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Roads, Railways and Decentralization of Chinese Cities

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Roads, Railways and Decentralization of Chinese Cities*

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Abstract: This paper investigates how the extent and configuration of Chinese road and railroad networks has shaped the spatial transformation and degree of compactness of Chinese urban regions in the last 20 years, a period in which center cities were experiencing strong population inflows but relative losses of industry to the urban periphery. We find strong evidence that the presence of radial roads and ring roads outside of the central city reduce central city population density. However radial roads have no effect on the spatial distribution of economic activity (GDP) in urban regions, though ring roads outside of center cities may contribute to industrial decentralization. Rather, in a country where inter-city trade relies heavily on rails, rail networks have significant impacts on the extent to which economic activity decentralizes. Historical transportation infrastructure provides identifying exogenous variation in more recent measures of such infrastructure.

J.E.L.: R4, O2

Keywords: China, Roads, Railroads, Infrastructure

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1. Introduction

In the early 1990s, China embarked on an ambitious initiative to rapidly build and upgrade its transportation infrastructure, particularly its highways. From a low level, spending on transportation infrastructure grew at 15% a year to about $200 billion in 2007, much of which occurred in cities. This was accompanied by rapid migration of rural populations to cities and economic growth rates averaging over 10 percent a year from 1990 to 2010. We investigate how the extent and configuration of Chinese highway, railroad, and public transit networks affected the decentralization of population and economic activity from central cities during this period. Since such decentralization may precipitate infrastructure investments, we rely on exogenous variation in transportation networks that predate China's conversion to a modern market based economy to estimate the causal effects of such infrastructure on urban decentralization.

For our investigation, we construct a unique data set describing population, economic activity and infrastructure in a panel of constant-boundary Chinese central cities in 1990 for metropolitan areas defined in 2005. These data integrate satellite images of lights at night from 1992 to 2009 with digitized national road and rail maps from 1962, 1990, 1999, 2005 and 2010. Our data also include census information by county from 1982, 1990, 2000, 2010, and information assembled from city and national urban yearbooks for GDP, investment and other variables for 1990-2005.

We find strong evidence that the presence of both radial highways and ring roads outside the central city reduce population density in central cities. Our estimates indicate that each additional radial highway displaced at least 4.2 percent of central city population to suburban regions. Since most Chinese central cities experienced rapidly growing population during our study period, such highways retarded centralization. Conditional on the radial and ring configuration of the highway network, total kilometers of roadways in or outside the center city do not affect central city population density. We find suggestive evidence that additional buses and trolleys in the central city increase central city population density. Together, these findings provide econometric evidence in support of the conventional wisdom (World Bank, 2002) that urban compactness is reduced by radial and ring road construction and enhanced by public transport.

We also present evidence that while no aspect of a prefecture’s railroad network impacts the allocation of population between central city and prefecture remainders, the location of industrial production does respond to the extent of a prefecture’s railroads. Each additional radial railroad line causes a displacement of about 17 percent of central city GDP and 26 percent of central city industrial sector GDP to surrounding regions. Ring roads built outside the central city additionally contribute to the displacement of central city production to outlying areas. However, radial highways and the overall length of the highway network do not cause decentralization of production in Chinese cities. That railroads, but not radial highways, affect the location of production probably reflects China's unusual heavy historical reliance on railroads and waterways for long haul and even short haul freight (World Bank, 1982). In 1978, perhaps 3% of freight (in ton-distance units) in China was carried on highways. By 2004, this number had risen to about 11%, but that is far less than the USA where 30% of freight moves by road.[1] With time and increased highway construction, the Chinese number will continue to rise.

Developing countries spend huge sums on transport infrastructure investments that shape their countries and cities for many decades to come. About 20% of World Bank lending for 2007 was for transport infrastructure, more than the Bank's lending on social programs. Given this commitment to transport investments, mayors and planners worldwide ultimately want to determine the optimal transport infrastructure networks for their cities (World Bank, 2002). Urban transportation improvements generate direct welfare benefits through reduced commuting and shipping costs. Changes in urban form, in particular urban compactness, likely additionally influence welfare through their effects on urban productivity, urban environmental costs and the amount of land available for agricultural production. Therefore, an indispensible component of identifying optimal urban networks is to empirically isolate causal impacts of various urban transportation infrastructure configurations on urban form.

Since Marshall (1890), economists have recognized that denser cities provide richer information environments, with agglomeration improving productivity and innovation (Jacobs, 1969, and Lucas, 1988). However, central city environments come with much higher land and labor costs. Only particular industries benefit sufficiently in terms of improved productivity from the richer information environment to pay these costs. As a result, in developed market economies large cities typically specialize in business and financial services and incubate small businesses, with standardized manufacturing found on the urban periphery and in small cities and towns (Kolko, 2000; Swartz, 1992). In contrast, manufacturing facilities in developing countries in the early stages of industrialization are often located in large cities, perhaps because learning and adaptation are critical to the successful transfer of technology from abroad (Duranton, 2007). This pattern was particularly true in vintage 1990 Chinese cities, where central planning often placed large factories in locations that completely dominated city landscapes. However as transferred technologies mature and economic growth

[1] China statistics are from Table 16-9 of the 2005 China Statistical Abstract. 11.3% of freight in ton-kilometers was carried on highways in 2004. The USA number is for ICC and non-ICC trucking for intercity freight, based on Table 1049 of the 2004-2005 USA Statistical Abstract.

proceeds, central city environments become expensive locations for standardized manufacturing; and, in a version of the product cycle (Duranton and Puga, 2001), industrial firms seek to decentralize to the urban periphery and beyond, where land and labor costs are lower.

The urban literature suggests that migration of these factories to the urban periphery, growth of rural industry, and the consequent development of business and financial services in central cities depend substantially on the ability of the transportation network to connect peripheral locations to the rest of the local economy as suggested in case studies (Lee and Choe 1990, Lee 1982, Hansen 1987, Henderson, Kuncoro and Nasution 1996). This paper is the first to investigate the extent to which different configurations of highway and railway networks help contribute to this transformation, for a large sample of cities with a clear identification strategy. Such transformation as facilitated by infrastructure investments may improve efficiency in production through better use of the rich information environments in central cities and operation of the urban version of the product cycle, thus promoting local economic growth.

Beyond the promotion of greater urban productivity, many Chinese policymakers have additional interests in promoting compact cities for two reasons. First, as elsewhere, they recognize that more compact cities have lower environmental costs (Kahn, 2006). Second, Chinese national officials are concerned about food security and thus worry about urban encroachment on productive rural agricultural lands. Our results show how transport networks affect compactness and the availability of agricultural land near cities.

Chinese cities have struggled to accommodate rapid population growth driven by a mass migration of peasants from the countryside that almost certainly ranks as the largest migration in human history.[2] To limit the inflow, authorities have utilized administrative barriers to migration. Given the rural-urban gap in income, these barriers impose high costs on the rural population. This study will thus also contribute to understanding how transport infrastructure can aid cities in successfully handling such large influxes of rural migrants by providing more residential options in suburban areas.

We note three important ways we improve on the existing literature relating infrastructure to urban form. First, the existing literature focuses almost exclusively on the United States in the late 20th century. We are among the first to investigate the effects of transport infrastructure on urban form in a developing country context where automobiles are less prevalent[3], household incomes are much lower,

[2] Recent estimates put the stock of migrants at 175 to 200 million.

[3] In 1990, car production was only 50,000 units. This increased to slightly more than 600,000 units by 2000, but a major portion of these sales were to institutions (as opposed to individuals). By 2010, car sales exceeded 10 million

and cities are much denser than in the United States. Second, we provide a more sophisticated analysis of the role of transportation network design than has previously been conducted. Our examination of the effects of ring roads and the competing influences of highways and railroads is entirely novel. The extant literature focuses on one mode or another, provides little insight into the effects of railroads on urban form, and has never considered ring roads. Third, our analysis is among the first to examine the relationships between transport infrastructure and the spatial distribution of production.

The validity of our conclusions relies on achieving exogenous variation in transport variables of interest. We generate such exogenous variation by using the configurations of urban transport infrastructure in 1962 as instruments for more recent transport infrastructure. The validity of this identification strategy depends crucially on the fact that Chinese roads and railways served very 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 5-year plans. Thus 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. The liberalization of urban economies during the 1990's that both started the operation of urban land markets and moved industry to a competitive market basis means that 1990 is an appropriate starting point for our analysis.

2. Literature and Context

2.1 Literature

A recent literature investigates the effects of infrastructure on the allocation of resources across and within regions. Michaels (2008) and Chandra and Thompson (2000) investigate the effects of U.S. interstate highways on the development of rural U.S. counties and Duranton, Morrow and Turner (2011) examine the effects of the interstate highway system on trade between cities. This literature shows that the interstate system has a modest effect on inter-regional trade flows and composition in the late 20th century U.S. Donaldson (2010) examines the impacts of railroads in late 19th and early 20th century India and finds large effects on trade and welfare. Puga and Nunn's (2011) investigation of the effects of topography on economic development suggest an important role for transportation costs, and hence,

units, most of which were to individuals. (Zhongguo chengshi gongye nianjian (China Automotive Industry Yearbook), various years.)

indirectly, for transportation infrastructure. In each of these papers, the authors address the possibility that economic activity causes infrastructure rather than vice-versa.

A smaller literature examines how within city transportation infrastructure affects the spatial development of cities. This literature began with Baum-Snow (2007) which finds that limited access radial highways caused economically important decentralization in U.S. metropolitan areas. We estimate a 4-5% decline in Chinese central city population for each radial highway over 20 years, comparable to Baum-Snow's estimate of 6% for the U.S. This suggests that roads have a major impact on urban form in different contexts. Complementing Baum-Snow's work, Duranton and Turner (2012) find that kilometers of interstate highways in a city have economically important impacts on the growth rate of population and employment in cities. 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 to the extent of other roads. Hsu and Zhang (2011) replicate this result using Japanese data. All of these papers rely on exogenous variation to identify the effects of roads on their particular outcome variable of interest and all investigate wealthy western countries. To our knowledge, only Deng et al. (2008) investigate the effect of roads on the development of Chinese cities. They find that roads are associated with an increase in the spatial extent of development in Chinese counties, but do not address the likely reverse causality problem.

A third literature empirically describes changes in the location of industrial production as countries develop. It shows that as development proceeds, standardized industrial activity in city centers decentralizes to ex-urban areas to take advantage of lower labor and land costs. At the same time, central city economies become more service oriented. Lee and Choe (1990) examine the issue for Seoul, Lee (1982) for Bogota, Hansen (1987) for Sao Paulo, and Henderson, Kuncoro and Nasution (1996) for Jakarta. These case studies assert that transport infrastructure facilitates decentralization but none of these papers actually measures infrastructure or deals with the possibility of reverse causality.

2.2 Context

Some exploratory descriptive evidence shows how the China and United States contexts differ. Table 1 shows the growth of economic activity and population in central cities and residual portions of prefectures for three samples of prefectures. Because it has more complete 1990 geographic coverage than other measures, we use lights at night (Henderson, Storeygard and Weil, 2012) as one measure of economic activity. Panels A and B describe the decentralization of population and lights at night while Panel C describes the decentralization of GDP and its industrial component only. Each panel is broken into central city versus prefecture remainders and shows growth over indicated time periods. Starting values in 1990 for population and GDP measures are noted.

Table 1 indicates that throughout our study period, population grew much more quickly in central cities than in suburban regions. Panel A shows that between 1990 and 2010 aggregate population growth was 55% in central cities relative to just 5% in city hinterlands, with somewhat more rapid growth in both regions during the 1990s than after 2000. In contrast to population, Table 1 shows that lights increased more quickly in suburban then central city regions. In the full sample of 257 observations, lights grew by 102% in center cities and 165% in prefecture remainders between 1990 and 2010.

Table 1 Panel C presents information on total GDP and industrial sector GDP growth by urban region for a smaller common sample of 108 areas for which we have consistent GDP data broken out by sector for the 1990-2005 period. It shows that overall suburban industrial GDP grew much more rapidly than central city industrial GDP from 1990-2005 at 794% versus 417%, indicating relative decentralization of manufacturing. Services and obviously agriculture did not shift so much, so that overall GDP only grew modestly more in suburban (605%) than central city locations (530%). Note the GDP numbers reflect China's very high rates of economic growth during our study period.

3. Data

3.1 City and Prefecture Geography

China is split into 34 provinces, 26 of which are primarily populated by Han Chinese and comprise our sample region. Below provinces are prefectures (Diqu), most of which have one prefecture city (Shiqu), numerous rural counties (Xian), and several county cities (Xianji Shi). [4] Prefecture cities are made up of urban districts (Qu). Prefecture cities are administered as one unit and are the nearest possible Chinese analog to central cities of U.S. metropolitan statistical areas. For this reason, we perform much of our analysis using these geographies, in addition to using prefecture geographies. Each rural county and county city is administered separately under the supervision of its prefecture. Most tabular data that we use is reported separately for the urban districts, county cities and rural counties in our study region.

Our most complete sample is a set of 257 2005 definition prefectures in primarily Han provinces of China. Of the total 286 prefecture units in this region, we exclude 3 because their central cities

[4] Some prefectures consist only of rural units and have no prefecture level city.

coincide with their full prefectures, precluding any analysis of decentralization.[5] An additional 8 observations are excluded because they had fewer than 50,000 inhabitants in 1990. Finally, 18 other prefectures in Han China are excluded as they do not include a central city. Our study area contains about 85% of China's population. Figure 1a illustrates the Han provinces of China, prefecture boundaries, and the boundaries of prefecture cities in 1990. We exclude the less developed non-Han territories in the West because data availability is much poorer in these regions.

As illustrated in Figure 1a, 1990 geography prefecture cities are typically much smaller than prefectures. As illustrated in Figure 1b for the Beijing area, they often consist of many urban districts. In Figure 1b we distinguish urban districts of the 1990 prefecture city in green versus the 2005 prefecture city with added urban districts in yellow. This shows how many counties experienced changes in administrative status during our study period. In addition, a number of new prefecture cities are created. 88 of the 257 year 2005 prefecture cities in our sample did not exist as prefecture cities in 1990. That is, in 1990 these 2005-definition prefectures did not contain a single urban district. We call such cities "promoted" cities, meaning that their administrative status was promoted. Whereas the extant literature sometimes treats the entire prefecture or county as the statistical city (Deng et al. 2008, Faber 2011), inspection of Figure 1 reveals that neither unit appears to be a defensible measure for cities.

Ours is the first study to develop data for China to analyze population allocation between consistently defined central cities and surrounding prefecture areas. We maintain year 2005 prefecture boundaries and year 1990 central city boundaries for our entire analysis. 2005 is the last year for which we have GDP data. We construct constant boundary central cities by describing prefecture cities in 1990 as a collection of 2005-definition counties. For prefecture cities that existed in 1990, our 1990 central cities consist of all year 2005 units that were designated as urban districts in 1990, or which overlap with 1990 counties having this designation.[6] For prefecture cities that came into being after 1990, our central cities consist of the county cities or rural counties that were the first to be promoted to urban status.[7] Of the promoted cities in our sample, 18 experienced boundary changes between 1990 and 2005 that had to be handled in our data construction while 52 sampled incumbent cities

[5] These cities are typically single urban units directly under the control of the provincial government.
[6] See the Data Appendix for more detail on dealing with situations in which unit boundaries changed over time.
[7] In most cases, just one unit was promoted, though in a few instances neighboring county cities were promoted together and combined into one prefecture city.

experienced boundary changes. We follow these same constant boundary central cities and prefectures through the four cross-sections covered by our data, 1990, 2000, 2005 and 2010.[8]

Chinese restrictions on internal migration impose larger barriers to population migration from one prefecture to another than from the rural to the urban part of a prefecture. This fact, together with the fact that the set of prefectures corresponds to the set of cities, suggests that the rural portion of prefectures represents the `hinterland' from which prefecture cities drew a large portion of their migrants, especially in the 1990s (Chan 2001, 2005) Thus, our analysis will be primarily interested in two geographical units, constant boundary 1990 prefectural cities, the ”central city”, and the surrounding prefecture from which it draws migrants.

3.2 Satellite Data

We use satellite data primarily as a source for lights at night. Henderson, Storeygard and Weil (2012) show that lights at night are a good proxy for GDP at the national level. As is hinted at in Table 1, lights and GDP are also strongly correlated at the Chinese prefecture level. We rely on six separate lights at night images of China (NGDC 1992-2009). These images are for 1992, 2000, 2005, and 2009, with two sets of data for 2000 and 2005. Lights at night data are first processed so that their projection and grid cells align with the 1 km square cells in 1992 landcover data described below. For each cell, these data report an intensity of nighttime lights ranging from 0-63. The codes 0-62 indicate intensity, while 63 is a topcode. Topcoding is rare in China, although it is common in cities of western countries.

We first use the 1992 lights at night data to identify the central business district in each 1990 central city. To accomplish this, we select the brightest cell in each central city. If there is not a single brightest cell, we break ties by summing the total light in successively larger rings surrounding each brightest cell. As a further check on the location of these CBDs we calculate the corresponding CBD for each of our different lights data sets and find that the location of the CBD is very stable. Figure 2a illustrates the resulting CBDs for Beijing and four nearby central cities. White-gray areas show three intensities of light from the 1992 lights at night data and dots identify CBD’s. As the figure demonstrates, our algorithm identifies points that `look' like the most central point of the 1992 lights data. In Figure 2b we show lights at night for the same area in 2009. In spite of the fact that light increases enormously over 17 years, 1992 city centers are still clearly brightest in 2009 as well. In Figure 4 we see that these points also tend be centrally located in the central cities' road networks. We also

[8] This approach is driven by the necessity of developing a way to track changes to administrative boundaries over time and the availability of electronic boundary files.

compare the location of our 1992 CBDs with the locations of old walled cities and find that they are almost always within a few kilometers of an old walled city. If they are not, it is usually because the old walled city is at one sub-center while our calculated CBD is at another. We also calculate total lights contained in each prefecture and in each central city drawn to 1990 boundaries in each sampled year.

We use 1992 land cover data (USGS 1992) to calculate the 1992 share of land in agriculture in each prefecture and central city. This is based on about 21 land cover classification codes that include urban and various agricultural uses.[9]

3.3 Demographic and GDP Data

We build demographic information at the 1990 definition city proper and 2005 definition prefecture levels using data from the 1982, 1990, 2000 and 2010 Chinese censuses of population. In 1982 we use data based on a 1% sample (NBS, 1982 Population Census). In 1990, we primarily use data aggregated to the prefecture level city, rural county or county city level based on a 100% count (China Statistics Press, 1992a). For 2000 and 2010, our census data are the 100% count aggregated to urban district and rural unit levels (China Statistics Press, 2002 & http://www.luqyu.cn, 2012). In 2010 we could only obtain data for 210 of the 257 prefectures in our sample.

Information on output is reported for most prefecture level cities, some large county cities that got promoted to prefecture level cities, and some prefectures back to 1990. Because less complete GDP information is available at the prefecture than central city level, we make only scant use of prefecture level GDP data. For 1990, we get GDP and industrial sector GDP information from various national and provincial printed data year books (China Statistics Press, 1992b & 1992c). Some of the cities included in these yearbooks were county level cities not yet promoted to prefecture level cities. In 2005 we use output information from the University of Michigan's Online China Data Archive at the rural county, county city or prefecture city levels according to contemporaneous definitions. We supplement with prefecture level printed yearbooks for urban district level data for 23 cities for GDP and 18 cities for industrial sector GDP. Because we do not have a comprehensive source for GDP information disaggregated below the city proper level, we are forced to exclude from our sample many cities that expanded geographically over time when studying effects of transport infrastructure on output growth in 1990 central cities. This restriction plus the lack of data availability for some central cities in 1990 leaves us with a sample of 205 when examining effects of transportation on GDP and 187 when

[9] Urban land is code 1 and agricultural land is codes 2-6.

examining its effects on industrial sector GDP. For this reason, our use of lights at night as an alternative GDP measure is valuable as it presents no sample selection difficulties.[10]

3.4 Infrastructure

To describe the Chinese road and railroad network, we digitize a series of large scale national transport maps. Mechanically, this involves scanning large paper maps, projecting the resulting image, and electronically tracing each of the transportation networks of interest. The resulting tracings are our digital road or railroad maps. We rely on national maps rather than more detailed provincial maps to ensure consistency within each cross-section. To have consistency across time, we selected maps from the same publisher drawn using the same projection and with similar legends. However, the physical characteristics of recorded highways change over time. For example, 1990 or 1962 highways are typically two-lane free access roads, some of which are not all-weather or even paved.

In this way we are able to construct digital maps for railroad and highway networks for each of the following years: 2010 from SinoMaps Press (2010), 2005 from SinoMaps Press (2005); 1999 from Planet Maps Press (1999); 1990 from SinoMaps Press (1990); 1980 from SinoMaps Press (1982); 1962 from SinoMaps Press (1962), and 1924 by Jiarong Su (1924). We also use a map of mid 18th century post roads. This map describes the imperial postal relay system, which connected the capital (Beijing) to provincial capitals.[11] The left panel of Figure 3 presents an image of Beijing taken from our 2005 map. The right panel shows the resulting electronic map of the 2005 railroad and national highway network.

Using these digital maps, we calculate radial and ring highway and railroad capacity measures and count the total length of each transportation network within each prefecture and 1990 definition central city. In 1999 and 2005 we allow both types of highways indicated on the national map to contribute to our roads measures. In 2010, whose map has a more detailed legend, we allow only the top two of three categories to contribute.[12] While all of the roads from 1999 on that we count appear to capture major highways of at least two lanes in each direction, the unavoidable inconsistency of maps

[10] Because boundary changes resulted in some rural counties being counted as part of 1990 central cities, we also need a measure of GDP for these rural counties in 1990. For these few rural counties, we impute GDP using information on value added and agricultural employment.

[11] These routes were plotted (and then digitized) by Tuanhwee Sng on the basis of the description of the routes provided in the Yongzheng edition of the "Collected Statutes of the Qing Dynasty Through Five Reigns". Yongzheng was the 5th Emperor of the Qing Dynasty and ruled 1722-1735.

[12] Attempts to use only the top road category rather than the top two for constructing road capacity measures yield too few roads to provide sufficient identifying variation across locations.

between 2010 and earlier years means that the road measures are not directly comparable over time. Most maps only have one railroad classification.

To calculate our radial road index, we first draw rings of radius 5km and 10km around the CBD of each central city. We then 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. Thus, this index measures the number of radial segments a particular network provides, while excluding segments which do not come sufficiently close to the city center. The left panel of Figure 4 illustrates this algorithm. In this figure, the green areas are central cities, the locations of CBDs are given by dots, the 2010 highway network is represented by red lines and the two relevant rings around each CBD are in black. The left panel of figure 4 indicates that our radial road index value is 6 for the 2010 highway network in Beijing, which is the same count one would choose if doing the calculation by eye.

Calculating the ring road index is more involved. Our goal is to generate an index number to measure the capacity of a particular central city road network to move traffic in a circle around the CBD. We proceed quadrant by quadrant. The right panel of Figure 4 illustrates the calculation of our ring road index for the 2010 national road network for the southwest quadrant of 3 cities. For each city, we begin by drawing two rays from the CBD, one to the south and the other to the southwest. We next restrict attention to intersections which lie between 5 and 9km from the center. In the figure, these are areas bounded by the two black circles. We next identify all intersections of each ray with the road network within the rings. In this case, for Beijing there is one each. The southwest quadrant ring road index for the 5 to 9 km ring is the minimum of these two counts of intersections, which is still one each. For the other cities shown the minimum is zero. To finish our calculation of the ring road index in the 5 to 9 km annulus centered on the CBD, we replicate this calculation for each of the four quadrants and sum the resulting quadrant by quadrant index numbers. Thus, a one unit increment in this index reflects a single road traveling about 45 degrees around the center while remaining between 5 and 9 km from the center. We replicate this calculation for roads that lie between 9 and 15 km from the CBD and 15-25 km from the CBD. These distances of 9, 15 and 25 are chosen so that the minimum angle is 54 degrees for a straight-line highway to intersect both rays in any distance-quadrant segment (as in the Beijing picture for the first distance-segment in the Southwest quadrant), so as to be counted as a ring road. For the empirical work, we sum the results of these three calculations and restrict attention only to roads which lie outside the central city. Because few cities had circumferential road infrastructure in 2010, we use an indicator of the existence of any ring road segment outside the central city as our primary ring road measure.

3.4 Supplemental data sources and summary statistics

We also use several supplemental data sources. We calculate the range in elevation and an index of the roughness of topography in each prefecture city and prefecture using a digital elevation map with 90m sq. resolution (ESRI, XXXX). [13] We calculate the distance from each CBD to the nearest point on the Chinese coastline and major river using data extracted from the ESRI world oceans file (ESRI, XXXX).[14] We construct yearly average temperature and total precipitation using data from 194 Chinese weather stations over the period 1971 to 2000. Each city is assigned the climate associated with the weather station nearest to its CBD. [15] Summary statistics for most variables used in the analysis are reported in Table A1.

4. Empirical strategy

4.1 Econometric model

Our goal is to determine how the configuration and extent of the road and railroad networks affect the population level and the level of economic activity within constant boundary central cities. We begin by conceptualizing a static economic model that describes the allocation of economic activity across space within a prefecture as in Alonso (1964), Muth (1969) and Mills (1967). In such a model, we take prefecture economic activity as given and investigate transportation's role in determining its allocation between the central city and suburban regions, whose characteristics and spatial configurations are described in our data. Define y_{tA} to be the outcome variable of interest: population or a measure of economic activity, where the year t takes the values 1990, 2000, 2005 or 2010. A indexes the administrative unit: either prefecture P or central city C. We denote a vector of additional control variables by x. Our data describe the road and railroad network in each of several years. Let r denote a vector of transport network measures. We will often be interested in first differences of our variables, and to denote this we use the symbol Δ_t where 1990 is always taken as the base year and t indicates

[13] Let v be the elevation of the subject pixel and s_1 to s_8 the elevations for the eight adjacent pixels. For each v in a given jurisdiction we calculate $g(v) = \sqrt{\sum_{i=1}^{8}(v - x_i)^2}$. Our roughness index is the mean of $g(v)$ over all pixels in the jurisdiction. This index, which is similar to the mean standard deviation in elevation between each pixel and its neighbors is used in Burchfield et al (2006) and was developed in Riley et al. (1999). This index provides an intuitive measure of roughness and is particularly simple to calculate with GIS software.

[14] Our map of Chinese rivers is downloaded from the China Earthquake Geospatial Research Portal at *http://cegrp.cga.harvard.edu/data.* Our map reports four different classes of river and is produced by the China National Fundamental GIS. We use only the largest rivers of the four types reported.

[15] China Meteorological Data Sharing Service System, URL: http://cdc.cma.gov.cn/.

the terminal year. Thus, $\Delta_{2000} \ln y_P$ denotes $\ln y_{2000P} - \ln y_{1990P}$, the change from 1990 to 2000 in outcome variable ln y measured at the prefecture level.

A simple way to estimate the effect of transportation infrastructure on urban form is with a levels equation such as:

(1) $$\ln y_{tC} = A_0 + A_1 r_t + A_2 \ln y_{tP} + B_0 x_t + \delta + \varepsilon_t$$

Equation (1) predicts central city population or economic activity as a function the infrastructure variables of interest r_t, total prefecture population or economic activity ln y_{tP}, and additional factors x_t that may influence ln y_{tC} and be correlated with *r*. Error term components δ and ε_t represent unobserved constant and time varying prefecture specific variables that influence central city population or economic activity. Inclusion of the control $\ln y_{tP}$ is central to our analysis. With this control included, the coefficient of interest A_1 indicates the fraction of central city population or economic activity displaced to prefecture remainders for each additional unit of transport infrastructure. We expect $A_1 < 0$. To describe an Alonso-Muth-Mills equilibrium, controls in x_{1990} include central city land area and a measure of land productivity in agriculture, which proxies for the cost to the city of obtaining rural land.

There are two problems with using (1) in estimation. First, the coefficients in (1) may describe an approximate Alonso-Muth-Mills equilibrium in urban land markets in China in 2010. However in 1990 the allocation we see is probably better described by a larger set of variables as it is not an Alonso-Muth-Mills equilibrium. Rather it is some planning allocation. Therefore, the coefficients in (1) may differ in 1990 and 2010. Second, a necessary condition for an estimate of A_1 to be a casual effect of infrastructure on density is that our infrastructure variables be conditionally uncorrelated with the two error terms. That is, $Cov(\mathbf{r}, \delta + \varepsilon \mid .) = 0$. This condition is unlikely to hold. In particular, we are concerned that historically productive or attractive city centers have been allocated more modern highways. In this case, the coefficient on highways reflects this unobserved attractiveness rather than a causal effect of infrastructure. For railroads, while we treat the 1990 and later period stocks as indistinguishable within cities in our data, we also worry that the allocation of railroads made in the 1980s and additions which occurred after 1990 are not randomized either.

As a response to these issues, we first specify an equation with different coefficients and additional variables q for 1990 and then first difference to examine growth in ln y_{tC} between 1990 and a later year. For 1990, the resulting analog to Equation (1) is

(2) $$\ln y_{1990C} = (A_0 + \Delta A_0) + (A_1 + \Delta A_1) r_{1990} + (A_2 + \Delta A_2) y_{1990P} + (B_0 + \Delta B_0) x_{1990} + C_0 q_{1990} + \delta + \varepsilon_{1990}$$

Differencing (1) from (2) yields

(3) $\Delta_t \ln y_C = \Delta A_0 + A_1 \Delta_t r + \Delta A_1 r_{1990} + A_2 \Delta_t \ln y_P + \Delta A_2 \ln y_{1990P} + B_0 \Delta_t x + \Delta B_0 x_{1990} - C_0 q_{1990} + \Delta_t \varepsilon$

By taking first differences, we remove time invariant aspects of the error term. This means that an estimate of A_1 in Equation 3, for example, only represents a causal effect of infrastructure on the spatial distribution of y if the infrastructure measure is conditionally uncorrelated with the remaining error term. This condition is arguably weaker than the corresponding condition for the levels equation but remains unlikely.

There are a number of practical difficulties in recovering the coefficients in Equation (3) using our data. First, while our 1990, 1999, 2005 and 2010 measures of roads are nominally the same, there is very little resemblance between a highway in 2010 and a `national road' visible on our 1990 map. In particular, 1990 highways near major cities were almost universally at most two-lane roads and were not necessarily paved. If such a 1990 road is recorded as a highway in 2010, it either was substantially widened and improved during our study period or it was an entirely new highway built alongside the old road. Therefore, we impose that all highway measures in 1990 are 0; we believe that treating the initial stock as zero will allow us to more accurately measure the change in highways over our study period. Thus, our measures of changes to the road network are simply levels at t, as in Baum-Snow (2007).

In contrast, railroad network quality changed little during our study period. Most of the intra-city railways that existed in 2010 had been built by 1990. The data do not distinguish track quality and maps in various years do not necessarily record the same minor branch lines. Because differences in measured rail infrastructure over our study period are likely to be primarily from measurement error, we get very similar estimates whether we use 1990 or year *t* rails as our infrastructure measure. We cannot use the change in rails as a predictor.

To recover causal effects of railroads, we include only the level of rails at time t and not the change. That is, we treat 1990 rails as having no effects on outcomes, or we assume that $A_1 + \Delta A_1 = 0$. Our reasoning is as follows. In 1990, there was still little freedom of movement of people or employment facilities within prefectures; there was little commuting or separation of living and workplaces, and no land market existed. Excepting a few special economic zones created before 1990, housing, factory, and even farm location patterns within areas defined as urban were largely unchanged since the 1960s. Only after 1990, with the freeing up of urban land and labor markets, was there much opportunity for urban form to change in response to market forces. The highways and railroads in place in 1990 could not be used for commuting or influence factory relocation within urban areas (Zhou and Logan, 2007).

Once economic reforms were in place, local economies began to adjust to Alonso-Muth-Mills equilibria in land markets. Correspondingly, our analysis of the effects of railroads examines the extent to which the level of railroad infrastructure shaped the changes documented in Table 1. That is, our estimates of railroads' effects on changes in outcomes between 1990 and later periods occur in an environment in which change in response to railroads was not possible prior to 1990, even though much of the 2010 stock existed in 1990. Because of this unique context, we see our analysis of the effects of highway construction between 1990 and later years on changes in urban form as analogous and comparable to our investigation of the effects of railroad levels in later years.

In summary, there are two reasons why our primary specification uses year *t* highways as the road measure when the dependent variable is a first difference from 1990: there were no highways in 1990 and urban spatial structure could not respond to whatever transport infrastructure that did exist in 1990. This second reason also justifies using year *t* railroads as our primary railroad predictor. The resulting base regression specification that we use is:

(4) $$\Delta_t \ln y_C = \Delta A_0 + A_1 r_t + A_2 \Delta_t \ln y_{tP} + \Delta A_2 \ln y_{1990P} + B_0 \Delta_t x + \Delta B_0 x_{1990} - C_0 q_{1990} + \Delta_t \varepsilon$$

We remain concerned that r_t is endogenous in Equation (4), or that transportation infrastructure was not randomly assigned to cities. To resolve these problems, we rely on instrumental variables estimation, which achieves the desired pseudo-randomization. In particular, we require instrumental variables z which satisfy:

(5) $Cov(z, r_t \mid x_{1990}, q_{1990}, \Delta_t x, \Delta_t \ln y_P, \ln y_{1990P}) \neq 0$ and $Cov(z, \Delta_t \varepsilon \mid x_{1990}, q_{1990}, \Delta_t x, \Delta_t \ln y_P, \ln y_{1990P}) = 0$

That is, conditional on controls, we require variables which predict our endogenous variables but are otherwise uncorrelated with the error term in our structural equation. As in Baum-Snow (2007) and Duranton and Turner (2011, 2012), we use historical network data as instruments for r_t, a strategy with particular appeal in the Chinese context.

Our resulting base regression specification includes four components: potentially endogenous transport infrastructure measures at time t for which we instrument, prefecture level growth in and the 1990 level of the dependent variable, growth in and base year levels of exogenous Alonso-Muth-Mills variables, and additional base year variables that influenced the 1990 planning allocation and also may be correlated with instruments. In order to maintain consistency in specification throughout our analysis of both population and components of GDP, in practice we always control for growth in both prefecture population and lights.[16] We use lights because GDP is not observed for most prefectures in

[16] In Section 7 we address the potential concern that these two controls are endogenous.

1990. Land use models also justify controlling for the growth in prefecture income, which can be proxied by lights growth, and growth in population. Land use models additionally justify including 1990 log central city area and a measure of agricultural land productivity.[17] There are three motivations for including log 1990 agricultural hukou population outside of the central city as a control. First, when combined with prefecture and central city areas, it proxies for agricultural land productivity. Second, because it has a high correlation of 0.81 with total 1990 prefecture population, it stands in for $\ln y_{1990}$ in population regressions.[18] Third, migration restrictions across prefectures mean that a large share of rural migrants to central cities have come from surrounding hinterlands (Chan, 2001 and 2005 and Au and Henderson, 2006). Therefore, it controls for population supply to central cities. Inclusion of log prefecture area also captures any restrictions on the size of the suburban region. Finally a provincial capital indicator is included as provincial capitals were favored manufacturing centers in the planning era. Additional controls discussed in Section 5 are included as robustness checks.

We emphasize that for IV regressions to return consistent estimates of A_1, we only strictly need to control for variables that are both correlated with instruments and might influence outcomes of interest. Therefore, though it is likely that we omit some relevant unobserved variables from both x and q, the IV estimator nullifies any resulting bias to A_1. As the following subsection explains in detail, the only crucial controls are the agricultural hukou population outside of the central city when examining the effects of highways and the provincial capital indicator when examining the effects of railroads.

4.2 Instrument validity

Our estimation strategy hinges on finding variables that only affect outcomes of interest through their shaping of recent transport networks conditional on appropriate control variables, thereby satisfying condition (5). We follow Duranton and Turner (2011 & 2012) by relying on historical transportation networks to predict modern networks. To be valid instruments, such historical variables must not predict recent central city growth except through their influences on the location and configuration of the modern transport network conditional on control variables. This means that instruments cannot be correlated with unobserved variables that themselves influence the post-1990 evolution of central city economies.

We have historical transport network data for 1980, 1962, 1924, and 1700. For each of these historical networks we construct ring and radial road indices and measure the extent of the network for

[17] Since these two variables are constant over time, we only control for their 1990 levels.

[18] Including both variables in regressions discussed in the following sections yields large standard errors on both coefficients.

each city and prefecture. We find that the 1962 road measures are good predictors of their modern counterparts, but that the earlier networks are not. Many urban highways built after 1990 followed the 1962 roads as a cost saving measure, as rights of way were already established and the local street networks already fed into these roads. Thus roads in 1962 have good predictive power for changes in highway road capacity experienced by cities between 1990 and later years. While some modern networks clearly follow routes laid out by the 1700 and 1924 networks, these networks are not extensive enough to predict the modern networks in a statistical sense. We worry that 1982 measures after the first output (though not input) market reforms (in the rural sector) in 1978 may be somewhat influenced by looking to the capitalist economy of the future.

Determining the set of appropriate control variables requires understanding the processes by which the 1962 transport networks were established and how these processes could relate to modern forces driving changes in urban form. For roads, one of the hallmarks of Sino-Soviet planning was to minimize commuting. Much of the housing stock was nationalized during this 1950s and urban residents lived increasingly adjacent to their work locations. Because little commuting occurred as of 1962, the road transport network was oriented almost entirely toward the movement of goods. However, because the little long-distance trade within the country that existed in 1962 moved almost exclusively by rail, there was little need for long distance roads. Most roads were local, with construction decisions made locally. Therefore, the vintage 1962 road network generally consisted of unimproved roads connecting rural farming regions to nearby cities. Indeed, there were almost no paved roads in 1962 and only about half of roads were passable in rainy weather (Lyons, 1985).

The highway system built after 1990 is designed to serve a modern economy in cities where places of work and residence are separated and commuting is common. It is therefore likely that 1962 road networks affect the growth of modern cities only through their affect on the modern road network. However, it is important to appropriately control for any variables that are correlated with 1962 measures and may cause changes in urban form or growth. For example since the strength of local agriculture ties and agricultural productivity could affect outcomes today, it is in principle important to control for agricultural activity in 1990 or 1982, which was little changed since the 1960s given the lack of urbanization and migration in the interval. Indeed, a regression of 1962 road rays on various 1990 observables reveals that agricultural population in the prefecture is a good predictor of the number of roads serving the prefecture level city, but other covariates such as 1990 prefecture area and population matter too. Prefecture agricultural population is thus potentially an important control in estimation as it is correlated with highway instruments and is likely to directly predict population and GDP allocation between cities and prefecture remainders, at least in 1990.

Chinese inter-city transportation networks up until 1962 consisted largely of railroads, more than two-thirds of which were built before the People's Republic of China was established in 1949. Major trunk lines constructed in the early 20th century ran north-south, and helped to link key political and commercial centers. Russian and later Japanese investment financed a major expansion in Manchuria (northeast China), which facilitated the extraction and export of agricultural goods and raw materials, and later helped to link emerging industrial centers, e.g. Shenyang and Changchun, with China proper. In the Maoist era railway construction decisions were centralized. Between 1949 and 1962 much of the railroad investment was subject to 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 to the Sichuan area, resulting in five additional strategic rail lines. Because most railways had been built prior to 1962 for long distance shipping of raw materials to fuel industrialization efforts that almost exclusively occurred in cities, manufacturing centers in particular had a lot of railway infrastructure in 1962. Because there was very limited trade between provinces, provincial capitals were the most important trade nodes and therefore received a lot of railroads. Indeed, a regression of 1962 railroad rays on 1990 observables reveals that while agricultural employment is not a good predictor of railroads, a provincial capital indicator is. Overall, railroad construction was influenced by the interests of colonial powers, Soviet advisors, and the designs of Chinese central planners. It is at least plausible that much of the rail network was constructed without regard to its impact on the internal organization of cities during the decades that followed the market reforms of the early 1990's. However, this conclusion is conditional on an indicator for cities being a provincial capital, as this indicator is both correlated with railroad instruments and is likely to influence the 1990 allocation of resources between cities and prefecture remainders.

Table 2 presents representative first stage results for the four transport network measures we emphasize in the paper. We instrument for each recent transport network variable with its analog built from the 1962 network; Table 2 shows results where all 1962 infrastructure measures are included. Evidence in Table 2 indicates that our instruments are individually strong conditional on the standard set of control variables used throughout our analysis, which are discussed in the following section. Therefore, there is useful available variation in the instruments that helps identify causal effects of transportation networks in later years. Each 1962 road ray predicts 0.37 of a 2010 ray and 0.32 of a 2000 ray. Each 1962 railroad ray predicts 0.50 railroad rays in 2005. Finally, each 1962 ring road predicts 0.44 of a ring road in 1999. Main coefficients on road and railroad infrastructure variables change little if additional regressors including region, land cover and weather variables are added to these regressions.

5. Main Results

In this section, we first examine the effects of various types of highway and then railroad infrastructure on population decentralization and then we examine this infrastructure's effects on the decentralization of GDP, particularly its manufacturing component.

5.1 Effects on Population

Table 3 reports baseline OLS estimates of the empirical relationship between highway rays and central city population decentralization, as specified in Equation (4). Columns 1 and 2 examine 1990-2010 changes whiles Columns 3 and 4 examine 1990-2000 changes using a more complete sample. Columns 1 and 3 include the 2010 radial road index as the only explanatory variable while Columns 2 and 4 add our base set of controls.

Regardless of specification, estimated OLS coefficients on highway rays are either near 0 or positive, while we expect the true causal relationship to be negative. As we explain above, there are reasons to believe that OLS is biased. There are many variables correlated with highways that likely also generate changes in central city population. For example, more robustly growing cities may induce more rapid increases in demand for roads which governments may fulfill. This suggests a positive relationship between roads and central city population that is not causal. While the sign on the highways coefficient turns negative in subsequent IV analysis, signs on the control variables remain remarkably stable across estimators. We delay a discussion of these control variable coefficients until after our discussion of the main IV results for highway rays.

Table 4 reports IV estimates of coefficients in Equation (4). All regressions in Table 4 use the road ray index for 1962 roads as an instrument for more recent measures of highway rays. Columns 1-3 examine effects of 2010 highways on the change in log central city population between 1990 and 2010 for our more limited sample of 210 prefectures, while columns 4-5 examine the 1990-2000 period using the complete sample of 257 prefectures. Beyond our base set of controls, in columns 3 and 5 we additionally control for various geography and weather variables in an attempt to better account for variation in agricultural productivity, housing supply elasticities and other exogenous features that might be correlated with 1962 transport infrastructure.

While OLS estimates of the effects of highway rays on decentralization are zero or positive, Table 4 column 1 with no controls shows an (insignificant) 3% reduction looking between 1990 and 2010. The addition in column 2 of our base set of controls yields an estimated significant highway ray coefficient of -0.046. Inclusion of additional weather and geography controls, none of which are significant, lower this estimate in absolute value to a marginally significant -0.038. Columns 4 and 5 show results for decentralization between 1990 and 2000 in the 22 percent larger sample. For this sample, estimates indicate that each highway ray significantly displaces 4.7 percent of central city population to prefecture remainders with basic controls and 4.2 percent with additional controls, some of which are now significant. These results are robust to inclusion of the 1990 agricultural population and prefecture population growth controls only. This sparser specification yields rays coefficients of -0.044 in the smaller sample and -0.039 in the larger sample that have similar significance levels to the rays coefficients reported in Columns 2 and 4.

The estimates in columns 2-3 and 4-5 for the different time periods are very similar. However they are not strictly comparable since we impose a lower standard in 1999 for what constitutes a highway than in 2010 and there is more heterogeneity in the amount of time cities in the 2010 sample were treated with highways than in the 2000 sample.

Because 1990 agricultural hukou population in the periphery is the only control variable significantly correlated with the highway rays instrument, inclusion of this one control variable alone generates rays coefficients that are statistically indistinguishable from those in Columns 2 and 4 at -0.091 (se=0.040) and -0.042 (se=-.019) respectively. Therefore, we view the inclusion of additional controls in our base specification as serving mainly to reduce the variance of the error term, and consequently provide us with more precise estimated causal effects of highway infrastructure. We note that while controlling for prefecture level population and lights growth does in theory matter for interpretation of transport coefficients, in practice our preferred estimates are not sensitive to the inclusion of these controls in a statistically significant way. In Section 7 we address potential endogeneity concerns with these variables and further discuss such interpretation issues.

Though not our focus, estimated coefficients on non-transport related regressors are also of interest. Prefectures with larger 1990 agricultural populations had faster growing central cities, with estimated elasticities between 0.053 and 0.076. These estimates likely reflect both the greater supply of migrants in more agriculturally productive prefectures and their greater opportunity cost of suburban land. Central cities of prefectures with more rapidly growing populations also grew more quickly, with estimated elasticites between 0.75 and 0.91. These are more than twice the size of elasticities found in

Baum-Snow (2007) for U.S. metro areas, reflecting the rapid urbanization of the Chinese economy during our study period.[19] Conditional on other controls, smaller area central cities in larger prefectures grew more quickly. This may simply reflect convergence in city size and the possibility that central cities of larger prefectures had fewer nearby cities competing for migrants. While the change in lights is intended to control for changes in area income, the sign of the coefficient on income is theoretically ambiguous since higher income means greater demand for suburban space but also a greater value of commuting time. Provincial capital center cities also grew a bit more quickly in population than would be expected given the remaining predictors in Columns 2 and 4. Significant geographic and climate features in Column 5 include a positive estimated effect of precipitation and a negative effect of central city elevation range conditional on prefecture elevation range. Higher precipitation may reflect more agriculturally productive land, while central cities with more variation in elevation may have lower housing supply elasticities which have impeded their population growth (Saiz, 2010).

Consistent with evidence for the U.S. in Baum-Snow (2007) and Duranton and Turner (2012), differences between OLS and IV highway rays coefficients suggest that our 1999 and 2010 radial roads indices are endogenous. In particular, while more roads were built in cities with more rapidly growing populations relative to their surrounding prefectures, these roads were themselves causing this population to decentralize. This indicates that while more rapidly growing Chinese cities received more transport infrastructure of various types, the decentralization that occurred because of this infrastructure is swamped by the growth that led to much of this infrastructure being built in the first place. That is, the use of pseudo-random variation from the 1962 network is absolutely essential to understand the true causal effects of these transport improvements on the spatial organization of economic activity within cities.

Table 5 reports estimated effects in addition to those of highway rays of total prefecture highway network length, highway network length outside of prefecture central cities and railroad rays on population decentralization. Our goal is to examine both the causal links from such additional infrastructure to population decentralization and confirm that correlations between the quantities of this other infrastructure and highway rays in 1962 and recent years are not driving the results in Table 4. Table 5 presents IV regressions using our base specification with the addition of one different additional

[19] Our control for the change in prefecture population is meant to account for potential changes in demand for living in the region overall. However, because prefectures are often much larger than their urban region, it is conceivable that there were differential shifts in demand for living in the more urbanized portion of the prefecture relative to the prefecture overall. This point represents a difference between this analysis and that in Baum-Snow (2007) and Duranton & Turner (2011).

transport measure beyond radial highway rays in each column. Columns 1-3 examine effects on central city population growth 1990-2010 while Columns 4-5 examine the 1990-2000 period with larger samples. Because of weak instruments difficulties, we could not credibly include more than two transport measures at once in a single regression, nor any type of interactions. Excluded from this analysis are ring roads which we analyze separately in Section 6.

Coefficients on highway rays reported in the top two rows of Table 5 are all well within the standard error bands of estimates reported in Table 4. Each of the additional transport measures we analyze has an insignificant positive coefficient, with somewhat weak first stages feeding through into relatively large standard errors. We find similar results for additional railroad network measures. For example, the coefficient on log total prefecture km of railroads in a regression like that in Column 3 is 0.03 with a standard error of 0.14. Given these results, while we can rule out that these other types of infrastructure were driving results in Table 4, we cannot rule out that they themselves have extra effects. However, we find that these measures are unlikely to contribute to decentralization given the positive coefficients. We conclude that whatever is the mass of highways and rails in the city, it is the radial highway system that is relevant for population decentralization.

While our estimates are in line with existing evidence from the United States, the underlying mechanism in China is clearly somewhat different. Because of the rapid increases in Chinese urban populations during our study period, highways contributed to population decentralization both by retarding the degree to which rural people living near central cities moved to these cities and by inducing rural migrants from further away to settle in these suburbanizing areas. Unlike in the post-WWII United States, actual decentralization of initial center city populations in China is likely either to have generally not occurred or to have been quite modest.

While we do not have sufficiently detailed migration data to determine how many suburban residents came from central cities and more outlying suburbs, we can provide some indirect evidence that highways retarded centralization of suburban residents. 51 of the cities in our sample expanded their jurisdictions beyond our definition of their central cities after 1990. The resulting conversion of rural counties to urban use resulted in dramatically less agricultural activity and much more opportunity to increase population density in these suburban regions than in unconverted rural counties adjacent to 1990 central cities. If we drop the 51 cities whose legal central cities expanded, highway rays coefficients for both 1990-2010 and 1990-2000 drop by 25-29% but remain statistically significant. This suggests that indeed a good portion of our results are driven by retarding rural in-migration from immediate outlying areas.[20]

5.2 Effects on Output

We now examine the roles of transport infrastructure in shaping the decentralization of production from central cities, with a focus on industrial GDP. Not only did new industry develop in suburban areas with the rapid industrialization that began in the 1980s, but many factories relocated away from central cities starting in the early 1990s.

Table 6 reports IV estimates of the effects of highway rays, railroad rays and total prefecture railroad length on the decentralization of three measures of production activity between 1990 and 2005. Results in columns 1-3 are for the industrial component of GDP, those in columns 4-6 are for entire GDP and those in columns 7-9 are for lights at nights. As we explain in Section 3.3, central city industrial GDP data are only available for 187 of the 257 cities in our full sample, with only an additional 18 cities with observed GDP data. Though our use of lights at night as a GDP proxy allows us to get results for the full sample, we recognize the limitation that residences also emit lights, making the two outcomes difficult to compare. To be consistent with our analysis of population decentralization, Table 6 uses the same base set of controls as in Tables 4 and 5. Prefecture lights and population growth are now intended to jointly control for prefecture GDP growth, which we directly observe for an unsatisfactorily small subset of prefectures.

Whether examining industrial GDP, GDP, or lights, results in Columns 1, 4 and 7 show that highway rays have no significant estimated effects on the decentralization of central city economic activity. A similar statement applies to highway network length, whether in the prefecture overall or just in suburban areas. However, each railroad ray is estimated to displace 26 percent of central city industrial GDP and 17 percent of central city GDP to prefecture remainders. This larger effect on industrial GDP is evidence that the industrial sector is primarily driving the estimated effects on total GDP. These rail effects are very strong. Similar strong results hold for prefecture railroad network length. Unfortunately, we do not have the statistical power to jointly estimate the effects of these two

[20] Of course sample selection difficulties lead us to treat this result with caution. Conversions predominantly took place in rapidly growing cities where suburban demand increases were large enough to overcome usually strong local opposition and regulation by the central government.

railroad network measures in one regression.[21] Results for lights at night in columns 8 and 9 are consistent with those for the other two GDP measures but somewhat weaker.[22]

Significant coefficients on railroad infrastructure in Table 6 are remarkably stable across specifications. For example, the -0.26 coefficient for industrial GDP in Column 2 is exactly the same without any covariates included and changes to -0.23 with inclusion of the complete set of geographic and weather controls used in Table 4 Columns 3 and 5, all of which are insignificant. These same conclusions hold true for coefficients on prefecture railroad network length and for total GDP as an outcome. As in our analysis of population decentralization, OLS appears to be biased toward 0. Table 6 Column 2 as estimated by OLS yields a significant coefficient of just -0.063. As with highways and population, this positive bias comes from the assignment of more new railroads lines after 1962 to central cities with more rapid GDP growth.[23]

Coefficients on control variables are in line with those in Table 4 in our analysis of population decentralization with a few exceptions. 1990 rural agricultural population predicts more rapid central city output growth and central city output growth is strongly correlated with prefecture population growth holding this base year agricultural population constant. When output is measured by lights, prefecture lights growth is associated with stronger central city growth in lights instead. Unlike in the analysis of population, coefficients on central city area are near 0 or positive while those on prefecture area are negative. We find no significant effects on output of being a provincial capital in regressions with railroad transport measures.

We believe railroads are so critical to Chinese industrial decentralization because they dominate trucking as the primary intercity shipping mode. More radial railroads provide more options for manufacturers to move out of central cities and maintain access to the national railroad network through sidings and, as we show in the following section, ring road connections. Industrial decentralization is likely a desired reorganization of urban production activities since cheaper land and rural labor is well-suited for the land intensive low skilled manufacturing sector. At the same time, CBD

[21] Both railroad network measures have large negative but insignificant coefficients and the overall first stage F-statistic is under 2. The inability to distinguish these two effects may not be surprising since most railroads emanate as spokes from central cities.

[22] We also examine the effects of transport infrastructure on the decentralization of service sector GDP. These results follow the sign patterns for total GDP but are statistically weaker. Analyzing the Chinese service sector is difficult because it is poorly measured in 1990, the business and financial service sector is tiny, and we cannot distinguish traded from non-traded services in the data.

[23] Unlike for population, we find no evidence that treatment effects are stronger in central cities with expanding jurisdictions. This is evidence that urban/rural status of counties had little influence on where industrial plants could locate.

land can be repurposed toward services which are less space intensive and typically benefit more from local agglomeration spillovers. Results in Tables 4 and 6 reveal that while roads matter for the location of people, in China railways matter for the location of goods production.

6. Effects of other transport measures

In this section we examine the effects of ring roads, public transport and rivers and canals on the decentralization of economic activity. As far as we know, these are the first results of the causal effects of ring roads and waterways on urban form anywhere in the literature.

6.1 Ring Roads and Network Design

Understanding effects on urban form of ring roads and how they interact with other elements of the urban transport network is important information for policymakers engaged in the planning of such networks. To date there has been almost no investigation of the effects of ring roads because of econometric identification difficulties. China is one of the very few contexts in which exogenous variation in the number of ring roads received across cities is available, but even for China this availability is limited. Scant ring infrastructure in 1962 forces us to focus only on estimating the effects of having any ring road capacity at all. We do not have sufficient statistical power to estimate causal effects of anything beyond this blunt measure. Cities with some ring road capacity had an average of XX, YY, ZZ values of our index of ring road capacity as explained in Section 3.4 for 1999, 2005 and 2010 respectively.

Table 7 reports IV regressions showing the effects of any amount of ring road capacity on the decentralization of population, industrial GDP and GDP. These regressions include other transport measures with significant effects in tables 4 and 6 and our base set of control variables. Each regression in Table 7 except one shows large significant estimated negative effects of the existence of a ring road on central city economic activity. These significant effects of ring roads come in addition to persistent separate effects of highway rays on population 1990-2000 and railway rays on log industrial GDP and log GDP 1990-2005.[24] Estimated ring road indicator coefficients are -0.20 for population change 1990-2000, -0.80 for industrial GDP and -0.46 for GDP, reported in columns 2, 4 and 6 respectively.[25] Estimated

[24] We do not have sufficient variation in the data to additionally estimate coefficients on interaction terms between the ring road indicator and other transport measures.

[25] We did experiment with other measures of ring road capacity and results are similar in magnitude but statistically weak; first stage F statistics are much smaller.

effects of ring roads on industrial GDP and GDP decentralization are not sensitive to the other transport measure included. Coefficients on highway rays in Column 2 and railroad rays in Columns 4 and 6 are statistically indistinguishable from those reported in Tables 4 and 6 without inclusion of the ring road measure. That is, it turns out that the effects of ring roads and other transport infrastructure can validly be evaluated independently. Results in columns 3 and 5 reveal similar coefficients on ring roads as those in Columns 4 and 6 and negative but insignificant coefficients on highway rays for industrial GDP and GDP decentralization respectively. While our estimate for 1990-2010 population change in Column 1 is not significant, it suffers from a weak first stage F-statistic of 4.66.

In summary, ring roads cause a huge amount of decentralization, particularly of industrial production. The greater effects for GDP than population fits the classic story of U.S. urban development in which highways facilitated the decentralization of manufacturing to urban peripheries with low shipping costs at highway interchanges. China's greater reliance on rail for intercity shipping means that industries have greater incentive to decentralize near radial railroad lines. But ring-roads also are clearly an important conduit for shipping of inputs and outputs to and from these firms.

6.2 Public transport and Waterways

Our final investigation is about the effects of public transit and waterways. While there exists a large literature about the economic consequences of public transit, mostly using travel demand modeling, precious little prior research examines transit's effects on urban decentralization, much less in a developing country context. Moreover, convincing econometric identification strategies are difficult to find for public transport. Therefore, despite some data limitations, we see our estimates of transit effects as novel and informative. There exists even less analysis of the effects of navigable waterways on urban form. While we have no instruments for these natural features, they are sufficiently difficult to alter such that we can plausibly analyze their effects using OLS only.

We examine the effects of the number of buses and trolleys in 2005 on measures of urban decentralization. Because such data are only reported at the prefecture city level of geography, we cannot account for city boundary changes and use reported 2005 numbers without modification. Results reported in Column 1 of Table 8 indicate an elasticity of 0.028 between the number of buses and trolleys in 2008 and central city population growth 1990-2010. In this regression, we instrument only for the number of 2010 highway rays. This supports the notion that public transport contributes to urban compactness, counteracting road infrastructure that pushes the population to suburbanize.

We recognize that if high growth cities get assigned more buses and trolleys, our estimated coefficient is biased upwards. We attempt to use the number of employees in the transport service sector in the 1990 city proper to instrument for buses and trolleys. Because these are primarily government jobs, transport service employment is politically difficult to reduce even as demand conditions for transit may have changed over time. Consequently, the first stage is strong. Doubling the number of prefecture transport service sector employees in 1990 caused 26 percent more buses and trolleys to be in service in the central city in 2005, conditional on other exogenous variables. However, it is not strong enough to yield a statistically significant coefficient in the second stage. While the coefficient on buses and trolleys increases to 0.047 with instrumenting, the standard error also increases to 0.047.[26]

Our investigation of the effects of navigable rivers and canals uses the analogous rays measure to those used for highways and railroads. Unfortunately, we cannot distinguish waterways' quality or capacity. Navigable waterways are an important shipping conduit for raw materials like coal and agricultural products, though less so for manufactures. About 75% of the cities in our sample have waterway rays. Columns 2 and 3 of Table 8 show that waterway rays had small and insignificant effects on industrial GDP and total GDP. Similarly small and insignificant effects are found for kilometers of prefecture waterways and when population decentralization is instead used as an outcome. These results are consistent with waterways' role in shipping non-manufactured goods.

7. Robustness

Our analysis in this section shows that our main results, reported in Tables 4 and 6, are robust to various concerns. First we address the potential endogeneity of prefecture population and lights growth as control variables. We then show that transport infrastructure built after 1990 cannot predict patterns of urban change prior to 1990. Finally, we investigate regional heterogeneity in estimated treatment effects.

7.1 Accounting for Potentially Endogenous Prefecture Growth

Here we address the potential concern that transport infrastructure may itself induce overall urban area population and economic growth (Duranton and Turner, 2012). This implies that the prefecture

[26] As a placebo exercise, we also evaluate whether buses and trolleys predict GDP growth. As expected, the buses and trolleys coefficient using this alternative outcome instead in a regression analogous to that in Column 1 of Table 8 is -0.01 and not significant.

population and light growth covariates in Tables 4-8 may be endogenous, spilling over to affect the validity of our coefficients on transport infrastructure measures. While we present results below in which we instrument for prefecture population growth, we note that in no case does removing the two prefecture growth covariates from regressions in Tables 4-8 affect the sign or significance of transport coefficients. For example, the estimate in Table 4 Column 2 rises slightly to -0.075 while that in Table 4 Column 4 falls slightly to -0.040 with the exclusion of these two control variables and both coefficients remain statistically significant. Coefficients on rail rays in Table 6 Columns 2 and 5 both change by less than 0.01 after excluding these controls.

If prefecture population growth is omitted from the regression, there are good reasons to believe that the estimated transport coefficient is positively biased. If transport infrastructure causes prefecture population growth, the transport coefficient in this more parsimonious specification incorporates both the impact of transport on the allocation of population between cities and suburbs and on the level of prefecture population response. Since some new arrivals drawn by better transport infrastructure settle in the city, this coefficient understates the magnitude of the negative effect on central city population holding prefecture population constant.

However, if there are unobservables or measurement error that partly drive variation in central city population, these same factors also enter into prefecture population growth, potentially introducing an endogeneity problem with this variable. Assuming a positive correlation between transport infrastructure and prefecture population growth, this will result in a transport coefficient that is negatively biased.[27] Because we can bound the transport coefficient by comparing results with and without the inclusion of prefecture population growth in the regression, we have indirect evidence that both sources of bias are small.

Despite our confidence that we have tight bounds on coefficients of interest, we also proceed with an IV strategy for prefecture population growth. While migration patterns give us some hope of instrumenting for prefecture population growth, there is little we can do to instrument for prefecture lights growth. Because coefficients on lights growth are mostly not significant, we focus on instrumenting for population growth and exclude lights from the associated regressions. We note that

[27] The econometrics of these biases is seen in the following simplified environment. Suppose that the underlying structural equation for central city population is $\ln y_C = \alpha_0 + \alpha_1 R + \alpha_2 \ln y_P + u$, $\ln y_P = \ln(e^{\ln y_C} + e^{\ln y_S})$ and R is uncorrelated with u. The OLS estimate of α_1 excluding $\ln y_P$ from the regression equation equals $\alpha_1 + \alpha_2 Cov(R, \ln y_P) / Var(R)$ while the OLS estimate of α_1 including $\ln y_P$ in the regression equation equals $\alpha_1 - Cov(R, \ln y_P) Cov(\ln y_P, u) / D,\ D > 0$. Our instrumenting for R ensures that R is uncorrelated with u.

migration across prefectures and provinces in China is strongly restricted, with formal restrictions (essentially "visa" requirements) before the early 2000s and informal restrictions including denial of local public services to ex-prefectural migrants thereafter (Au and Henderson, 2006a and 2006b). Thus we do not expect strong migration responses to changing prefecture economic conditions. [28]

We instead use as instruments variables that generate variation in population supply elasticities across locations due to variation in competition for migrants and the stock of potential migrants. Because cities primarily draw rural migrants from nearby prefectures (Zhang, 2011), they compete with nearby cities for these migrants. Base year urban and rural hukou populations in nearby prefectures but outside a central city's prefecture plausibly affect rural migration and are thus plausible instruments for population growth in our context. In particular, we use as instruments the logs of these rural and urban population counts in prefectures for which any part of their boundaries falls within 300 kilometers of a given central city in 1982. The first stage competition effect of nearby urban hukou we expect to have a negative sign while the stock effect of nearby rural hukou should have a positive sign. It turns out that while the competition effect is significant with an estimated elasticity of -0.06 in the most complete sample, the stock effect is never significant. For this reason, we only use the competition instrument in examining robustness to endogeneity of prefecture population growth.[29]

Table 9 Panel A reports coefficients and standard errors on highway or railroad rays in regressions analogous to those in Table 4 Columns 2 and 4 and Table 6 Columns 2 and 5 except that we exclude prefecture lights growth and instrument for prefecture population growth. First stages are sufficiently weak in the 1990-2010 population and the GDP regressions such that the revised coefficients are not informative. However, coefficients hardly change in the other two regressions. In Column 2 we see that the highway ray coefficient drops slightly to -.042 (from -048) while Column 3 shows no change in the railroad rays coefficient for industrial GDP at -0.025. Given this evidence, we conclude that endogenous prefecture population growth introduces at most a small bias to our coefficients of interest.

7.2 Placebo Regressions

We run "placebo" regressions in which our expected estimated effects of transport infrastructure are zero to evaluate the validity of our identification strategy. In particular, we run regressions analogous to

[28] Indeed, attempts to use Bartik style industry shift-shares to predict population growth yields a weak first stage.

[29] We also experimented with using the ratio of women age 10- 24 to the population in 1990 as a fertility control for natural population growth in the prefecture in the face of the one child policy and an indicator for being one of the special cities that had received FDI by 1990 as instruments. Neither has sufficient first stage explanatory power to be valid.

those in Table 4 Columns 2 and 4 but using population changes between 1982 and 1990 instead of after 1990. If our identification strategy is working correctly, highways built between 1990 and 1999 or 2010 should have no effects on changes in the spatial distribution of the population in urban areas prior to 1990. Because we do not observe lights at night before 1992, we omit this regressor in our analysis. Geography changes rendering it impossible to build outcomes for some 1990 spatial units using 1982 boundaries reduce our sample by 20 prefectures for this analysis.

Table 9 Panel B presents the results of this placebo exercise. It shows that highway rays in 2010 or 1999 predict essentially zero decentralization between 1982 and 1990, as they should. In particular, our point estimates are -0.017 and -0.012 respectively with large standard errors. These point estimates are considerably smaller than those in Table 4. We hope these results provide confidence that our 1962 instruments are not correlated with unobservables that drive population decentralization, conditional on base control variables. Unfortunately we cannot carry out a similar exercise for GDP as it is not observed before 1990.

7.3 Heterogeneous Effects

We recognize that our estimates of causal effects of transport infrastructure on decentralization potentially mask heterogeneity across different types of cities. For example, because decentralization primarily took the form of displacing some city growth to more peripheral regions, one might expect transportation to have a larger effect in more rapidly growing regions. We evaluate the extent to which regional differences are important for our results by estimating versions of our key regressions in which we interact transport measures with region. After some experimentation, we find that we can at most break up China into two regions, the East and the remainder of the country, without losing first stage power.

Table 9 Panel C shows the results of this exercise. It shows that for population decentralization, estimates are not significantly different in the middle or western parts of the country. However, we do find some evidence that the effect of railroad rays on industrial GDP decentralization in weaker in these regions. Off of a baseline coefficient of -0.45 for the entire country, these more interior cities had an estimated 30 percentage points less decentralization of industrial GDP per ray. This coefficient is significant at the 10 percent level. It may be the case that market pressures of rising central city land and labor costs were not as severe in these cities, which have grown less quickly, and thus industry responded less dramatically to available decentralization opportunities.

8. Conclusions

Transport infrastructure networks have profound and long-lasting impacts on urban form and the compactness of cities. In this study we find that this common assessment applies to a large developing country where there is yet to be widespread usage of automobiles for commuting and trucks for intercity movement of goods. For population decentralization within cities, we find that both radial highways and ring roads lead to substantial decentralization, while increased bus supplies contribute to compactness. For production, we find that more radial railroads enhance industrial decentralization as do ring roads, with the latter presumably proving links to rail siding and suburban nodes.

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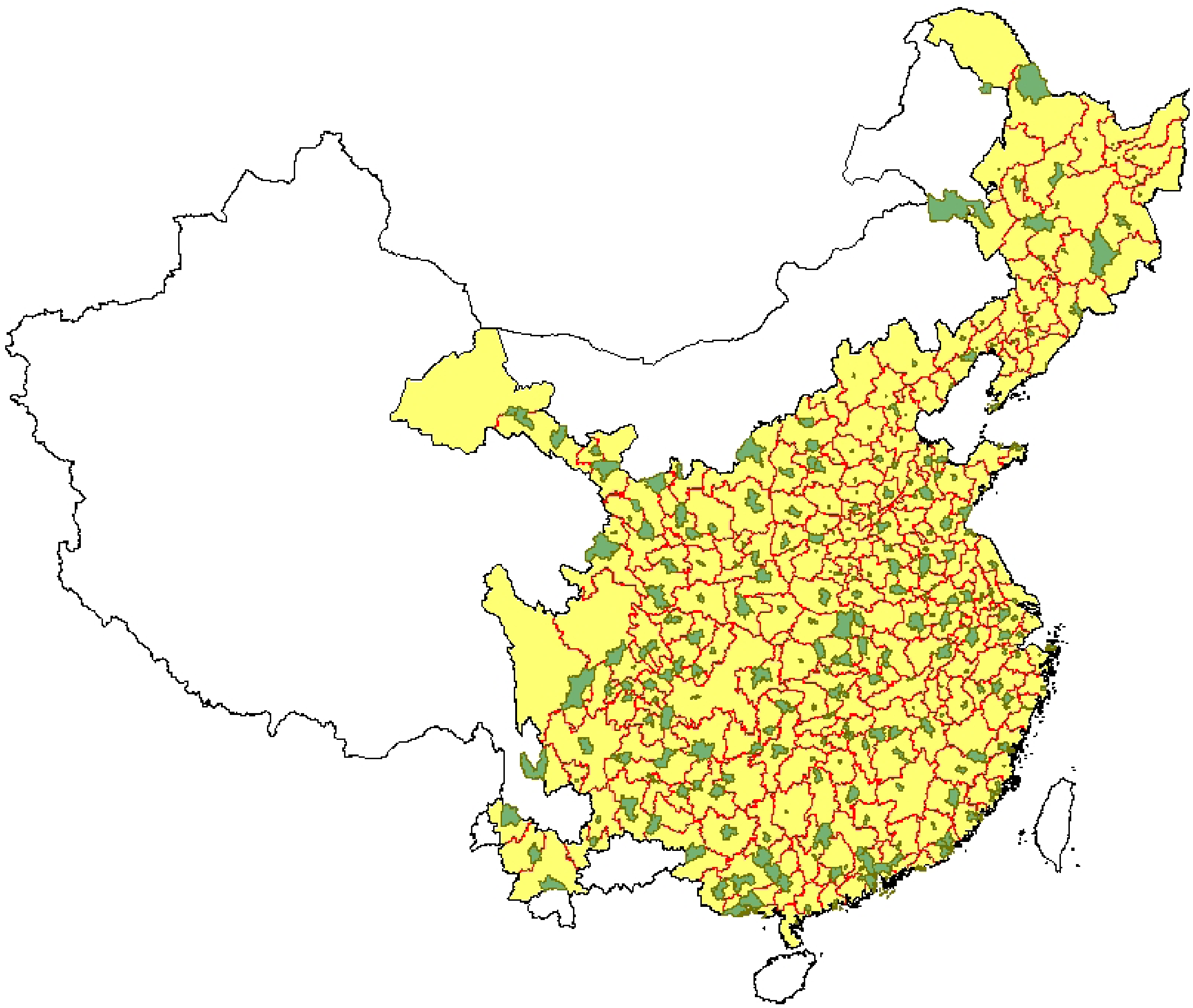

Figure 1a: Study area. The yellow area includes the prefectures included in our study. Red lines indicate prefecture boundaries. Green indicates the extent of constant boundary 1990 prefectural cities.

Figure 1b: Beijing and surrounding prefectures. Counties and prefectures are drawn based on 2005 boundaries for each. The green counties make up the 1990 city prefecture city, the center city. The yellow counties are counties converted to urban districts after 1990. The dots are the city centers, the locations of which are discussed later.

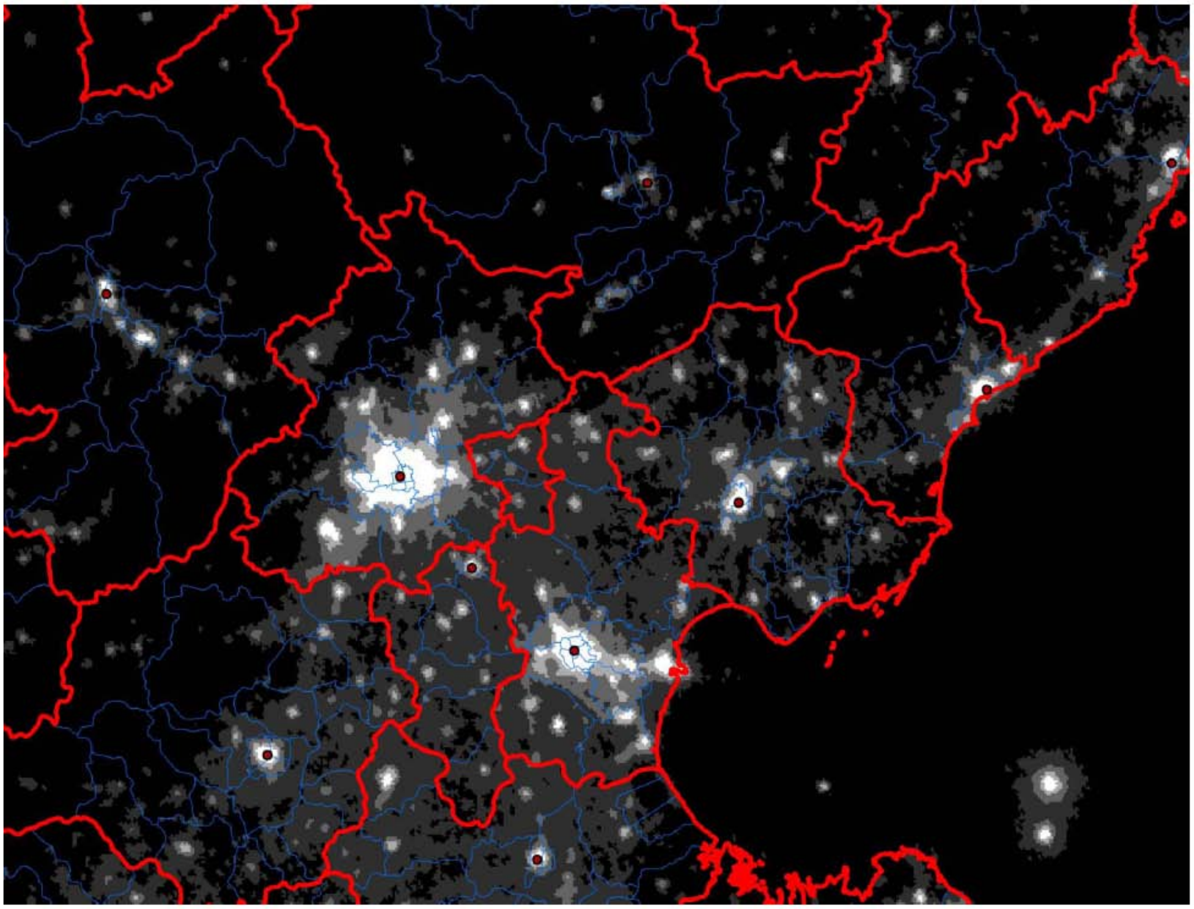

Figure 2a. Boundaries, lights and CBDs in 1992. For the map in Figure 1b, we show lights at nights in 1992 with white to grey shading showing three intensity bands. Red dots circled in black indicate the location of the city center.

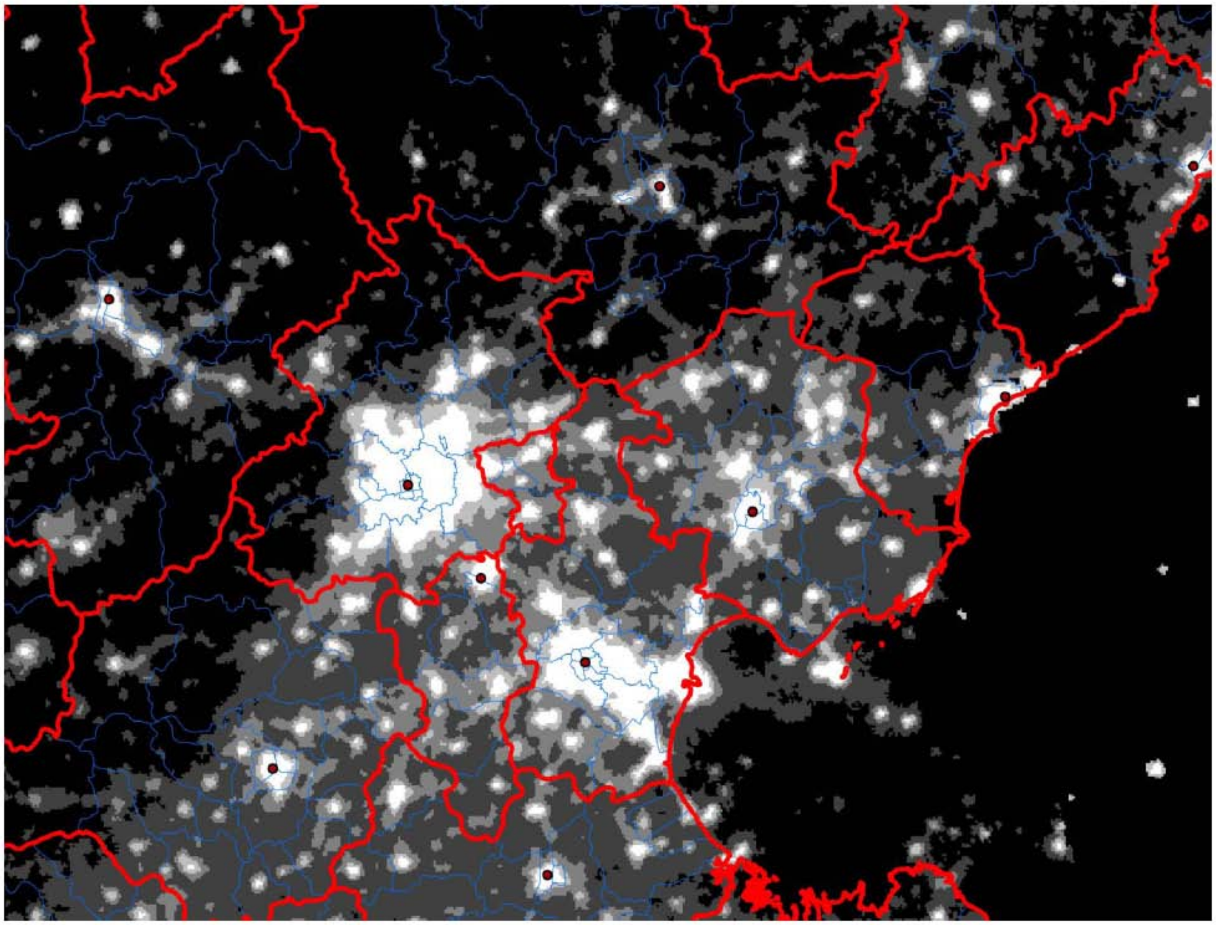

Figure 2b. Lights in 2009

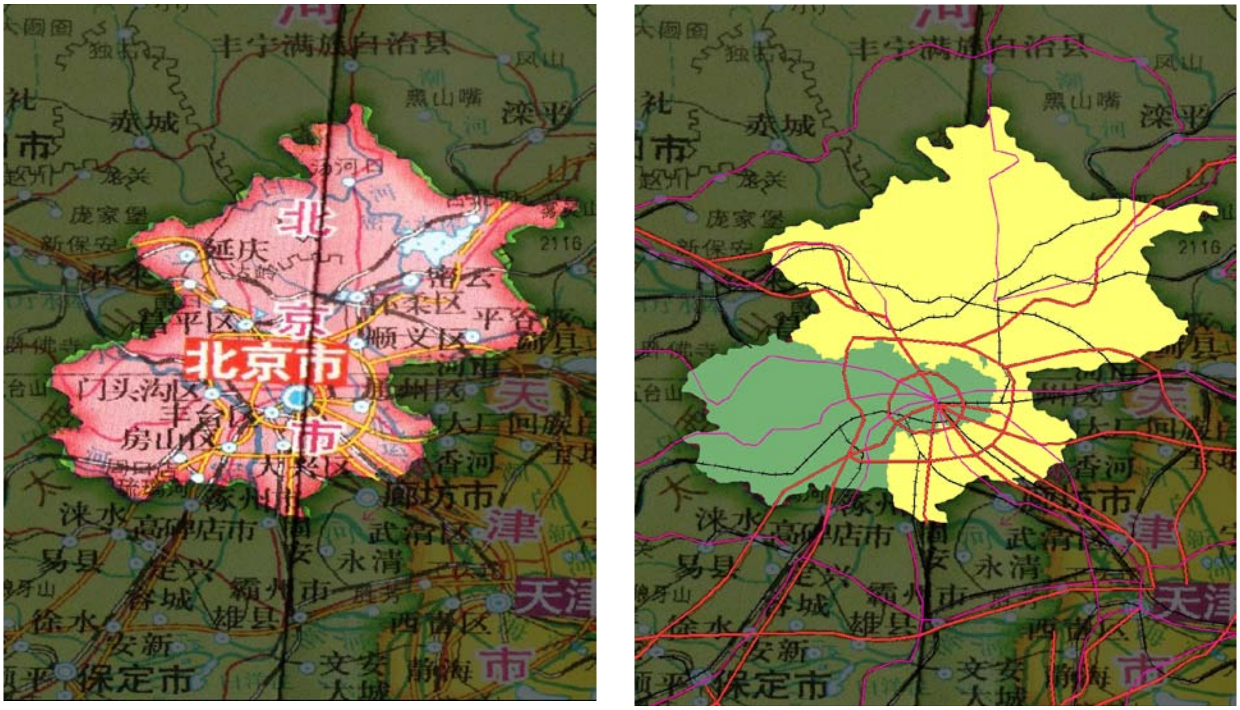

Figure 3: Geocoding maps. The right panel shows and image of Beijing taken from our 2010 national map of China, with area outside of Beijing shaded dark. The right panel shows the resulting digital map. Green indicates the extent of the province of Beijing, tan the extent of the 1990 center city, hatched lines the 2005 railroad line, and solid lines the 2005 national road network with 2 grades of highways (black versus color).

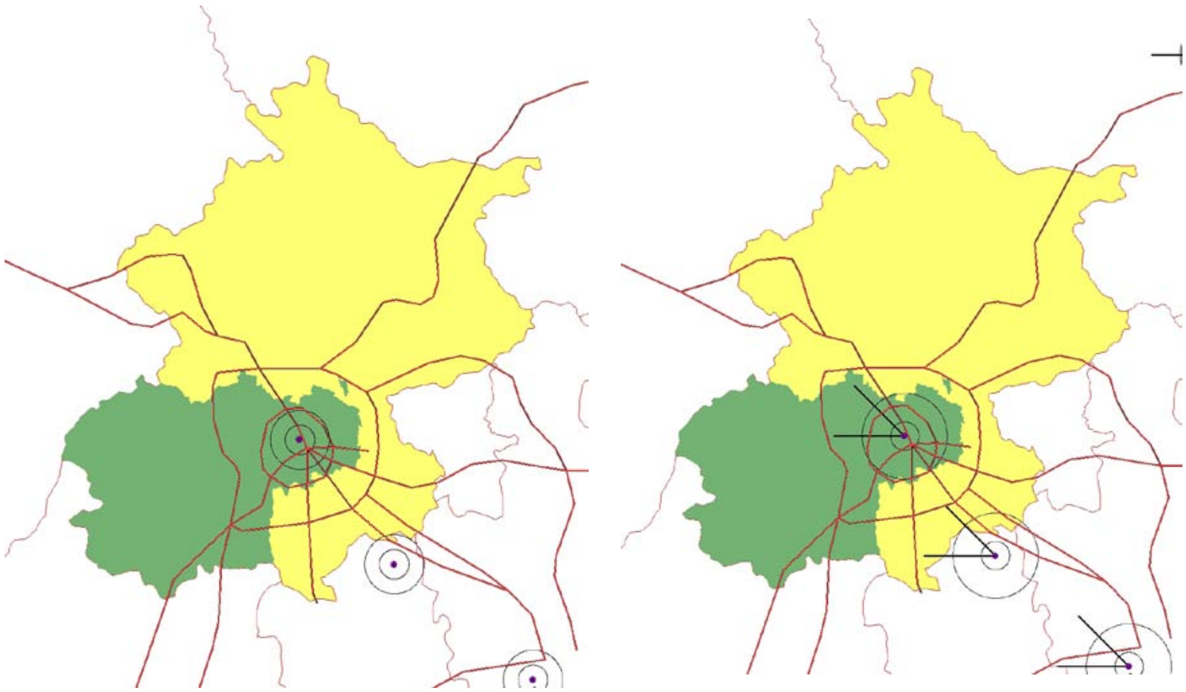

Figure 4: Illustration of radial and ring road index algorithms for 2010 roads. The panels illustrate the calculation of our radial and ring road indices for the Beijing region. Roads are in red. The calculations are detailed in the text.

Table 1: Growth in Aggregate Lights,
Population and GDP by Location, 1990-2010

	City Proper		Prefecture Remainder	
Panel A: 2010 Sample of 210 Prefectures				
	Lights	Population	Lights	Population
(Mean in 1990)		(982,333)		(2,995,989)
1990-2000	54%	27%	99%	4%
2000-2010	33%	22%	37%	1%
1990-2010	105%	55%	172%	5%
Panel B: 2000 Sample of 257 Prefectures				
	Lights	Population	Lights	Population
(Mean in 1990)		(955,683)		(2,953,557)
1990-2000	52%	25%	94%	4%
2000-2010	33%	NA	36%	NA
1990-2010	102%	NA	165%	NA
Panel C: Sample of 108 Prefectures With GDP Data				
	GDP	Industrial GDP	GDP	Industrial GDP
(Mean in 1990)	(20.5)	(12.3)	(17.5)	(7.0)
1990-2000	183%	138%	309%	366%
2000-2005	122%	117%	72%	92%
1990-2005	530%	417%	605%	794%

Notes: The sample in Panel A is used for all regressions examining central city population changes between 1990 and 2010 in subsequent tables. The sample in Panel B is used for regressions examining population changes between 1990 and 2000. The sample in Panel C is smaller than that used for regressions in Tables 6-9 involving GDP because for this table only we exclude prefectures without valid GDP data in 1990 while Tables 6-9 only use central city GDP information. All GDP numbers are deflated using provincial deflators.

Table 2: First Stage Regressions

	2010 Hwy Rays (1)	1999 Hwy Rays (2)	2005 Rail Rays (3)	1999 Hwy Rings (4)
Highway Rays in 1962	0.37***	0.32***	0.022	-0.0043
	(0.080)	(0.079)	(0.082)	(0.018)
Railroad Rays in 1962	0.24*	0.17**	0.50***	0.0045
	(0.13)	(0.078)	(0.057)	(0.023)
Highway Rings in 1962	0.55	-0.56	0.013	0.44***
	(1.04)	(0.37)	(0.26)	(0.12)
Log Central City Area	0.039	0.16	0.069	-0.073***
	(0.16)	(0.11)	(0.12)	(0.023)
Log Prefecture Area	0.25	0.23	-0.13	-0.030
	(0.20)	(0.14)	(0.16)	(0.043)
Log(1990 Agric. Hukou Pop Outside Central	0.0098	0.36**	0.19	0.0059
City)	(0.14)	(0.14)	(0.12)	(0.020)
Log(1992 Prefecture Lights)	0.44***	-0.042	0.030	-0.0087
	(0.15)	(0.13)	(0.17)	(0.032)
Δ log(Prefecture Population)	-0.18			
1990-2010	(0.60)			
Δ log(Prefecture Population)		1.76***	-1.55***	0.15
1990-2000		(0.48)	(0.41)	(0.13)
Δ log(Prefecture Lights)	-0.15	0.020	-0.46	0.044
1992-20xx	(0.53)	(0.32)	(0.36)	(0.061)
Provincial Capital Indicator	1.91***	1.44***	0.096	0.13
	(0.42)	(0.46)	(0.24)	(0.096)
Constant	-5.06*	-6.30***	-0.62	0.86*
	(2.49)	(2.14)	(1.79)	(0.49)
Observations	210	257	205	257
R-squared	0.31	0.29	0.29	0.16

Notes: Each column shows coefficients from a separate OLS regression of the variable listed at top on the variables listed at left. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

Table 3: OLS Relationships Between Highway Rays and Central City Populations

	Δ ln(CC Pop), 1990-2010		Δ ln(CC Pop), 1990-2000	
	(1)	(2)	(3)	(4)
Highway Rays in 2010	0.014	-0.011		
	(0.011)	(0.0073)		
Highway Rays in 1999			0.022***	0.011
			(0.0076)	(0.0073)
Log Central City Area		-0.12***		-0.063***
		(0.021)		(0.016)
Log Prefecture Area		0.031		0.016
		(0.030)		(0.014)
Log(1990 Agric. Hukou Pop		0.070**		0.035*
Outside Central City)		(0.029)		(0.018)
Log(1992 Prefecture Lights)		0.021		0.016
		(0.026)		(0.012)
Δ log(Prefecture Population)		0.79***		0.80***
1990-20xx[a]		(0.11)		(0.085)
Δ log(Prefecture Lights)		0.090*		0.072**
1992-20xx		(0.046)		(0.034)
Provincial Capital Indicator		0.087		0.0017
		(0.059)		(0.032)
Constant	0.36***	-0.43	0.17***	-0.28
	(0.058)	(0.38)	(0.031)	(0.24)
Observations	210	210	257	257
R-squared	0.01	0.56	0.03	0.39

Notes: Each column shows coefficients from a separate OLS regression of the variable listed at top on the variables listed at left. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

[a]Growth is from 1990 to 2010 in Columns (1) and (2) and to 1999 in the remaining columns.

Table 4: IV Estimates of Effects of Highway Rays on Central City Population

	Δ ln(CC Pop), 1990-2010 (1)	(2)	(3)	Δ ln(CC Pop), 1990-2000 (4)	(5)
Highway Rays in 2010	-0.030	-0.046**	-0.038*		
	(0.030)	(0.022)	(0.022)		
Highway Rays in 1999				-0.047***	-0.042***
				(0.014)	(0.013)
Log Central City Area		-0.12***	-0.13***	-0.054***	-0.052***
		(0.020)	(0.020)	(0.016)	(0.016)
Log Prefecture Area		0.043	0.058*	0.032***	0.055***
		(0.027)	(0.034)	(0.011)	(0.012)
Log(1990 Agric. Hukou Pop		0.076***	0.064*	0.065***	0.053***
Outside Central City)		(0.028)	(0.035)	(0.020)	(0.018)
Log(1992 Prefecture Lights)		0.036	0.037	0.013	0.0053
		(0.027)	(0.030)	(0.016)	(0.019)
Δ log(Prefecture Population)		0.79***	0.75***	0.91***	0.91***
1990-20xx[a]		(0.088)	(0.092)	(0.095)	(0.098)
Δ log(Prefecture Lights)		0.083*	0.076	0.073*	0.050
1992-20xx		(0.045)	(0.053)	(0.038)	(0.039)
provincial capital indicator		0.16**	0.16**	0.097**	0.097**
		(0.081)	(0.076)	(0.042)	(0.039)
log(precipitation)			0.029		0.029**
			(0.039)		(0.014)
central city elevation range			8.1e-06		-0.000038**
			(0.000023)		(0.000016)
prefecture elevation range			1.3e-07		8.9e-06
			(0.000011)		(8.7e-06)
log(distance to coast)			-0.0086		-0.0084
			(0.014)		(0.0057)
Constant	0.49***	-0.66*	-0.77**	-0.76**	-0.87***
	(0.11)	(0.35)	(0.37)	(0.30)	(0.31)
Observations	210	210	210	257	257
First stage F	30.3	23.2	26.3	17.0	15.2

Notes: Each column is a separate IV regression of the variable listed at top on the variables listed at left. The number of road rays in 1962 instruments for the two transport variables considered. First stage results are in Table 2. Columns (1)-(3) use the sample of cities for which we have data on population in 2010 while Columns (4)-(5) use the more complete sample of prefecture level cities in our study region. Estimated coefficients on road measures in specifications identical to those in Columns (2) and (4) except that they exclude prefecture population growth, and 1992 lights levels and lights growth are statistically significant at -0.075 and -0.040 respectively. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

[a]Growth is from 1990 to 2010 in Columns (1) through (3) and to 1999 instead in the remaining columns.

Table 5: IV Estimates of Additional Transport Infrastructure Effects on Central City Population

	Δ ln(CC Pop), 1990-2010			Δ ln(CC Pop), 1990-2000	
	(1)	(2)	(3)	(4)	(5)
Highway Rays in 2010 or 1999	-0.054**	-0.052**	-0.052**	-0.047***	-0.047***
	(0.025)	(0.023)	(0.024)	(0.015)	(0.018)
log(km of highways in prefecture) in 2010 or 1999	0.045			-0.0034	
	(0.17)			(0.085)	
log(km of highways in prefecture outside of CC) in 2010 or 1999		0.027			
		(0.071)			
Railroad Rays in 2010 or 1999			0.039		0.0013
			(0.048)		(0.024)
Log Central City Area	-0.12***	-0.11***	-0.12***	-0.054***	-0.054***
	(0.019)	(0.025)	(0.024)	(0.016)	(0.016)
Log Prefecture Area	0.021	0.020	0.045	0.034	0.032***
	(0.11)	(0.074)	(0.028)	(0.065)	(0.011)
Log(1990 Agric. Hukou Pop Outside Central City)	0.071	0.076**	0.071***	0.065***	0.065***
	(0.047)	(0.035)	(0.024)	(0.021)	(0.020)
Log(1992 Prefecture Lights)	0.022	0.025	0.030	0.014	0.013
	(0.031)	(0.023)	(0.025)	(0.018)	(0.018)
Δ log(Prefecture Population) 1990-20xx[a]	0.79***	0.79***	0.82***	0.91***	0.92***
	(0.093)	(0.095)	(0.087)	(0.10)	(0.100)
Δ log(Prefecture Lights) 1992-20xx	0.077*	0.077*	0.100*	0.075*	0.074
	(0.044)	(0.045)	(0.058)	(0.041)	(0.048)
provincial capital indicator	0.17**	0.17**	0.15*	0.098**	0.096**
	(0.083)	(0.079)	(0.079)	(0.043)	(0.041)
Constant	-0.51	-0.55	-0.64**	-0.76*	-0.75**
	(0.79)	(0.57)	(0.31)	(0.42)	(0.30)
Observations	209	205	210	255	257
First stage F	6.15	11.0	8.19	6.99	6.51

Notes: Elements of the 1962 road and rail infrastructure instrument for indicated elements of road and rail infrastructure from 1999 and 2010. Some regressions have fewer observations than are in the full sample because of dropped cities with 0 km of road or rail. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

[a]Growth is from 1990 to 2010 in Columns (1) through (3) and to 1999 instead in the remaining columns.

Table 6: IV Estimates of Transport Infrastructure Effects on the Decentralization of Production

	∆ln(Ind Sect GDP)			∆ln(GDP)			∆ln(Lights)		
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Highway Rays in 2005	-0.028			0.0049			0.015		
	(0.083)			(0.048)			(0.029)		
Railroad Rays in 2005		-0.26**			-0.17***			-0.044*	
		(0.11)			(0.064)			(0.026)	
log(2005 km of railroads in prefecture)			-0.82***			-0.54***			-0.22*
			(0.24)			(0.15)			(0.12)
Log Central City Area	0.12*	0.11*	0.11	0.015	0.015	-0.0011	0.071***	0.076***	0.072***
	(0.066)	(0.068)	(0.065)	(0.047)	(0.048)	(0.047)	(0.024)	(0.023)	(0.023)
Log Prefecture Area	-0.29**	-0.31***	0.22	-0.20**	-0.20***	0.17	-0.090*	-0.087**	0.040
	(0.13)	(0.11)	(0.17)	(0.077)	(0.070)	(0.11)	(0.048)	(0.042)	(0.088)
Log(1990 Agric. Hukou Pop Outside Central City)	0.28***	0.31***	0.29***	0.13**	0.17***	0.16***	-0.00041	0.024	0.030
	(0.11)	(0.11)	(0.11)	(0.056)	(0.063)	(0.063)	(0.042)	(0.036)	(0.038)
Log(1992 Prefecture Lights)	-0.010	0.054	0.15	0.072	0.090	0.15*	0.020	0.020	0.063
	(0.13)	(0.11)	(0.14)	(0.076)	(0.063)	(0.082)	(0.040)	(0.032)	(0.041)
∆ log(Prefecture Population) 1990-2000	1.67**	1.37**	0.80	0.51**	0.31	-0.0054	-0.053	-0.088	-0.33*
	(0.82)	(0.69)	(0.64)	(0.24)	(0.20)	(0.23)	(0.17)	(0.14)	(0.17)
∆ log(Prefecture Lights) 1992-2005	0.31	0.14	0.046	0.30**	0.17	0.081	0.93***	0.89***	0.81***
	(0.22)	(0.28)	(0.24)	(0.15)	(0.17)	(0.16)	(0.080)	(0.079)	(0.085)
provincial capital indicator	-0.40**	-0.31	-0.22	-0.057	0.036	0.12	-0.11*	-0.066	-0.033
	(0.19)	(0.21)	(0.19)	(0.097)	(0.13)	(0.13)	(0.065)	(0.051)	(0.052)
Constant	-0.63	-0.86	-2.56	0.68	0.37	-0.75	0.076	-0.19	-0.76
	(1.67)	(1.64)	(2.09)	(0.95)	(1.06)	(1.26)	(0.38)	(0.30)	(0.49)
Observations	187	187	184	205	205	202	257	257	248
First stage F	16.7	48.3	16.4	16.9	76.4	25.8	35.8	90.1	20.9

Notes: Infrastructure measures from 1962 instrument for those in 2005. Sample sizes are larger than in Table 1 Panel C because we observe more GDP data for existing or soon to be promoted prefecture level cities in 1990 than we do GDP data for full 2005 definition prefectures. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

Table 7: Effects of Ring Roads and Network Variables on Decentralization

	∆ln(CC Pop)		∆ln(CC Ind. GDP)		∆ln(CC GDP)	
	1990-2010	1990-2000	1990-2005		1990-2005	
	(1)	(2)	(3)	(4)	(5)	(6)
Highway Rays at time t	-0.038	-0.054***	-0.089		-0.073	
	(0.024)	(0.019)	(0.12)		(0.10)	
Railroad Rays at time t				-0.28**		-0.18***
				(0.11)		(0.071)
Highway Ring Outside CC	0.055	-0.20**	-0.76*	-0.80***	-0.54*	-0.46**
indicator at time t	(0.099)	(0.086)	(0.42)	(0.28)	(0.31)	(0.22)
Log Central City Area	-0.11***	-0.072***	0.029	-0.00036	-0.041	-0.050
	(0.024)	(0.018)	(0.075)	(0.067)	(0.046)	(0.043)
Log Prefecture Area	0.038	0.030**	-0.27**	-0.32***	-0.19**	-0.21***
	(0.025)	(0.013)	(0.14)	(0.10)	(0.084)	(0.064)
Log(1990 Agric. Hukou Pop	0.073***	0.067***	0.36***	0.35***	0.21**	0.19***
Outside Central City)	(0.026)	(0.024)	(0.10)	(0.089)	(0.098)	(0.064)
Log(1992 Prefecture Lights)	0.034	0.011	-0.036	0.059	0.047	0.097*
	(0.026)	(0.016)	(0.11)	(0.093)	(0.072)	(0.054)
∆ log(Prefecture Population)	0.79***	0.95***	2.26***	1.77***	0.69*	0.28
	(0.087)	(0.11)	(0.86)	(0.66)	(0.36)	(0.21)
∆ log(Prefecture Lights)	0.092**	0.079**	0.25	0.094	0.25	0.15
1992-20xx	(0.039)	(0.038)	(0.23)	(0.30)	(0.16)	(0.18)
provincial capital indicator	0.14	0.13**	-0.38*	-0.34	0.046	0.057
	(0.088)	(0.053)	(0.22)	(0.25)	(0.14)	(0.14)
Constant	-0.65*	-0.58*	-0.72	-0.40	0.46	0.73
	(0.36)	(0.35)	(1.68)	(1.54)	(1.21)	(0.95)
Observations	210	257	187	187	205	205
First stage F	4.66	8.61	9.20	9.92	5.01	5.63

Notes: Year t as indicated in variable names at left is the end year of the dependent variable listed at the top of each column. Road and rail network measures in 1962 instrument for these measures in later years. Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

Table 8. Effects of Public Transport and Waterways

	∆ln(CC Pop) 1990-2010 (1)	∆ln(CC Ind. GDP) 1990-2005 (2)	∆ln(CC GDP) 1990-2005 (3)
Highway rays in 2010	-0.039*		
	(0.022)		
Log buses & trolleys 2008 in 2005 central city	0.028*		
	(0.016)		
Railroad Rays in 2005		-0.26**	-0.16**
		(0.11)	(0.066)
River & Canal Rays		0.011	0.020
		(0.023)	(0.015)
Log Central City Area	-0.12***	0.11*	0.017
	(0.019)	(0.068)	(0.047)
Log Prefecture Area	0.046	-0.31***	-0.20***
	(0.028)	(0.11)	(0.071)
Log(1990 Agric. Hukou Pop Outside Central City)	0.067**	0.30***	0.16**
	(0.029)	(0.11)	(0.068)
Log(1992 Prefecture Lights)	0.021	0.057	0.096
	(0.031)	(0.11)	(0.064)
∆ log(Prefecture Population) 1990-2000 or 1990-2010	0.76***	1.37**	0.33*
	(0.090)	(0.69)	(0.19)
∆ log(Prefecture Lights) 1992-20xx	0.095**	0.14	0.17
	(0.041)	(0.28)	(0.17)
Provincial Capital Indicator	0.10	-0.33	0.00033
	(0.083)	(0.21)	(0.12)
Constant	-0.61	-0.85	0.39
	(0.38)	(1.64)	(1.04)
N	208	187	205
First stage F	28.0	44.2	67.0

Notes: Standard errors in parentheses are clustered by province. *** p<0.01, ** p<0.05, * p<0.1

Table 9: Robustness

	∆ln(CC Pop) 1990-2010 (1)	∆ln(CC Pop) 1990-2000 (2)	∆ln(CC Ind GDP) 1990-2005 (3)	∆ln(CC GDP) 1990-2005 (4)
Panel A: Instrumenting for Prefecture Population Growth				
Highway Rays in 2010 or 1999	-0.033	-0.042***		
	(0.034)	(0.015)		
Railway Rays in 2005			-0.25***	-0.14**
			(0.094)	(0.057)
N	210	257	187	205
First stage F	2.49	8.63	8.01	2.65
Panel B: Placebo Regressions Using Outcomes 1982-1990				
Highway Rays in 2010	-0.017			
	(0.04)			
Highway Rays in 1999		-0.012		
		(0.028)		
N	237	237		
First stage F	7.28	12.6		
Panel C: Heterogeneous Effects by Region				
Highway Rays in 2010 or 1999	-0.060*	-0.049***		
	(0.032)	(0.015)		
Highway Rays X Middle or West	0.026	0.0042		
	(0.039)	(0.024)		
Railroad Rays in 2005			-0.45***	-0.22***
			(0.12)	(0.086)
Railroad Rays X Middle or West			0.30*	0.095
			(0.17)	(0.11)
N	210	257	187	205
First stage F	11.5	9.22	12.8	17.9

Notes: All regressions in Panel A additionally include the same non-transport control variables as in Table 4 Column 2 or 4, or Table 6 Column 2 or 5 except prefecture lights levels and growth. Regressions in Panel A use the aggregate central city population within 500 km of each central city as an instrument for prefecture population growth. Regressions in Panel B use 1982-1990 central city population growth as the outcome and control for the same variables as in Table 4 Column 2 except prefecture lights levels and growth, prefecture population growth and 1990 prefecture agricultural population. Instead, log 1982-1990 prefecture population growth and log 1982 prefecture population are included as controls. Regressions in Panel C use the same specifications as in Table 4 Column 2 or 4, or Table 6 Column 2 or 5 but additionally include a middle/west region dummy variable. As in Tables 4 and 6, 1962 transport infrastructure instruments for transport infrastructure variables in all regressions.

Table A1: Summary Statistics

	Sample of 210 1990-2010				Sample of 257 1990-2000			
	Mean	Stdev	Min	Max	Mean	Stdev	Min	Max
Panel A: Transport Measures and Instruments								
Highway Rays at End of Period	2.97	2.02	0	11	2.84	1.69	0	8
log(km of highways in prefecture)	5.86	0.72	3	7.63	5.96	0.69	1.60	7.93
Ring road indicator at End of Period	0.22	0.41	0	1	0.14	0.34	0	1
Railroad Rays at End of Period	1.78	1.23	0	5	1.64	1.39	0	6
log(km of railroad in pref outside cc)	4.72	1.05	-2	6.71	4.70	0.83	2	6.35
1962 Highway Rays	1.94	1.24	0	6	1.87	1.26	0	6
1962 log (km of highways in pref)	5.55	0.87	0.00	7.42	5.58	0.85	0.00	7.42
1962 Ring Road Indicator	0.03	0.18	0	1	0.05	0.23	0	1
1962 Railroad Rays	1.01	1.18	0	4	1.08	1.16	0	4
1962 log(km of highways in pref)	2.70	2.19	0	6.36	2.83	2.17	0	6.36
Panel B: Dependent Variables								
∆log(Central city population)	0.40	0.30	-0.25	1.42	0.23	0.21	-0.08	1.48
∆log(Central city GDP)	1.83	0.45	0.47	3.00	1.81	0.44	0.47	3.00
∆log(Central city industrial GDP)	1.75	0.65	-0.84	3.86	1.74	0.65	-0.84	3.86
∆log(central city lights)	0.63	0.41	-0.26	2.58	0.60	0.41	-0.26	2.58
Panel C: Control Variables								
Log Central City Area	7.15	0.95	4.63	9.88	7.10	0.95	4.63	9.91
Log Prefecture Area	9.31	0.75	6.95	12.03	9.31	0.74	6.95	12.03
Log(1990 Agric Hukou Pop Outside CC)	14.50	0.85	12.03	16.96	14.50	0.83	12.03	16.96
Log(1992 Prefecture Lights)	9.61	0.94	6.88	11.97	9.64	0.93	6.88	11.97
∆log(Prefecture Population)	0.14	0.21	-0.17	1.83	0.09	0.12	-0.10	1.44
provincial capital indicator	0.11	0.32	0	1	0.10	0.30	0	1
log(precipitation)	6.84	0.52	4.47	7.80	6.81	0.52	4.47	7.80
central city elevation range	827	646	15	4129	794	614	15	4129
prefecture elevation range	1598	1334	34	8837	1575	1362	26	8837
log(distance to coast)	5.32	1.86	-5.38	7.43	5.25	1.84	-5.38	7.43
middle/west region indicator	0.61	0.49	0	1	0.58	0.50	0	1

Notes: The two GDP outcome measures reported in Panel B are for the 1990-2005 time period on both sides of the table and reflect fewer observations than for other reported variables. For ∆log(Central city GDP) there are 185 observations in the restricted sample and 229 observations in the broader sample. For ∆log(Central city industrial GDP) there are 165 and 207 observations in each respective sample. ∆log(Central city lights) is reported for the 1992 to 2005 period.

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