21) immediately.

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