ROADS, RAILROADS, AND DECENTRALIZATION OF CHINESE CITIES

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Abstract—We investigate how urban railroad and highway configurations have influenced urban form in Chinese cities since 1990. Each radial highway displaces 4% of central city population to surrounding regions, and ring roads displace about an additional 20%, with stronger effects in the richer coastal and central regions. Each radial railroad reduces central city industrial GDP by about 20%, with ring roads displacing an additional 50%. We provide evidence that radial highways decentralize service sector activity, radial railroads decentralize industrial activity, and ring roads decentralize both. Historical transportation infrastructure provides identifying variation in more recent measures of infrastructure.

I. Introduction

DEVELOPING countries spend huge sums on transportation infrastructure projects that shape their cities for decades to come. Currently, about 20% of World Bank lending goes for transportation infrastructure, more than the bank's lending for social programs. In a modern city, highway and rail investments are central to land use planning and policy, the development of feeder roads and street networks, and the spatial layout of utilities. Transportation infrastructure generates direct welfare benefits through reduced commuting and shipping costs, changes urban form, and affects urban environmental costs and the supply of land available for agricultural production.

In the early 1990s, China began to build and upgrade its transportation infrastructure, particularly its highways. From a low level in 1990, investment in transportation infrastructure grew at approximately 15% a year, much of it in cities. As central planning constraints on economic activity relaxed, Chinese cities transformed; central cities were torn down and rebuilt, Maoist-era residential and industrial buildings disappeared, and industries decentralized into previously agricultural areas. This happened during a period when economic growth averaged at least 10% a year, yielding a GDP per capita today of about $7,750 (Penn World Tables).

We investigate how the extent and configuration of Chinese highway and railroad networks contributed to the relative decentralization of population and industrial production from central cities to suburban and ex-urban areas during this period. Since decentralization can precipitate infrastructure investments, we rely on exogenous variation in transportation networks predating China's conversion to a modern market-based economy to estimate the causal effects of this infrastructure on urban decentralization.

We find strong evidence that radial highways and suburban ring roads reduce population density in central cities. Our estimates indicate that each additional radial highway displaced about 4% of central city population to suburban regions and that the existence of some ring road capacity in a city reduced city population by about 20%. However, radial railroads did not influence the allocation of population between central cities and suburban regions. In addition, conditional on the radial and ring configuration of the highway network, urban population decentralization is not influenced by total kilometers of either highways or railroads.

In their classic work, Meyer, Kain, and Wohl (1965) suggest that in mid-twentieth-century America, a "circumferential highway . . . provides an almost ideal site for the performance of truck-to-rail transfers. . . . Large parking lots for storing and moving containers for truck trailers, and rail sidings required to create piggyback or containerized trains are conveniently located there. Manufacturing and other businesses requiring transport inputs can be expected to locate reasonably close to these new transportation facilities" (p. 19). Consistent with this intuition, we find that marginal radial railroads displace about 20% of central city industrial GDP, while the existence of some ring road capacity displaces about 50% of central city industrial GDP. These components of the urban transport network generate similar estimated responses of the residential and work locations of manufacturing workers. However, we find no effect of radial highways on the location of industrial production. That railways play such an important role in the decentralization of production overall may be enhanced by China's unusually heavy historical reliance on railroads for long-haul and even short-haul freight (World Bank, 1982). In 1978, less than 5% of freight (in ton kilometers) in China was carried on roads. While this share increased over time, by 2005 it was still reportedly less than 15%, well below the United States, where just over 40% of freight moved by road in 2007.[1]

We view this displacement as primarily involving decentralization of a given amount of prefecture industrial activ-

Received for publication July 9, 2015. Revision accepted for publication July 11, 2016. Editor: Amitabh Chandra.

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We are grateful to International Growth Centre grant RA-2009-11-013 for generously funding this research. N.B.-S. and M.T. thank the Lincoln Institute of Land Policy for additional support. L.B. and M.T. are grateful to the Canadian Social Science and Humanities Research Council for funding. We also thank Magda Besiada, Rong Zhang Wang, Jie Ciao, Huaihong Su, Yujin Cao, Hyunjoo Yang, Xiaolu Li, Ying Chen, and particularly Zhi Li and Zhi Wang. We are also grateful to Byron Moldofsky, the University of Toronto Cartography lab, and the Neptis Foundation for their support and for their assistance with GIS data.

A supplemental appendix is available online at http://www.mitpressjournals.org/doi/suppl/10.1162/REST_a_00660.

[1] Since heavy, low-value goods travel long distances by rail, shares by value are higher for truck. In 2009, about 30% of ton-km is reported to travel by road, mostly reflecting a discontinuous jump from 2008 (China Statistical Abstract, table 16-9). The U.S. number is for truck ton-miles as a fraction of all ton-miles, to be comparable with Chinese data (*Statistical Abstract of the US*, 2012, table 1070).

The Review of Economics and Statistics, July 2017, 99(3): 435–448

doi:10.1162/REST_a_00660

ity to suburban areas, but it can also entail a change in the composition of prefecture economic activity. Trying to separate out and quantify how China's investment in transport infrastructure differentially affected prefecture economic composition would be the subject of a different paper, which becomes clear from the discussion of the literature and our data. Duranton, Morrow, and Turner (2014) show that overall, urban area industrial composition responds to infrastructure investments according to the weight-to-value ratios of products within sectors. With this caveat in mind, we explore briefly some of Meyer et al.'s (1965) ideas concerning differential responses of products to transport investments based on weight-to-value ratios.

Overall, the paper extends the initial work on population decentralization by Baum-Snow (2007a) to a developing country situation and introduces consideration of additional transport modes and decentralization of different types of economic activity. The paper addresses the distinct policy question of how infrastructure investments affect local urban form.[2] The developing country context is very different than Baum-Snow's United States analysis. While central cities in the United States experienced absolute declines in population after 1950, central cities in China saw large absolute and proportionate population gains after 1990 relative to their rural suburbs. Thus, rather than radial highways causing absolute decentralization, in China they retard the high rate of centralization.

Since Marshall (1890), economists have recognized that denser cities provide richer information environments, which in turn improve productivity and increase innovation (Jacobs, 1969; Lucas, 1988). However, central city environments have much higher land and somewhat higher labor costs than suburban and hinterland locations. As a result, in developed market economies, central cities typically specialize in business and financial services, which benefit sufficiently from richer information environments to justify these higher factor costs (Arzaghi & Henderson, 2008). Standardized manufacturing is typically found on the lower-cost urban periphery and in small cities and towns (Kolko, 2000; Schwartz, 1992). The situation in developing countries more resembles the United States in the early twentieth century when industry was concentrated in central cities, as in Chinese cities circa 1990. Manufacturing facilities in developing countries often start in central cities, perhaps in part because of localized externalities in learning and adaptation of technologies from abroad (Duranton, 2007). However, as transferred technologies mature, central cities become expensive locations for standardized manufacturing; in a version of the product cycle (Duranton & Puga, 2001), industrial firms decentralize to find lower land and labor costs. Meyer et al. (1965) describe this process in the United States from 1940 through the 1960s and Rothenberg (2013) for Indonesia in the 1990s.

Case studies suggest that migration of manufacturing to the urban periphery and beyond and the subsequent development of business and financial services in central cities all depend substantially on the ability of the transportation network to connect peripheral locations to the rest of the local economy (Lee, 1982; Hansen, 1987; Henderson & Kuncoro, 1996). This paper is the first to investigate how different highway and railroad network configurations contribute to this transformation with a research design identifying causal effects.

Our conclusions rely on achieving exogenous variation in the transportation variables of interest. We generate this variation by using the configurations of urban transportation infrastructure in 1962 as instruments for more recent transportation infrastructure. The validity of this identification strategy depends crucially on the fact that Chinese roads and railroads served different purposes in 1962 than they do today. In 1962, roads existed primarily to move agricultural goods to local markets, while railroads existed to ship raw materials and manufactures between larger cities and to provincial capitals according to the dictates of national and provincial annual and five-year plans. Thus, conditional on the control variables enumerated below, we expect 1962 road and railroad measures to affect the organization of population and production in modern market-based Chinese cities only through their effects on the modern transportation network.

II. The Context

Table 1 shows the growth of population and economic activity in core cities (central cities) and residual portions of prefectures. Results in the left block indicate that population grew much more quickly in central cities than in surrounding regions between 1990 and 2010. Aggregate population growth was 54% in central cities relative to only 5% in city hinterlands. This is urbanization—the flow of migrants from rural counties into central cities primarily within prefectures.

We use lights-at-night data to describe the decentralization of economic activity for the complete sample of cities. While lights at night may also reflect residential development, Henderson, Storeygard, and Weil (2012) show a strong relationship between growth in lights and GDP. The middle block of table 1 shows that lights grew more quickly in suburban areas, especially in the 1990–2000 period, despite the much faster population growth in central cities. In the sample for which data are available or could be imputed, the right block of table 1 presents industrial sector GDP growth. Suburban industrial GDP grew by 1,673% between 1990 and 2010 relative to 873% for central cities, indicating relative decentralization of industry. We focus on industry since decentralization patterns for total GDP are similar and the service sector is not measured consis-

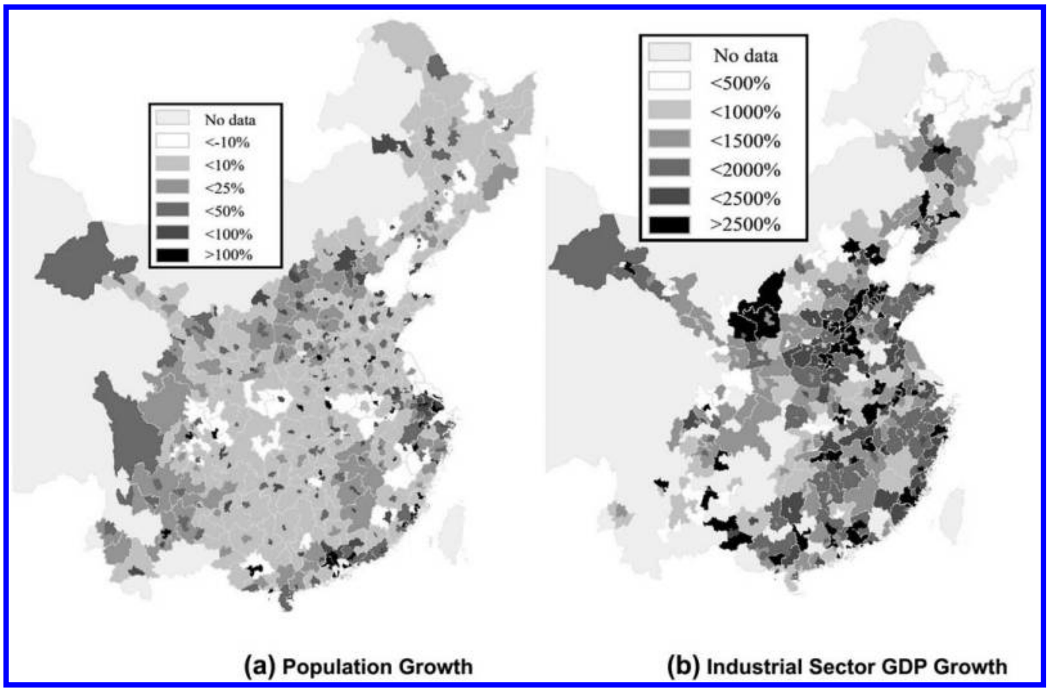
[2] Duranton and Turner (2011) find that driving within a city depends sensitively on the extent of the interstate highway network in the city, and slightly less sensitively on the extent of other road networks. Hsu and Zhang (2014) replicate this result for Japan.

TABLE 1.—GROWTH IN AGGREGATE POPULATION AND GDP BY LOCATION, 1990–2010

	Population Growth (257 Prefectures)		Lights Growth (257 Prefectures)		Real Industrial GDP Growth (189 Prefectures)	
	Central City	Prefecture Remainder	Central City	Prefecture Remainder	Central City	Prefecture Remainder
Mean in 1990	955,683	2,953,557			9.28	6.56
1990–2000	25%	4%	52%	94%	158%	343%
2000–2010	23%	1%	33%	36%	277%	300%
1990–2010	54%	5%	102%	165%	873%	1,673%

Our primary sample comprises 257 prefectures. Of the 189 prefectures in the final two columns, statistics for 93 prefecture remainders include imputed information for 1990. Industrial GDP (100 million RMB) is provincially deflated.

FIGURE 1.—GROWTH IN CENTRAL CITIES AND PREFECTURE REMAINDERS, 1990–2010



tently over time. Figure 1 gives the spatial variation in the 1990–2010 changes. Prefecture boundaries are shown, and central cities are visible when their growth differs. Figure 1a shows that almost all central city populations grew more rapidly than surrounding prefecture populations. Figure 1b shows that, unlike population, industrial GDP decentralized rapidly in most of the prefectures for which we can construct complete data.

The institutional context is critical to understanding these changes in spatial configurations. In 1990, the urban and rural sectors were under separate institutional and economic regimes. People held citizenship in either the urban or rural sector (as a birthright), and migration between the two sectors was rare and strictly controlled (Chan, 2001; Au & Henderson, 2006). Industry and land in the rural counties surrounding central cities were owned by local collectives. In cities, industry and land were owned by the state (Naughton, 2006). Chinese institutions at this time did not provide a formal mechanism for urban residents or firms to acquire the rural land rights to move out from the central city.

These institutional barriers to the mobility of labor and capital mean that roads and railroads in 1990 could not be used for commuting or influence factory relocation to potential suburbs, a point made by Zhou and Logan (2007). Except for a few special economic zones created before 1990, housing, factory, and farm location patterns within areas defined as urban were largely unchanged from the 1960s. Only after 1990, with the advent of land and labor market reforms, could urban form change in response to market forces. Given that urban reforms start in the early 1990s and that 1990 is a census year, it is a natural base period for our analysis.

This change in economic regime during our study period is critical for two reasons. First, slower reforms and heavier state presence in housing markets in western China provided fewer opportunities for spatial allocations to respond to infrastructure, offering a nice comparison with the rest of China. Second, even without extensive growth in railroads since 1990, we are able to infer effects of railroad allocations on urban form on the basis of the regime switch in land and labor markets. We will demonstrate that market reforms allowed population decentralization to occur only once highways were built. Existing pre-1990 roads had no effect on population decentralization before 1990. Therefore, the logic of the regime switch says that pre-1990 railroads could not have led to changes in the locations of production facilities before 1990 either.

Of course, the locations of railroads and highways are not randomized, and a key aspect of our estimation strategy must be to achieve pseudo-randomization. We return to this issue in section IV.

III. Data

Our analysis focuses on constant boundary 1990 core cities of prefectures (central cities), and the surrounding prefecture regions from which they draw migrants. We define these regions because their attributes can be consistently measured over time and because they correspond closely to theoretical analogs in land use models thet we summarized. Our most complete sample is the 257 prefectures with urban and rural areas located in primarily ethnic Han provinces drawn to 2005 boundaries, as illustrated in figure 1a. Figure A1 in the online appendix illustrates the spatial extent of 1990 core cities for the Beijing area and changes in their administrative boundaries during our study period.

We construct demographic data for the full sample using information from various population censuses. Incomplete GDP data in 1990 lead to a sample of 241 (out of 257) cities for which we observe industrial sector GDP in both 1990 and 2010. Prefecture-level information on GDP in 1990 is much more limited. We use the national economic censuses from 1995 and 2008 for industrial employment information by location and industry type. We identify central business districts (CBDs) as the brightest cell in 1992 lights-at-night data in each central city.

We digitize large-scale national maps to construct railroad and highway networks for various years. Using these digital maps, we calculate radial and ring highway and railroad capacity measures and various measures of network extent. Our radial index is built as follows. We draw rings of radius 5 km and 10 km around the CBD of each central city and count the number of times a particular transportation network crosses each of these two rings. Our index of radial roads is the smaller of these two counts of intersections. Figure A2a illustrates this algorithm, in which the green area is the Beijing central city, city centers are shown by dots, 2010 high-grade highways are represented by red lines, and the 5 km and 10 km rings around each center are in black. Figure A2a indicates that our radial road index value is 6 for the 2010 high-grade highway network in Beijing, exactly the calculation by eye.[3] Calculating the ring road index is more involved. We look for the existence of any ring road capacity at 5 to 9 km, 9 to 15 km, or 15 to 25 km from city centers outside central cities in any of the four 90-degree quadrants. Figure A2b illustrates the process for the northwest quadrant of Beijing and two nearby cities for the 5–9 km doughnut demarcated by the two black circles. For each city, we draw two rays from the center—one to the west and the other to the northwest. We identify all intersections of the two rays with the road network within the two rings. In the case of Beijing, there is one each. We then take the minimum of these two counts, which is still one. For the other two cities, the minimum is zero. We replicate this calculation for all quadrants for the three distance rings and sum to get an index. Because only 29% of prefectures had any ring road capacity in 2010, we use a simple indicator for the existence of any ring road capacity in all empirical work.

The data appendix provides data construction details. Table A1 shows summary statistics.

IV. Empirical Strategy

A. *Econometric Model*

To motivate our estimating equations, we review the basics of urban land use theory. Equilibria of land use models typically entail most people commuting toward the city center to work and the strongest agglomeration spillovers between firms in the center. Higher rents nearer the city center capitalize both commuting costs for residents and higher agglomeration economies for firms. Residents and firms thus consume less land nearer the city center, ceteris paribus, so population densities are higher there. Holding the spatial distribution of employment fixed, a reduction in transport costs reduces the relative value of locations nearer the city center for commuting purposes. For the same population, the city land rent and population density gradients typically shift down at the center and rotate in such a way that the city spreads out into the surrounding agricultural area as transport costs fall. This occurs in simple models, as well as those that allow consumer heterogeneity and other extensions.

Theoretical predictions on the impacts of transportation infrastructure on firm location are less clear. If firms locate near the periphery, they face lower land and labor costs because commuting is shorter for workers and land is cheaper. If firms locate in the center, they are more productive because of agglomeration economies but face higher costs. The equilibrium location pattern of firms that results from this trade-off is complicated and sensitive to model assumptions and parameter values (Fujita & Ogawa, 1982), with inconclusive comparative statics with respect to transport costs.[4] As such, we organize empirical work on the location of industrial production around the hypotheses suggested by Meyer et al. (1965) that ring roads facilitate

[3] We use all 2010 highway rays for estimation. In total, Beijing has eleven 2010 highway rays.

[4] In Fujita and Ogawa's (1982) model, high commuting costs imply no commuting and mixed land use, while low commuting costs imply a monocentric city. However, no clear prediction exists for intermediate commuting costs.

decentralization of manufacturing to peripheral locations with access to rail terminals and sidings.

Define y_{tC} and y_{tP} to be the population, employment, or output in year t and central city C and prefecture P. x denotes a vector of observed control variables, and r denotes transportation network measures. We use Δ_t to denote a first difference between 1990 and year t. A simple way to characterize the relationship between transportation infrastructure and decentralization is with a levels equation of the form

$$\ln y_{tC} = A_0 + A_1 r_t + A_2 \ln y_{tP} + B_0 x + \delta + \varepsilon_t. \tag{1}$$

Equation (1) follows directly from versions of the models described above, though a careful accounting for the endogeneity of $\ln y_{tP}$ will be important in the empirical work. Error term components δ and ε_t represent unobserved constant and time-varying prefecture-specific variables that influence the outcome. The coefficient of interest, A_1, indicates the portion of central city population, employment, or output displaced to prefecture remainders for each additional unit of transportation infrastructure. Consistent with theoretical predictions described above, we expect $A_1 < 0$ for population but have no strong prior for other outcomes. The following related specification describes the central city share of y as a function of infrastructure:

$$\ln y_{tC} - \ln y_{tP} = A'_0 + A'_1 r_t + B'_0 x + \delta' + \varepsilon'_t. \tag{2}$$

In equation (2), A'_1 captures effects of infrastructure on combined prefecture and central city outcomes, whereas A_1 in equation (1) captures the effect of infrastructure on the allocation of the outcomes between central cities and prefecture remainders, holding the prefecture outcome constant in equation (1). Although we are primarily interested in estimating A_1, we also present estimates of A'_1.

For a different perspective, we note that equation (2) can be decomposed into

$$\ln y_{tC} = A'_{a0} + A'_{a1} r_t + B'_{a0} x + \delta'_a + \varepsilon'_{at} \text{ and} \tag{2a}$$

$$\ln y_{tP} = A'_{b0} + A'_{b1} r_t + B'_{b0} x + \delta'_b + \varepsilon'_{bt}. \tag{2b}$$

Since y_{tP} is the sum of central city and prefecture remainder outcomes, A'_{a1} captures some combination of the direct effect of infrastructure on the central city outcome and the indirect effect that operates through the influence of infrastructure on the prefecture outcome. For example, roads may cause central city population to fall through displacement to the prefecture remainder and to rise because they draw in new population to the overall prefecture. Therefore, isolating the decentralization effects of infrastructure requires estimation of equation (1) rather than equation (2) or (2a). In practice, estimates of A'_{b1} are near 0. As a result, estimates of A_1, A'_1, and A'_{a1} coincide for all outcomes and transport measures considered.

A complete characterization of the effects of infrastructure on locations of industrial output and employment in particular sectors requires at least four equations, one each for output or employment in each sector in the central city and the prefecture (or its remainder). One logical step is to express the effect of infrastructure on the sectoral allocation between central cities and prefecture remainders using $\ln y_{ktC} = A_0 + A_1 r_t + A_2 \ln y_{ktP} + B_0 x + \delta + \varepsilon_t$, in which y_{ktA} is employment or output in sector k at time t in region A. However, that formulation needs to account for the endogenous reallocation of prefecture activity across sectors, as in Duranton et al. (2014). In principle, one can simultaneously characterize such reallocation and decentralization effects by estimating versions of equations (2a) and (2b) for each sector. However, the absence of prefecture-level data on output by sector leads us to estimate reduced-form relationships between infrastructure and central city sector-specific outcomes instead, as in

$$\ln y_{ktC} = A_{0k} + A_{1k} r_t + A_{2k} \ln y_{tP} + B_{0k} x + \delta_k + \varepsilon_{kt}. \tag{1'}$$

Here, A_{1k} compounds the effects of infrastructure on decentralization of sector k with sectoral reallocation. Limited information about prefecture GDP leads us to measure y_{tP} as prefecture population or employment at time t, even if the outcome is central city industrial GDP.[5]

In addition to the probable endogeneity of y_{tP} noted above, there are two other challenges in using equations (1) and (1′) directly for estimation. First, a necessary condition for an estimate of A_1 to be a causal effect of infrastructure is that our infrastructure variables be conditionally uncorrelated with the two error terms. We are concerned that historically productive central cities have been allocated more modern highways, so that a coefficient on highways would partly reflect this unobserved attractiveness rather than a causal effect. Second, while coefficients should describe approximate land use equilibria in Chinese cities in 2010, the 1990 planning process is probably better described by a larger set of variables, with the overlapping variables having different coefficients.

As a response to these issues, we specify levels equations for 1990 with different coefficients and first differences to examine growth in $\ln y_{tC}$ to later years. For 1990, the equation is

$$\begin{aligned}\ln y_{1990C} = {} & (A_0 + \Delta A_0) + (A_1 + \Delta A_1) r_{1990} \\ & + (A_2 + \Delta A_2) \ln y_{1990P} \\ & + (B_0 + \Delta B_0) x + \delta + \varepsilon_{1990}.\end{aligned} \tag{3}$$

Subtracting equation (3) from equation (1) yields

$$\begin{aligned}\Delta_t \ln y_C = {} & -\Delta A_0 + A_1 \Delta_t r - \Delta A_1 r_{1990} + A_2 \Delta_t y_P \\ & - \Delta A_2 \ln y_{1990P} - \Delta B_0 x + \Delta_t \varepsilon.\end{aligned} \tag{4}$$

First differencing removes time-invariant unobservables that may be correlated with r and drive decentralization,

[5] Baum-Snow (2014) estimates a similar system of equations for U.S. cities 1960 to 2000.

thereby strengthening identification. We follow an identical procedure for equation ($1'$) when estimating the effects of infrastructure on industrial output.

There are practical difficulties in recovering the coefficients in equation (4) using our data. First, while our 1990 and 2010 highway measures are nominally the same, there is little resemblance between a highway in 2010 and a national road visible on our 1990 map. The 1990 highways near major cities were almost universally one- or two-lane roads and were often unpaved. Treating the 1990 highway stock as 0 allows us to more accurately measure the change in highways over our study period. We evaluate the validity of the 0 initial stock assumption below.

As with highways, we include only the level of railroads at time t to recover their causal effects. That is, we assume that 1990 railroads have no effect on outcomes; more formally, $A_1 + \Delta A_1 = 0$. The limited freedom of central city firms to decentralize to suburban regions in 1990, evidence for which we show below, justifies this assumption. Once economic reforms were in place, cities began to adjust to market equilibria with production decentralization. Our analysis of rails examines the extent to which the level of rail infrastructure shaped changes that became possible only after 1990. Since most intracity rails in 2010 were built by 1990, we recover similar estimates whether we use 1990 or year t railroads as our infrastructure measure.[6] Because of the unique context, we see our analysis of the effects of highway construction between 1990 and later years on changes in urban form as comparable to our investigation of the effects of railroad levels in later years. Our primary estimation equation thus becomes

$$\begin{aligned}\Delta_t \ln y_C = & -\Delta A_0 + A_1 r_t + A_2 \Delta_t \ln y_P \\ & - \Delta A_2 \ln y_{1990P} - \Delta B_0 x + \Delta_t \varepsilon. \end{aligned} \quad (5)$$

There are potentially serious estimation concerns that $r_t, \Delta_t \ln y_P$, and $\ln y_{1990P}$ in equation (5) are correlated with the error term. We address each one in turn.

We rely on instrumental variables to address potential endogeneity of r_t. Conditional on appropriate controls, we require instruments that predict endogenous variables but are otherwise uncorrelated with the error term in our structural equation. Similar to Baum-Snow (2007a), Duranton and Turner (2011, 2012), Garcia-López, Holl, and Viladecans-Marsal (2015), and Hsu and Zhang (2014), we use information about networks in 1962 as instruments for r_t. We consider the validity of this class of instruments in section IVB.

We use migration shocks to handle the potential endogeneity of $\Delta_t \ln y_P$, following Bartik (1991) and Card (2001), where historical migration pathways help predict recent migration. The instrument is the interaction of the fraction of out-migrants from each province going to each prefecture between 1985 and 1990 with the total number of out-migrants from each province between 1995 and 2000. While not ideal because mechanically it can only predict 1995–2000 growth, it is all we can do with available data. Fortunately, it is a significant predictor of 1990–2010 prefecture population growth.[7] The identification assumption is that 1985–1990 internal migration flows are uncorrelated with unobservables (like productivity shocks) driving changes in central city population between 1990 and 2010. Because the instrument is based on data from the premarket reform period, this assumption seems plausible. Controlling properly for population growth in estimation allows us to interpret infrastructure coefficients as only capturing decentralization.

We pursue two additional strategies to avoid relying exclusively on the Card instrument. First, we calculate bounds on estimates of A_1; second, we estimate a differenced version of the shares, equation (2), which excludes prefecture population as an explanatory variable. While those estimates combine effects of transport investment on decentralization and prefecture growth, the latter turns out to be 0.

A remaining issue is the potential endogeneity of $\ln y_{1990P}$ in equation (5), which may arise from the mechanical correlation between the outcome and $\ln y_{1990P}$. We handle this by controlling for $\ln y_{1982P}$ instead. In the x controls, we use 1982 rather than 1990 variables to reduce the possibility that they are correlated with later shocks to $\Delta_t \ln y_C$.

In sum, our main regression specification has three components. First, we include and instrument for the potentially endogenous transportation infrastructure measures at time t. Second, we include and instrument for prefecture population growth. Third, we include controls that are potentially correlated with instruments and outcomes. These are historical levels of prefecture population, central city, and prefecture land areas, an indicator of whether the city is one of four provincial-level cities or 26 provincial capitals, historical educational attainment levels, and historical specialization in manufacturing. We emphasize that for IV regressions to return consistent estimates of A_1, we need only control for variables that are correlated with instruments and influence outcomes of interest.

Effects of infrastructure on decentralization likely vary with city characteristics such as land use planning policy, housing supply elasticity, the availability of alternatives to auto travel, and local *hukou* policies governing migration. Unfortunately, we have limited information on these specific items. We explore whether a slower pace of reform affects results by excluding cities in the west, where the state maintains a stronger role and the size of the state sector is larger. The fact that historical infrastructure is a strong predictor of modern infrastructure for various subsets of the sample, as

[6] Nationally, network length increased by about 20% between 1990 and 2010, with some additional double-tracking of 1990 railroad lines. We cannot use the change in railroads as a predictor because we do not have strong instruments for it, nor do we consider it to be the relevant measure given our discussion in section II.

[7] We do not have information on migrant origins or migration flows for any other time periods. Industry shift-share type instruments for prefecture population growth, as in Bartik (1991), are insufficiently strong.

established below, suggests that the treatment effects we estimate represent averages over a broad set of prefectures.

B. Instrument Validity and First Stages

To be valid instruments, 1962 transport network components must only predict recent central city growth through their influences on the location and configuration of the modern transportation network, conditional on control variables. In addition, they cannot be correlated with unobserved variables that influence highways and the post-1990 evolution of central city economies.

Selecting the set of appropriate control variables requires understanding the processes by which the 1962 transportation networks were established. Sino-Soviet planning featured nationalization of the housing stock in the 1950s and minimization of commuting by placing residents near workplaces. The strict institutional separation of the urban and rural sectors made suburbanization impossible. With little commuting, the 1962 road network outside central cities served primarily to connect rural counties to the rest of the nation. Lyons (1985, p. 312) states, "At least through the 1960s most roads in China (except perhaps those of military importance) were simple dirt roads built at the direction of county and commune authorities. . . . Most such roads were not fit for motor traffic and half of the entire network was impassable on rainy days." Lyons also notes that average truck speeds were below 30 km/hr due to poor road quality. All long-haul and most short-haul movement of goods was by rail. A major effort in the early 1960s aimed to facilitate transport within prefectures to and from villages. The *People's Daily* (June 11, 1963) stated, "The present effort at building roads aims at opening up commercial routes to the villages to facilitate the transport of locally-produced goods as part of the policy of priority given to agriculture. Better roads are being built by provincial governments, but most of them are being built at local initiative. They are rarely fit for motor traffic; on the better roads horses and ox-carts may travel; on others hand-carts . . . can be pushed or pulled by man" (Lippit, 1966 p. 115). Despite the low quality of vintage roads, the established rights of way provide a solid first stage.

The highway system built after 1990 is designed to serve a modern economy in cities where places of work and residence are separated and commutes are common. Since the strength of local agricultural ties between central cities and surrounding regions in 1962 could influence outcomes today as well, it is in principle important to control for either relative agricultural activity or its effective converse, relative industrial activity, in prefectures prior to 1990. Since 1982 is the earliest year with county-level census data, we include the share of prefecture employment in manufacturing in 1982 as a control. As shown in table A2, this control is significantly negatively correlated with 1962 radial roads. The 1982 controls for prefecture population and education are also important because they may directly predict subsequent changes in population and GDP allocation between cities and prefecture remainders. The 1982 population is positively related to 1962 roads, while 1982 fraction high school is negatively related to 1962 roads. We also control for log prefecture and central city areas and a provincial capital indicator throughout. Prefectures that were larger in area and provincial capitals had more 1962 road rays, all else equal. Overall, our baseline controls explain 14% of the variation in 1962 radial roads (table A2).

More than two-thirds of Chinese railroads were built before the People's Republic was established in 1949. Major trunk lines constructed in the early twentieth century ran north-south and helped to link key political and commercial centers. Russian and Japanese investment financed a major expansion in Manchuria (northeast China) to facilitate extraction of agricultural goods and raw materials, and later helped to link emerging industrial centers (e.g., Shenyang and Changchun) with China proper. Between 1949 and 1962, much of the railroad investment was under Soviet influence and served to connect resource-rich regions of the west with manufacturing centers in the east. After 1964, the Third Front policy moved military and other strategic production westward, adding five strategic railroad lines. Because there was little trade between provinces (Lardy, 1978), provincial capitals were important trade nodes and therefore received main rail lines. Given the variety of actors and motives behind the construction of the pre-1962 network, it is plausible that much of the rail network was constructed without regard to its impact on the post-1990 internal reorganization of cities conditional on our base controls. As seen in table A2, significantly more 1962 railroads existed in more populous (but not larger) and more highly educated prefectures, with a large, positive relationship with provincial capitals and fraction working in manufacturing as well. Overall, our control variables explain 24% of the variation in 1962 radial railroads.

Columns 1 to 4 of table 2 show representative first stage results for the three 2010 transportation network measures we emphasize and one for 1999, which we use in our consideration of dynamics. Instruments are individually strong conditional on the common controls used throughout, and each modern transport measure is predicted by its 1962 counterpart. Each 1962 road ray predicts about 0.35 of both 1999 and 2010 highway rays conditional on base controls and other instruments. Because the coefficient on 1962 radial roads is statistically identical in these two regressions, this instrument does not predict changes in roads between 1999 and 2010, noting that these road measures are not directly comparable. These facts mean that we cannot empirically isolate effects of radial highways built between 1999 and 2010. Each 1962 railroad ray predicts 0.37 railroad rays in 2010, and the existence of any 1962 ring road capacity increases the probability of such capacity in 2010 by 0.52.[8] For completeness, column 5 of table 2

[8] As seen in table A2, our base controls only explain 3% of the variation in the ring road indicator; as such, we are not as confident in our understanding of the data-generating process for ring roads.

TABLE 2.—FIRST-STAGE REGRESSIONS

	2010 Radial Highways	1999 Radial Highways	2010 Radial Railroads	2010 Ring Indicator	Δln(PrefPop) (1990–2010)
1962 radial roads	0.361***	0.350***	0.0211	−0.0234	−0.00462
	(0.0860)	(0.0801)	(0.0345)	(0.0228)	(0.00594)
1962 radial railroads	0.177	0.166*	0.373***	0.00517	0.00453
	(0.107)	(0.0924)	(0.0528)	(0.0326)	(0.00851)
1962 ring road indicator	−0.617	−1.082***	−0.232	0.522***	−0.0237
	(0.427)	(0.302)	(0.305)	(0.146)	(0.0322)
Card migration instrument	2.08e-06*	2.05e-06***	−1.01e-06	−2.36e-07	7.61e-07**
	(1.10e-06)	(6.92e-07)	(7.09e-07)	(1.40e-07)	(3.02e-07)
ln(central city area)	0.125	−0.0527	−0.0135	−0.181***	−0.0265**
ln(prefecture area)	0.0419	0.239	−0.0551	0.0294	−0.0431
Provincial capital indicator	1.369**	1.239**	0.198	0.0910	0.162***
ln(pref. pop., 1982)	0.703***	0.302*	0.435***	0.0747	−0.0818***
Fraction high school or more in prefecture 1982	4.523	1.846	4.586**	−0.203	−0.188
Fraction high school or more in prefecture 1982	−4.416**	−1.513	−1.403**	0.360	0.0833
Constant	−9.114***	−4.596**	−4.783**	0.196	1.890***
R^2	0.330	0.340	0.252	0.242	0.500

The text explains the use of 1985–1990 migration pathways to construct the migration instrument. SE in parentheses are clustered by province. Some SEs are omitted to conform to journal formating requirements. There are 257 observations. $***p < 0.01$, $**p < 0.05$, $*p < 0.10$.

TABLE 3.—OLS RELATIONSHIPS BETWEEN TRANSPORT INFRASTRUCTURE AND POPULATION OUTCOMES

	Δ ln(CC Pop) 1990–2010					
	(1)	(2)	(3)	(4)	(5)	(6)
2010 radial highways	0.0097	−0.0114**	−0.0118**	−0.0123**		−0.0108*
	(0.0088)	(0.0050)	(0.0050)	(0.0048)		(0.0055)
ln(highway km in prefecture remainder, 2010)			0.0221			
			(0.0276)			
2010 radial railroads				0.0105		
				(0.0100)		
2010 ring road indicator					0.0320	0.0273
					(0.0322)	(0.0323)
Δ ln(Pref Pop) 1990–2010		0.9212***	0.9113***	0.9221***	0.9075***	0.9230***
		(0.0641)	(0.0691)	(0.0650)	(0.0655)	(0.0630)
Base controls	No	Yes	Yes	Yes	Yes	Yes
R^2	0.004	0.490	0.491	0.492	0.488	0.492

Each column shows coefficients from a separate OLS regression of the variable listed at the top on transport infrastructure types listed at the left and, if indicated included, ln(central city area), ln(prefecture area), a provincial capital indicator, ln(prefecture population, 1982), fraction high school or more in prefecture, 1982 and share employed in manufacturing in prefecture, 1982. Standard errors in parentheses are clustered by province. Each regression has 257 observations. $***p < 0.01$, $**p < 0.05$, $*p < 0.10$.

presents a representative first-stage regression for prefecture population growth, for which we instrument in all base results.[9]

V. Results for Population Decentralization

A. Baseline

Table 3 reports baseline OLS estimates of empirical relationships between urban transport infrastructure and 1990–2010 central city population decentralization. We limit attention to two network measures at a time because of the inability to instrument with any power for more. OLS coefficients on radial highways are small, as are coefficients on other transport network attributes. For radial highways and ring roads, the small or insignificant effects reflect a classic identification problem. While we expect rays and ring roads to lead to slower central city growth, such investments may be allocated to faster-growing central cities.

Table 4 reports IV estimates of equation (5) with the same format as table 3. Column 1 has no controls and an estimated 0 coefficient on radial highways. Column 2 adds the base controls and reports a coefficient of −0.042 on radial highways, significant at the 6% level. The control variable that influences the radial highways' coefficient the most is log of 1982 prefecture population. More populous prefectures had more roads in 1962 and experienced more rapid central city population growth, reflecting that growth was fueled by within-prefecture migration. Absent the control for 1982 prefecture population, the coefficient on highway rays reflects both the negative causal effect of this infrastructure and the positive effects of the omitted vari-

[9] Relevant 1962 transport network coefficients are statistically significant at the 5% level with the correct sign for eight of the twelve 1990 central city population tercile/transport network measure pairs. Similarly, such measures work for six of the eight East versus center/west region by transport measure pairs. The 1962 highway rays coefficients are insignificant at the 5% level for medium-sized and eastern cities when 2010 rays are the outcome, and small cities when 1999 rays are the outcome (with marginal insignificance for eastern cities). The 1962 railroad rays coefficient for medium-sized cities is insignificant when 2010 railroad rays are the outcome. The 1962 ring capacity indicator is insignificant for large cities and noneastern cities when 2010 ring capacity is the outcome.

TABLE 4.—IV ESTIMATES OF EFFECTS OF TRANSPORT INFRASTRUCTURE ON POPULATION OUTCOMES

	Δ ln(CC Pop) 1990–2010					
	(1)	(2)	(3)	(4)	(5)	(6)
2010 radial highways	−0.0067	−0.0423*	−0.0448**	−0.0412*		−0.0587**
	(0.0186)	(0.0223)	(0.0228)	(0.0246)		(0.0259)
ln(highway km in prefecture remainder, 2010)			0.0885			
			(0.0797)			
2010 radial railroads				−0.0105		
				(0.0485)		
2010 ring road indicator					−0.1873**	−0.2520**
					(0.0916)	(0.1111)
Δ ln(Pref Pop) 1990–2010		0.8124***	0.7555***	0.7975***	0.6228***	0.7752***
		(0.1389)	(0.1801)	(0.1657)	(0.1479)	(0.1733)
ln(central city area)		−0.1178***	−0.0966***	−0.1188***	−0.1620***	−0.1662***
ln(prefecture area)		0.0508***	−0.0335	0.0495**	0.0388	0.0566**
Provincial capital indicator		0.1751**	0.1864**	0.1798**	0.1393**	0.2233***
ln(prefecture population, 1982)		0.1101***	0.0784	0.1140***	0.0699**	0.1387***
Fraction high school or more in prefecture, 1982		−0.3790	−0.4185	−0.3062	−0.4779	−0.2465
Fraction employed in manufacturing in prefecture, 1982		−0.2845	−0.2652	−0.2881	−0.0415	−0.2884
Constant	0.4349***	−0.7535	−0.1754	−0.7846	0.1749	−0.7697
First-stage F	36.2	13.1	8.81	7.02	7.13	4.05

First-stage results are in table 2. Each regression has 257 observations. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

able. Adding controls for other transport infrastructure generally sharpens this coefficient and allows us to investigate the heterogeneity of effects. Additions of total kilometers of highways in the prefecture remainder (column 3) or the entire prefecture (unreported) yield coefficients of 0 on these variables. Column 4 adds the count of radial railroads, which also has no effect on central city population. Nor does a control for total kilometers of railroads (unreported).

Columns 5 and 6 of table 4 introduce ring roads and contains key results. Understanding the effects of ring roads on urban form is important for policymakers. While China is one of the few contexts for which exogenous variation in ring road capacity across cities is available, there are some limitations. In particular, few roads in 1962 looked like ring roads. Even in 2010 only 29% of cities in our sample have some ring road capacity. In these cities, these roads serve an average of only about 38% of the circumference of the city. In 1962 only 5% of our cities register any ring road capacity with a maximum of 25% circumference covered. Therefore, these IV results must be viewed with some caution, although the point estimates are large.

Conditional on highway rays, ring road capacity reduces central city populations by about 25%, although the joint F on the first stage (4.1) is low. Because of low power in the first stage, we cannot identify an additional separate interaction effect between rays and rings. We also note that ring roads and rays may be substitutes in designing urban transport networks, which may be why controlling for ring roads enhances and sharpens the highway ray effect in column 6 relative to column 2, raising the coefficient in magnitude from −0.042 to −0.059.

Coefficients on nontransportation-related covariates are also of interest. In column 2, a 1% increase in prefecture 1990–2010 population growth leads to a 0.81% increase in 1990–2010 central city growth holding 1982 prefecture population constant. A persistent 1% increase in 1982 prefecture population, however, is associated with just a 0.11% increase in 1990–2010 central city population growth. The growth elasticity is higher than related estimates in Baum-Snow (2007a) for U.S. metro areas, reflecting the rapid urbanization of China in the study period. Conditional on other controls, more spacious central cities grew more slowly. Population in provincial capitals grew more quickly, which may reflect political influence. The 1982 controls for prefecture education and manufacturing share are insignificant. Coefficients on control variables are similar for OLS results in table 3 (unreported).

Consistent with evidence in Baum-Snow (2007a) and Duranton and Turner (2012) for the United States, differences between OLS and IV highway ray and ring road coefficients suggest that our highway indices are endogenous. While more highways were built in central cities with more rapidly growing populations relative to their surrounding prefectures, these roads were themselves causing population to decentralize. The decentralization that occurred because of this infrastructure is more than offset by the growth that precipitated construction of this infrastructure. As a result, the use of pseudo-random variation from the 1962 network is essential to estimating the true causal effects of these transportation improvements.

We do not have detailed information on individual cities' institutions governing land markets, supply constraints, and market reforms. However, we do know that in general, cities in the West have been slower to introduce reforms. They are also poorer, with lower automobile use. Table A3 repeats table 4 but excluding cities in the West. The radial highway effects in columns 2 to 6 increase to at least −0.059 and the ring road effects in columns 5 and 6 to at least −0.213. The effect of highway infrastructure investments on central city population growth is somewhat stronger in coastal and center region cities than in the west, where reform is slower.

B. Robustness

The validity of the "no initial highways" assumption employed so far rests on the assumptions that 1990 roads were not highways and that prereform urban China did not permit market responses to cross-city differences in transportation networks. Table A4, panel A, columns 1 and 4 (column 4 drops the West), include 1990 road rays as an additional (uninstrumented) control. This approximates the exact first-difference specification in equation (4) and also addresses the possibility that some 1990 roads may persist and affect decentralization. The technical problem with adding the 1990 control is that 1962 and 1990 rays are strongly correlated, so that the first-stage F-statistic is low. Noting that, the coefficient on 1990 roads is an insignificant 0.05, while that on 2010 roads increases to −0.081. These results suggest that 1990 road rays do not contribute to decentralization, while 2010 highway rays do. This supports estimation of equation (5) rather than equation (4).[10]

An alternative way to test the validity of the no-initial-highways assumption is to show that cities did not decentralize in response to old roads during the prereform period. To address this hypothesis, table A5 reports the impact of 1980 road rays and the highly correlated 1990 rays on decentralization during the 1982–1990 pre–urban reform period.[11] These estimates are analogous to those in table 4, column 2, but for the 1982–1990 period. Estimated effects of 1980 or 1990 road rays on 1982–1990 decentralization in columns 1 and 2, respectively, are indistinguishable from 0, evidence that roads started to cause decentralization only after the urban market reforms of the early 1990s. We already know rails are not related to population decentralization. Therefore, in columns 3 to 6 of table A5, we show that, ceteris paribus, 1980 and 1990 transport infrastructure had no effects on 1990 levels of central city population or industrial GDP. However, in the last column, they have a strong impact on central city 2010 industrial GDP. In summary, infrastructure effects on urban form are a post-1990 phenomenon.

In columns 2 and 5 of panel A in table A4, we add controls for 1982 central city population, the fraction with a high school diploma, and the fraction employed in manufacturing. We refrain from using such controls in our prime specifications because of concerns with introducing variables that are serially correlated with 1990 central city population. Offsetting this is the desire to control for variables that could affect subsequent central city growth and be correlated with our instruments. In column 2, the radial highways coefficient is 15% smaller than in table 4, column 2 but in column 5, where we drop western prefectures, the coefficient is only 7% smaller than in table A3, column 2. Given that added controls increase the length of the variable list and can be thought of as objectionable, we conclude that the results are robust with respect to them.

Finally, one might worry that larger cities drive our results, under the notion that small cities lack measured suburbs to which people can decentralize. This is mostly a measurement issue, as land use models do not suggest that differential effects should exist per se. Columns 3 and 6 of table A4, panel A, exclude cities in the top 5% of prefecture population in 1990. Both coefficients are modestly enhanced, suggesting that results are not driven by the largest cities.

In table A4, panel B presents estimates of coefficients in differenced versions of equations (2a), (2b), and (2) for the full sample (columns 1–3) and excluding the west (columns 4–6). Column 3 relates transport infrastructure to central city population shares, confounding decentralization with overall prefecture growth effects. Equations (2a) and (2b) separate out effects of infrastructure on central city and prefecture populations, although the former does not identify the coefficient of interest in equation (1) because equation (2a) does not hold prefecture population constant.

The key result in panel B of table A4 is in column 2, which shows no prefecture growth effects of radial highways. This means that the coefficients on radial rays in columns 1 and 3 fully reflect decentralization effects, because prefecture population growth is not correlated with the instrument. Consistent with this logic, radial highways coefficients of −0.048 and −0.041 in panel B, columns 1 and 3, are very close to our headline estimate of −0.042 in table 4, column 2. Dropping the west, coefficients of −0.066 and −0.059 in columns 4 and 6 are very close to −0.060 in table A3, column 2.

We also estimate bounds on our coefficient of interest as an alternative to instrumenting for prefecture population growth. It is straightforward to show that the true value of A_1 is bounded by the estimate arising from estimating equation (5) when $\Delta_t \ln y_P$ is included and when it is not.[12] Using the specification in table 4 column 2, when $\Delta_t \ln y_P$ is included (uninstrumented), the coefficient on highway rays is −0.041, and when it is excluded, the coefficient is −0.048 (table A4, panel B, column 1). These bounds are tight, bookending our headline estimate of −0.042.

[10] An alternative to controlling for 1990 roads is to estimate the effect of the 1990–2010 difference in measured roads despite the differing qualities in the two years. The first stage for this regression is very weak, but it also yields a roads coefficient that is much larger in absolute value than our primary estimate in table 4, column 2.

[11] Since 1980 and 1990 roads are more comparable than are 1990 and 2010 highways, the case for using levels is driven entirely by statistical considerations. Our instrument predicts 1980 and 1990 roads but not their difference.

[12] The logic of this bounding argument is seen in the following simple example. Suppose the structural equation for central city population is $\Delta_t \ln y_C = \alpha_0 + \alpha_1 r_t + \alpha_2 \Delta_t \ln y_P + u$, where r_t is instrumented with r^{62}, which is uncorrelated with u. The IV estimate of α_1 excluding $\Delta_t \ln y_P$ from the regression equals $\alpha_1 + \alpha_2 \mathrm{Cov}(r^{62}, \Delta_t \ln y_P)/\mathrm{Cov}(r_t, r^{62})$. This expression reflects the possibility that infrastructure promotes prefecture population growth, which includes some central city population growth as well. The IV estimate of α_1, including $\Delta_t \ln y_P$ in the regression, equals $\alpha_1 - \mathrm{Cov}(r^{62}, \Delta_t \ln y_P)\mathrm{Cov}(\Delta_t \ln y_P, u)/D$, $D > 0$, where mechanically $\mathrm{Cov}(\Delta_t \ln y_P, u) > 0$. Therefore, regardless of the sign of $\mathrm{Cov}(r^{62}, \Delta_t \ln y_P)$, these are bounds on the true value of α_1.

Table 5.—Time Pattern of Responses to Highway Treatments

	Δ ln(CC Pop)			
	1990–2010		1990–2000	2000–2010
	(1)	(2)	(3)	(4)
Radial highways in year t	−0.0420*	−0.0436**	−0.0229	−0.0181*
	(0.0216)	(0.0191)	(0.0167)	(0.0107)
Year t	2005	1999	1999	1999
First-stage F	13.8	12.8	9.14	25.7

Entries show coefficients from IV regressions of the central city population growth rate during the indicated period on radial highways measured as of the indicated year using analogous specifications to that in column 2 of table 4. Δln(Pref Pop) matches the timing of Δln(CC Pop). All regressions except those in column 4 instrument for Δln(Pref Pop). It is included as an uninstrumneted control in column 4. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

Table 6.—Effects of Transport on Industrial Sector GDP, 1990–2010

	Δln(Central City Industrial GDP) 1990–2010							
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2010 radial highways	0.0277		0.0514			−0.0103		
	(0.0528)		(0.0635)			(0.0709)		
2010 radial railroads		−0.239**	−0.267**	−0.187**			−0.236**	−0.338***
		(0.0971)	(0.1177)	(0.0941)			(0.1130)	(0.0738)
ln(railroad km in prefecture remainder, 2010)				−0.1174				
				(0.1101)				
2010 ring road indicator					−0.562**	−0.574*	−0.710**	
					(0.2787)	(0.3220)	(0.3351)	
Δ ln(Pref Pop) 1990–2010	−0.7585*	−0.9617	−1.1525	−0.9942	−0.8840*	−0.8570*	−1.2235	
	(0.4606)	(0.6491)	(0.7139)	(0.6198)	(0.5331)	(0.4837)	(0.7736)	
First-stage F	10.9	24.3	5.69	5.63	6.67	4.24	3.90	79.2

The 1962 network measures instrument for these measures in 2010. Predicted migration flows instrument for Δln(Pref Pop) 1990–2010. The control variables in columns 1–7 is the same as in table 4. Column 8 has no control variables. There are 241 observations. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

C. *Dynamics*

Our data also allow for a limited investigation of the rate at which decentralization occurs in response to changes in the road network. The first two columns of table 5 report estimates of the effects on 1990–2010 population decentralization of radial roads in place by 2005 and 1999, respectively. Coefficients on the two highway measures are similar to those in table 4, noting from section 4.2 that 1962 radial roads predict 1999 radial highways but not post-1999 radial highway growth. Importantly, this suggests a refinement in interpretation. Since our first stage predicts radial roads built by 1999, regardless of the nominal year of the endogenous radial road variable, our second-stage results must also describe the effect of radial roads built by 1999, also regardless of the nominal year of the endogenous radial road variable.

Column 3 of table 5 shows the effect of radial roads in place by 1999 on 1990–2000 decentralization, while column 4 shows their effect on 2000–2010 decentralization. Other details of the regressions are analogous to our preferred specification in column 2 of table 4, except for column 4, where we are not able to instrument for prefecture population growth. Estimated decentralization responses are −0.023 and −0.018 over the 1990–2000 and 2000–2010 periods, respectively, adding up to the full 1990–2010 decentralization response reported in column 2. This suggests that about half of the total 1990–2010 decentralization caused by radial highways built between 1990 and 1999 occurred by 1999 and half occurred between 2000 and 2010.[13] Results that drop cities in the west show roughly the same pattern, though with somewhat stronger effects of 1999 radial highways in the first decade relative to the second decade.

VI. Decentralization of Production

We begin this section by examining the effects of transportation networks on the 1990–2010 growth of central city industrial GDP. We then use the 1995 and 2008 industrial censuses to confirm that the same patterns hold for the growth of central city industrial employment. We square these results with the population results reported in section V by showing similar effects on the residential locations of people employed in industry. Finally, we comment on the determinants of employment decentralization as a function of weight-to-value ratios.

A. *Central City Industrial GDP*

Table 6 reports IV estimates of the effects of elements of transport networks on central city industrial production between 1990 and 2010, holding prefecture population constant. We use the same set of controls as for our analysis of population decentralization. Commensurate with our dis-

[13] Subtracting 1990–2000 growth from 2000–2010 growth effectively yields a rate of change specification. Consistent with the results just reported, estimating the rate of change on the same covariates yields a coefficient of about 0 on 1999 radial highways.

Table 7.—Population versus Employment Decentralization

	Δln(CC Population), 1990–2010		Δln(CC Working Res.), 1990–2010		Δln(CC Res. Working in Manuf.), 1990–2010		Δln(CC Manuf. Employment), 1995–2008	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2010 radial highways	−0.0412*	−0.0562**	−0.0438	−0.0620*	0.0087	−0.0086	−0.0008	−0.0063
	(0.0246)	(0.0277)	(0.0351)	(0.0319)	(0.1113)	(0.1102)	(0.0920)	(0.0950)
2010 radial railroads	−0.0105	−0.0047	−0.0475	−0.0404	−0.3499**	−0.3431**	−0.2784**	−0.2762**
	(0.0485)	(0.0551)	(0.0541)	(0.0568)	(0.1623)	(0.1632)	(0.1288)	(0.1294)

Control variables match those in table 4, column 2, with the following exceptions. In columns 1, 3, 5, and 7, the predicted change in prefecture population using migration flows instruments for the actual change, with an overall first-stage F-statistic of 7.02. In columns 2, 4, 6, and 8, the same instrument instead enters for 1990 to 2010 prefecture employment growth, with an overall first-stage F-statistic of 4.02. Each regression has 257 observations. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

cussion in section IVA, estimates in table 6, while indicating decentralization, may also reflect shifts in prefecture sectoral composition.

Results in columns 1, 3, and 6 of table 6 reveal that highway rays have insignificant effects on central city industrial GDP, regardless of other elements of the transportation network. In contrast, results in column 2 show the central role of radial railroads for facilitating central cities' loss of industry. Each radial railroad causes about a 24% decline in the growth of central city industrial GDP. Column 4 reports a horse race between rail rays and total kilometers of the rail network in the prefecture remainder. Rail rays win with the rail rays coefficient little changed and an insignificant coefficient for kilometers. We obtain the same result if we control for total kilometers of rails in the entire prefecture, rather than just the remainder.

Columns 5 to 7 report estimates of the effect of ring roads alone and, then, combined with highway rays and rail rays, respectively. Regardless of the other infrastructure considered, ring roads have a large effect. The existence of some ring road capacity causes more than a 50% decline in industrial GDP growth in the central city, though the standard error is large. While the first-stage F-statistic is less than 6 when ring road capacity is included along with either highway or rail rays, the coefficient on ring capacity remains large. Results in table 6 indicate that railroad rays and ring roads play important roles in industrial decentralization, much as Meyer et al. (1965) suggest.

As with our analysis of population decentralization, unreported analogous OLS estimates appear to be positively biased, reflecting the assignment of railroads and ring roads to central cities with more rapid GDP growth. For example, the coefficients of OLS rail rays and ring roads for the specification in column 7 are −0.041 and −0.145, respectively, compared to the IV estimates of −0.24 and −0.71 reported in table 6.

From our discussion in section IVB of the processes by which 1962 roads and railroads were assigned, the crucial control variables in table 6 differ from those for population decentralization. Instead of 1982 prefecture population, the most important controls are the provincial capital indicator and 1982 prefecture manufacturing employment share, driving differences between the no-controls IV coefficient on rail rays of −0.34 in column 8 and the primary estimate of −0.24 in column 2. Some results on controls also differ. The 1982 education share now has significant coefficients in some cases and signs of area coefficients reverse (unreported). Central city industrial GDP growth is lower in prefectures with higher education in 1982; perhaps service sector development is positively influenced by the local human capital stock. A greater share of manufacturing in 1982 also leads to lower central city industrial GDP growth, perhaps due to convergence.

Table 6 indicates that radial rails and ring roads caused some combination of industrial GDP decentralization and reallocation of production toward other sectors. Unfortunately, the limited quality of our prefecture GDP data and an inability to find a viable instrument for GDP growth preclude a serious investigation of the extent to which the second mechanism is important.

B. *Decentralization of Residents and Jobs*

Results in tables 4 and 6 reveal that while roads matter for the location of people, in China rails matter for the location of industrial production. Because production requires workers, these differing roles may seem mutually inconsistent. However, table 7 indicates that our estimated effects of radial highways and rails are in fact consistent. Table 7 shows that radial railroads caused similar declines in central city residents employed in manufacturing as declines in industrial GDP and firm manufacturing employment. Pairs of regressions in table 7 are identical except for the prefecture growth control. Odd columns use population and even columns employment. Our population-based card instrument predicts employment less well in the first stage in even-numbered columns.

Columns 1 and 2 in table 7 confirm that radial highways contribute to decentralization of population but radial rails do not. Columns 3 and 4 examine the effects of transport on the decentralization of the residential locations of workers. Estimated effects of infrastructure on residential location are almost the same as for population. However, columns 5 and 6 reveal that, unlike for all workers, radial rails caused a dramatic decline in central city residents working in manufacturing. Each radial rail causes about 35% of central city residents working in manufacturing to move to the prefecture remainder or switch sectors, with no significant effect of radial highways. Results in columns 7 and 8 indicate that each radial railroad caused about 28% of central city manu-

TABLE 8.—INFRASTRUCTURE AND CENTRAL CITY MANUFACTURING EMPLOYMENT

	Δln(Central City Residents Working in Manufacturing), 1990–2010				Δln(Central City Manufacturing Employment), 1995–2008			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2010 radial highways	−0.0266		−0.0841		−0.0289		−0.0424	
	(0.0835)		(0.0952)		(0.0806)		(0.0866)	
2010 radial railroads		−0.3454***		−0.3367**		−0.2788***		−0.2760***
		(0.1222)		(0.1377)		(0.0986)		(0.0943)
2010 ring road indicator			−0.8850***	−0.9774***			−0.2073	−0.3123
			(0.3217)	(0.3476)			(0.2785)	(0.2930)
Δ ln(Pref Pop) 1990–2010	1.4265***	0.9605*	1.2957***	0.6369	0.6885**	0.2902	0.6579*	0.1868
	(0.3343)	(0.4962)	(0.3700)	(0.6606)	(0.3481)	(0.4621)	(0.3586)	(0.5124)
First-stage F	13.1	21.5	4.05	4.26	13.1	21.5	4.05	4.26

Regressions in columns 1–4 are analogous to those in table 7, column 5, though with different transport measures considered. Regressions in columns 5–8 are analogous to those in table 7, column 7. Each regression has 257 observations. ***$p < 0.01$, **$p < 0.05$, *$p < 0.10$.

facturing jobs to leave, with no effect for highways. These effects are similar to the estimated −0.24 reported in table 6 for the effect of rail rays on central city industrial GDP.

Without reliable data on the location of nonmanufacturing employment, we cannot have a complete picture of how infrastructure affected the distribution of population and employment by location and sector. However, we can try to make inferences. The population decentralization promoted by highways could either reflect more intensive commuting from suburbs to central cities or decentralization of nonmanufacturing jobs. There are few systematic data about commuting mode choice for China, but based on various sources, it seems that the fraction commuting by car or transit is still very limited.[14] If those in nonmanufacturing compared to manufacturing jobs have similar commuting patterns, this suggests that highways promote decentralization of service jobs and workers, while rails promote decentralization of manufacturing jobs and workers and, potentially, some sectoral shift in prefecture economic activity. That railroads do not affect the allocation of the total working population between cities and suburbs means that railroads likely promote central city shifts toward the service sector. Ring roads decentralize all types of activities.

In table 8, we further investigate effects of infrastructure on central city manufacturing employment. Columns 1 to 4 show effects on 1990–2010 growth in central city residents working in manufacturing, and columns 5 to 8 show effects on 1995–2008 growth in central city manufacturing jobs. Results are similar. While highway rays have no effect on central city industry, each rail ray causes about a 30% decline in residents working in manufacturing or in manufacturing jobs. In column 4, ring road capacity reduces central city residents working in manufacturing by about an additional 62% (1-$e^{-0.977}$). However, results in column 8 for effects of ring road capacity on central city manufacturing jobs are weaker.

Meyer et al. (1965) suggest detailed patterns for the exodus of industry from central cities in the United States in the 1950s and 1960s. They thought large plant heavy industry would be slower to leave central cities and would, for a while, continue to rely on central city rails. However, intermediate-weight footloose production would move to city fringes, where ring roads facilitate the trucking of goods to suburban rail sidings. Low-weight products could rely more on trucking for long-haul moves, with radial highways providing quick exits to interregional highways and ring roads providing connections. We investigate how infrastructure influenced central city employment in five industry groups characterized by weight-to-value ratios of their output shipments.[15]

Based on specifications analogous to those in table 8, columns 6 to 8, results in table A6 indicate that heavy goods respond the least to railroads, while low-weight goods such as textiles, apparel, leather, and high tech respond the most. Radial highways play no role for heavy and medium-weight goods, but each radial highway reduces central city employment in the lightest-weight industries by 20% to 25%. Horse races between rail and highway rays have no statistical power (unreported). Ring road effects are large in most industries, but are significant only for high tech, which could be the poster child for the Meyer et al. hypothesis on the role of ring roads.

VII. Conclusion

Our analysis suggests that transportation infrastructure networks had profound and long-lasting impacts on urban form in China. Both radial highways and ring roads promoted substantial population decentralization out of central cities, and radial railroads and ring roads promoted the decentralization of industrial production and its workforce.

These results come with caveats. First, they depend on the pseudo-randomization of transport infrastructure by our 1962 network instruments conditional on control variables.

[14] For example, Zhou, Deng, and Huang (2013) report on a survey of 1,000 people in Guangzhou, in which 75% bicycle or walk, 15% take transit (buses), and 10% use private automobiles to get to work. Car ownership rates reported in various city yearbooks confirm an upper bound on private automobile commuting of about 20%.

[15] We use Duranton et al.'s (2014) table relating weight to value for shipments of goods by U.S. industries. Land use intensity could be a key factor driving responses, but we know of no data on such land intensities.

Serially correlated unobservables that predict both residualized 1962 networks and post-1990 changes in urban form would invalidate our identification strategy. We believe the unique context of China's transition to a market economy limits this concern. Second, the efficacy of the instrument for ring roads is limited. Results are strong and intriguing, but more evidence on the effects of ring roads is essential to our understanding of transport networks.

Our results also point to welfare gains. Given that we find that infrastructure influences prefecture population, we reason likely welfare consequences in a closed city environment. New infrastructure lowers the cost of accessing space, allowing consumption of more space through standard substitution effects. Living costs decline with cheaper housing and lower commuting costs per unit distance. Cheaper space increases firms' allocation of space per worker, thereby increasing real wages and improving residents' welfare. Baum-Snow (2007b) simulates welfare gains of 2% to 3% per additional highway ray for U.S. cities based on commuting cost effects. With less commuting in China, these might be smaller. But there are also potential productivity gains from rails facilitating the movement of industrial production out of central cities, freeing up space for less land-intensive activities such as tradable services that benefit more from agglomeration spillovers. Quantification of the size of these forces is an important area for future research. We hope that estimates in this paper can be a useful in such calculations.

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