Railways, divergence, and structural change in 19th century England and Wales[1]

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Abstract

Railways transformed inland transport during the nineteenth century. In this paper, we study how railways led to local population change and divergence in England and Wales as it underwent dramatic urbanization. We make use of detailed data on railway stations, population, and occupational structure in more than 9000 spatial units. A network of least cost paths based on major towns and the length of the 1851 rail network is also created to address endogeneity. Our instrumental variable estimates show that having a railway station in a locality by 1851 led to significantly higher population growth from 1851 to 1891 and shifted the male occupational structure out of agriculture. Moreover, we estimate that having stations increased population growth more if localities had greater initial population density and for those 3 to 15 km from stations, they had less growth compared to localities more distant from stations. Overall, we find that railways reinforced the population hierarchy of the early nineteenth century and contributed to further spatial divergence. Their implications for the geographic distribution of population were large.

Keywords: Urbanization, railways, transport, reorganization, divergence

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1. Introduction

Britain's urbanization was exceptional during the nineteenth century. Between 1800 and 1900 the percentage of its population living in cities of 5000 or more increased from 19 to 67. In the whole of Europe, the urbanization rate increased far less from 11 to 30 between 1800 and 1900 (Bairoch and Goertz 1986). Britain's urbanization process was remarkable in another respect. Between 1850 and 1900 its urban areas grew dramatically, but rural areas experienced little growth. This was not true elsewhere in the world. For example, population growth was more balanced between urban and rural in much of continental Europe during the late nineteenth century (see Cameron 2003, p. 193).

In this paper we study how railways contributed to population change and spatial divergence in a key part of the British economy, England and Wales. We use theories on how transport improvements affect the spatial distribution of economies and emphasize agglomeration. Our starting point is that commercial and industrial firms would have had an incentive to locate near railway stations because the cheapest, high speed transport network could be easily accessed there. That implies that population should increase near railway stations because of greater employment opportunities. However, growth may not be uniform across locations which get stations. New Economic Geography (NEG) models featuring agglomeration imply that population and production will concentrate more in space when transport costs decline (Fujita, Krugman, and Venables 1999, Fujita and Thisse 2002, Lafourcade and Thisse 2011). This would suggest that when more densely populated areas get a railway station, their resulting population growth will be larger than when less densely populated areas get a station. Thus, railways could reinforce the existing population hierarchy and contribute to further spatial divergence. Theory suggests other economic changes could occur. Near stations accessible land has more demand, land rents rise, and less value-added activities are expelled to the periphery. This implies the occupational structure should move out of agriculture near stations and into either manufacturing or services.

We use a uniquely detailed and highly granular dataset of 9,489 spatial 'units' constructed from parishes, townships, and hamlets reported in the British Census.[7] We observe populations in every decennial census year from 1801 to 1891 and male occupational shares in agriculture, secondary, and tertiary in 1851 and 1881. We also incorporate highly accurate GIS data on railway lines and stations in each census year, geographic characteristics, like coastline and coal, and pre-rail infrastructure networks like turnpike roads, ports, and inland waterways.

The empirical analysis estimates how being near a railway station in the mid-nineteenth century affected local population growth and changes in occupational structure over the following decades. Our baseline specification studies population change from 1851 to 1891 and uses an indicator for having a station within a unit's boundary by 1851 as the main railway variable. Endogeneity is a major challenge, especially as English and Welsh railways were built and owned by private companies pursuing profits. As a solution, we construct a network of least cost paths (LCP) based on the length of the 1851 railway network and locations of large towns, serving as nodes in the LCP network. The main instrumental variable is an indicator for having the LCP in a unit. It is a strong predictor for having a station by 1851 since it captures favorable railway routes and stations were very dense along lines. The exclusion restriction is likely to be satisfied if the sample excludes units near the nodes, and we also have a rich set of controls for the potential confounding factors.

The preferred estimates imply that having an 1851 station caused unit population to grow by an additional 0.87% per year from 1851 to 1891. This effect is large, implying railways had a major impact on the population distribution in England and Wales. Using the same methods, we also estimate that having a station by 1851 led to a 0.121 *decrease* in the share of agricultural occupations between 1851 and 1881 and a 0.063 *increase* in the share of secondary occupations. Both effects represent a c. 35% change relative to each sector's average occupational share in 1851, which again implies a large impact.

One of our main extensions examine how railways reinforced the population hierarchy of the early nineteenth century and contributed to further divergence in the spirit of NEG models.

[7] Unfortunately, our population data do not include Scotland or Ireland, and thus we cannot study the whole UK.

We find that having stations increased population growth significantly more when units had greater log population density in 1801. Moreover, station growth effects were close to zero for units in the bottom six deciles of the 1801 population distribution.

Another related extension estimates population displacement based on distance to station. Building on NEG models, being very close to stations offer the advantage of much reduced transport costs and the resulting agglomeration, while due to the dispersion effect being far away could provide protection from competition and help maintain population. However, the effect for locations in-between is ambiguous and could even lead to relative population decline. We estimate that being less than 3 km from 1851 stations led to significantly higher population growth, while being 3 to 15 km led to significantly lower population growth, both compared to units more than 20 km from stations. Therefore, these estimates suggest railways altered the spatial equilibrium, effectively hollowing out the population in areas that had no obvious benefits from agglomeration or dispersion.

We also quantify the distributional impact of railways using a thought experiment. Specifically, we estimate how the observed 1891 population total in England and Wales would have been distributed differently across units assuming none had railway stations by 1851. Special attention is given to the share of population residing in the top 5% of spatial units in terms of population size, which includes nearly all urban areas. The data show that the population share in the top 5% was 0.554 in 1851 and 0.676 in 1891. In our most conservative specification, we estimate that the population share in the top 5% would have increased to 0.624 in 1891 if no units had railways in 1851, or just over half as much as the observed growth rate. Therefore, without railways significantly more of the population would have lived in rural rather than urban areas.

Our results contribute to a large literature on railways and the English and Welsh economy. Several studies point to the importance of railways in affecting local populations.[8] Among the quantitative studies there is agreement that getting railway stations was associated with

[8] See Simmons (1986), Gourvish (1986), and Kellet (2012) for examples.

increased population density.[9] However, the causal effects of getting stations in England and Wales have not been established. We address endogeneity by constructing a novel network of LCPs. Through heterogenous effects, we also estimate how railways fostered spatial divergence in this economy , which despite its remarkable features is relatively under-studied from a quantitative or theoretical approach.[10] Our research also complements the approach taken by Heblich, Redding, and Sturm (2020), who use a quantitative urban model to show railways had a large impact on London's population. We show urban areas throughout England and Wales generally gained from railways.

We also make three contributions to a large literature studying railways, population, and economic change generally.[11] First, with few exceptions most studies use counties, districts, or cities as their spatial unit. We use small-scale spatial units, approximately at the village or town-level. Our study also introduces a richer set of geographic variables, like coal endowments, and a richer set of pre-railway infrastructures like roads and ports. Second, in constructing LCPs as instruments, most studies use straight lines to connect network nodes, however these are less accurate for small-scale spatial data. We use information on historical costs to create non-linear LCPs that incorporate gradients in the landscape.[12] Third, several studies analyze the effects on firms and factories, but few examine occupational change, one of the key transformations in economic development.[13] We estimate railways effects on changes in male agricultural, secondary, and tertiary occupations.

How do our findings specifically relate to other historical studies on railways? One of the few to analyze finely grained spatial population data is Buchel and Kyburz (2020), who study municipalities in Switzerland. Employing a similar identification framework, these authors show that having a station increased annual population growth by 0.6%. Buchel and Kyburz also find evidence for population displacement 2 to 8 km from stations. By comparison, we find that in

[9] See Gregory and Martí Henneberg (2010), Casson (2013), Casson et. al. (2013), Alvarez-Palau et. al. (2013)
[10] See Hanlon (2020) for an exception.
[11] See Tang (2014), Hornung (2015), Berger and Enflo (2017), Atack, Bateman, Haines, and Margo (2010), Donaldson and Hornbeck (2016), Hodgson (2018), Jedwab, Kerby, and Moradi (2015), and Donaldson (2018).
[12] Berger (2019) also uses slope and geographic impediments to create the LCP.
[13] Hornung (2015) studies number and size of firms, Attack, Haines, and Margo (2008) study factories, Tang (2014) studies firm capitalization.

England and Wales having stations increased annual population growth by 0.87%, with displacement effects reaching 15 km from stations. We think the greater strength of agglomeration in the English and Welsh economy is likely to be one reason for the differences. Berger (2019) is the only study we know of that estimates how railways affected occupational change using a similar framework. Studying Sweden, Berger shows that having a trunk railway line in a parish increased its secondary occupational share. Paired with our finding, this suggests that in two different environments, railways contributed to greater employment in manufacturing.

Finally, our results contribute to a broader literature studying the effects of transport infrastructure, regional development, and structural change.[14] Most focus on local and regional outcomes in recent decades. Historical contexts complement this literature by demonstrating whether infrastructures create population gains as well as losses decades after they are built. The English historical context is particularly useful because it is closest to many current settings where infrastructure is built in developed economies with strong agglomeration.

The paper is organized as follows. Section 2 provides background, while 3, 4 and 5 introduce data and methods. Section 6 describes baseline results for population change, while 7 and 8 examine heterogeneity and displacement. Section 9 focuses on occupational change. Section 10 reports broader distributional impacts and 11 concludes.

2. Background on urbanization and railways

2.1 Urbanization and occupational change

England and Wales became highly urbanized in the nineteenth century. Decadal trends are reported in table 1 using the definition of urban as a census place with a population of 2500 or more (Law 1967). Up to the year 1841 urban growth exceeded rural growth, but both were positive. After 1841 urban growth remained high, while rural growth stagnated or declined. The greatest divergence between urban and rural occurred in the 1840s, 1860s, and 1870s. Many

[14] See Duranton and Puga (2014) for a survey. Also see Baum-Snow (2007), Duranton and Turner (2012), Michaels, Rauch, and Redding (2012), Faber (2014), Jedwab et. al. (2015), Garcia-Lopez et. al. (2015), Storeygard (2016), Ghani (2016), Holl (2016), Baum-Snow et. al. (2017, 2020), Gibbons et. al. (2019), and Pogonyi (et. al. 2019).

high growth areas were near the northern industrial centers of Manchester, Liverpool, and Leeds. The other high growth areas were near London, industrial Birmingham, and Cardiff in the South Wales coalfield. However, outside of these 'hotspots' there were few rapidly growing areas in Wales, the south, and east of England. Many villages and small towns had close to zero population growth after 1851.

Table 1: Decadal trends for urban and rural population in England and Wales, 1801-1891

	(1)	(2)	(3)	(4)	(5)	(6)
year	Urban Pop.	% of Urban in total pop.	Urban growth rate over previous decade	Rural Pop.	% of Rural in total pop.	Rural growth rate over previous decade
1801	3,009,260	33.8		5,883,276	66.2	
1811	3,722,025	36.6	23.7	6,442,231	63.4	9.5
1821	4,804,534	40.0	29.1	7,195,702	60.0	11.7
1831	6,153,230	44.3	28.1	7,743,567	55.7	7.6
1841	7,693,126	48.3	25.0	8,221,022	51.7	6.2
1851	9,687,927	54.0	25.9	8,239,682	46.0	0.2
1861	11,784,056	58.7	21.6	8,282,168	41.3	0.5
1871	14,802,100	65.2	25.6	7,910,166	34.8	-4.5
1881	18,180,117	70.0	22.8	7,794,322	30.0	-1.5
1891	21,601,012	74.5	18.8	7,401,513	25.5	-5.0
1901	25,371,849	78.0	17.5	7,155,994	22.0	-3.3

Sources and Notes: Law (1967, p. 130). Urban includes census places with at least 2500 people.

Differences in net migration were the primary reasons for varied population growth. Shaw-Taylor and Wrigley (2014) show that industrial counties grew by 38% more than the average county between 1801 and 1851, but the rate of natural increase (birth rate minus death rate) in industrial counties was only 6% higher, and therefore the net migration rate must have been higher there. The primacy of migration was even stronger near London where population growth was above average and the rate of natural increase below. Many individuals migrated within regions, but some moved greater distances. Better employment opportunities, especially outside of agriculture, appears to have been the key reason. [15]

[15] See Redford (1964), Boyer and Hatton (1997), Pooley and Turnbull (2005), Long (2005), Schurer and Day (2019), Day (2019).

There was an evolution in occupational structure related to increasing urbanization. The data are well established for males, especially in the nineteenth century. Shaw-Taylor and Wrigley (2014) report the share of males in agricultural occupations decreased from 0.27 in 1851 to 0.19 in 1871. The secondary share increased from 0.45 in 1851 to 0.46 in 1871. Tertiary increased the most from 0.23 to 0.28. The mild change in the secondary share obscures the fact that secondary employment was becoming more spatially concentrated in the late nineteenth century, especially near Manchester and Birmingham.

2.2 Development of railways

England and Wales were leaders in developing railway networks and locomotives. But it is important to recognize that this economy had an exceptionally well-developed transport network before.[16] By 1830 there were many good roads suitable for coaches and wagons and a large inland waterway network for barges. There was a thriving coastal shipping trade based on sailing vessels. Coastal ships could unload at hundreds of ports, 50 of which were major harbors with a total of 391 acres of wet dock space (Pope and Swann 1960). Along the coastline there were nearly 38 lighthouses with a visibility range of at least 15 miles.[17]

The pre-railway network was created and financed through local and private initiative. Government's role was to approve or reject proposals, assist land purchases, and regulate user-fees. Railways were developed using this system. Local business groups would introduce a bill in parliament that specified where the proposed railway would go and called for the creation of a company to finance construction and operate after. If approved, the company then collected subscription money from investors, and the construction process started.

The first fully steam-locomotive powered freight and passenger rail service opened in 1830 between Liverpool and Manchester. It was followed by several others in the mid-1830s. At this early stage, railway companies were mainly interested in connecting the largest urban centers,

[16] For a general summary see Bogart (2014).
[17] See Buxton-Dunn et. al. (2020).

because they had the most pre-existing passenger and freight services. By 1841, 9 of the 10 largest cities in England and Wales had railway connections, along with towns along their route.

The 'railway mania' of the mid-1840s saw the biggest expansion of the network. Between 1845 and 1847, 330 Railway Acts were passed to establish new railway companies or extend company networks. At the height of the mania the capital devoted to railways was more than twice as much as the British state spent on the military (Odlyzko, 2010). The mania was partly driven by the early railway company's strategy to maintain their position serving the large cities and by politicians wanting railway stations in their constituencies.[18]

The significance of the mania can be seen in the growth of railway lines. Between 1845 and 1851 railway km increased by 6,626, compared to an increase of 1,896 km in the previous 6 years (You and Shaw-Taylor 2020). By 1851 regional networks had formed around the medium and large towns in addition to connections via the trunk lines (see figure 1). Yet there were still some regions that were under-served, most notably Wales and the southwest.

The rail network further expanded and was nearly 25,000 km in 1881, or twice its size in 1851. Railway lines were now in every region of England and Wales (see figure 2). Within these regions there were some towns and rural areas that were better served than others, but none was very far from a railway. The network continued to be owned and operated by private companies, but a process of consolidation left only 7 companies, each with a network greater than 1,000 km by 1910 (Crafts, Leunig, and Mulatu 2008).

Railways came to dominate most internal transport because they were superior in either speed or cost. Stagecoaches were displaced almost immediately when stations opened. Passenger miles increased at annual rates of 20% and 10% in the 1840s and 1850s. The growth rate of passenger miles fell to less than 5% by the 1860s, reflecting a rate of increase closer to GDP growth (Hawke 1970, p. 50).[19] Inland waterways, like canals, offered some competition as barges charged similar freight rates, but they were slower and eventually lost traffic (Maw

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[18] For the literature on the railway mania see Casson (2009), Odlyzko (2010), Campbell and Turner (2012, 2015), Esteves and Geisler Mesevage (2017).

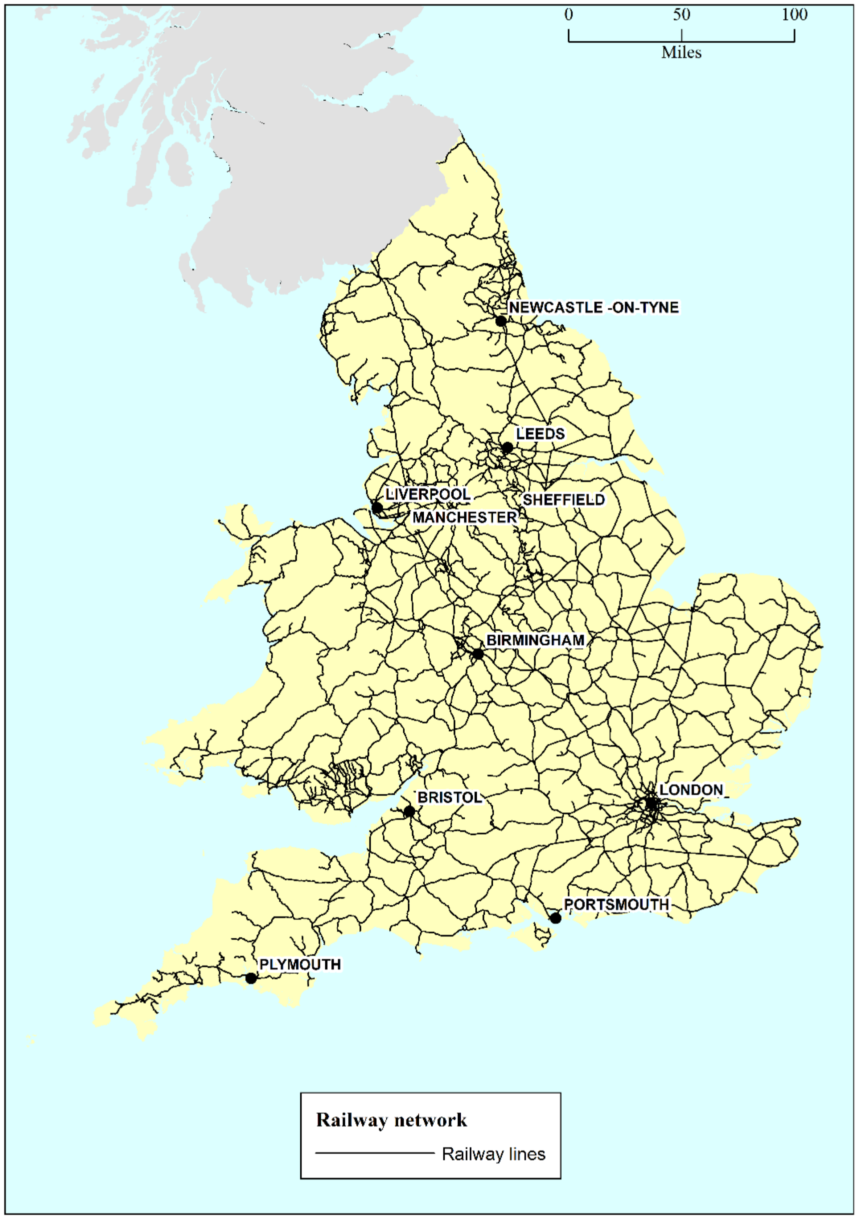
[19] Another revealing statistic is that there were 0.65 railway journey per head of population in 1841; 20 in 1881 and 32 in 1911. See Mitchell, *British Historical Statistics*, pp. 545-7.

2013). Railways managed to compete with coastal shipping, despite low shipping rates. One revealing statistic is that railways accounted for only 10% of the coal imported into London in 1851. The rest came by coast. But in 1870 railways accounted for 55% of the coal imported to London (Hawke 1970). Improvements to steamships led to a lower railway share by 1901, but they remained an important shipper of coal in London and most towns (Armstrong 2009).

Figure 1. The railway network in 1851

Source: Shaw-Taylor and You (2020).

Figure 2. The railway network in 1881



Source: Shaw-Taylor and You (2020).

In our analysis one crucial issue relates to the routing of lines and placement of stations. The main consideration for lines built in the 1830s and 40s was to connect large towns by the most direct and level route to save construction and operating costs (Simmons 1986, pp. 169-171). Land acquisition costs were another consideration and when railways approached large towns, they sometimes avoided built-up areas (Kellet 2012). When placing stations along the line, railway companies balanced the economic potential in the surrounding area against land acquisition costs (Casson 2009, Odlyzko 2010). In urban areas, which served as the terminus, stations were placed as close to the center as possible, sometimes in poor neighborhoods to save on land costs (Kellet 2012). In rural areas it was expected that individuals would travel to stations and were often placed at road junctions or near coaching inns to collect traffic.[20]

3. Data

While previous works establish the broad population trends as seen in table 1, our analysis uses much more spatially detailed data based on British censuses available every decade starting in 1801. Individuals are counted at the smallest place where they lived, usually the parish or township. The population counts have been digitized for each 'census year' from 1801 to 1911. Wrigley and Satchell (2011) performed the initial digitization and linking across time, which was carried forward by the Integrated Census Microdata project or I-CeM (Schurer and Higgs 2014). Male occupational shares for agriculture, secondary, and tertiary sectors have also been digitized at the smallest census place from 1851 to 1911 by I-CeM.[21] Currently, 1851 and 1881 provide the best and most consistent occupational data for our analysis.

To address boundary changes over time, we have created 9,764 consistent spatial 'units' between 1801 and 1891 linked with census population and male occupation data. Appendix A.1 provides a detailed description. Our sample size becomes 9,489 after excluding units that have missing variables. Note that spatial units in our data are contained within 55 counties, which were an important administrative unit of local government. The exception are units associated with metropolitan London, which we treat as four 'counties,' including south, west, east, and central London.

[20] For example, the Harrow & Wealdstone station, opened by the London and Birmingham railway in 1837. Harrow had a small population in 1831 and would not have generated much traffic in 1837. According to its residents, Harrow was not a commuter stop but rather a link between London and the Midlands (Bolton, King, Wyld and Yaxley 1971). The station was not even placed in Harrow town, but instead at a nearby road crossing.
[21] Mining and fishing occupations are available in I-CeM but excluded as outcome variables in our analysis since they are clearly tied to local resources. The unspecified occupation category is also omitted.

We also associate each unit with a center to calculate distance variables in GIS. The center corresponds to a town marketplace, if the unit had a town within its boundary at some point between 1600 and 1850.[22] If there was no town, the centroid is used, which arguably makes sense for a rural unit without a marketplace. Regardless, little error is introduced by using the town market or centroid since our units are only 15 square km on average.

Our railway data includes GIS shapefiles for lines and stations in every census year starting in 1831. They were created using accurate historical maps.[23] From this we create two measures for access to railway stations: (1) an indicator if there was an open station within the boundaries of the unit in a particular year and (2) the distance from the center of each unit to its nearest station in a particular year.[24]

In addition to railways we create a rich set of variables on 'first and second nature geography'. For each unit first natures include an indicator for being on exposed coalfields, an indicator for being on the coast, average elevation and slope, the standard deviation of slope, rainfall, temperature, wheat suitability, latitude, longitude, and the share of land in 10 different soil types. Coastal is identified using an intersection of the seacoast with unit boundaries. Elevation and slope are calculated in GIS (see appendix A.2). The wheat suitability index and annual rainfall and temperature (both averaged from 1961 to 1990) were derived from FAO.[25] The soils data comes from Cranfield University.[26] Satchell and Shaw-Taylor (2013) identify

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[22] Satchell, Potter, Shaw-Taylor, Bogart (2017) provide a dataset on 1746 towns and their centers, which are based on marketplace, or other markers, like parish, if there was no marketplace. These are treated as points in GIS. We should stress that some towns in this data were very small and did not have most urban characteristics, therefore they are best described as 'candidate towns.' 746 of our units have at least one candidate town point in their boundary. If there is a single candidate town, its center is chosen, otherwise the town center with the largest 1801 population is used.

[23] They are derived from derived from a railway atlas by Cobb (2005). See Martí-Henneberg, Satchell, You, Shaw-Taylor, and Wrigley (2017) created the GIS of England, Wales and Scotland railway stations 1807-1994.

[24] Note it was rare for stations to close in the nineteenth century (Simmons 1986, p. 325). But it did happen, which means a few units get more distant from stations.

[25] See the Global Agro-Ecological Zones data at http://www.fao.org/nr/gaez/about-data-portal/agricultural-suitability-and-potential-yields/en/. We selected low input and rain fed for wheat suitability.

[26] Soils data (c) Cranfield University (NSRI) 2017 used with permission. The 10 soil categories are based on Avery (1980) and Clayden and Hollis (1985). They include (1) Raw gley, (2) Lithomorphic, (3) Pelosols, (4) Brown, (5) Podzolic, (6) Surface-water gley, (7), Ground-water gley, (8) Man made, (9) peat soils, and (10) other. See http://www.landis.org.uk/downloads/classification.cfm#Clayden_and_Hollis. Brown soil is the most common and serves as the comparison group in the regression analysis.

those areas with exposed coal bearing strata (i.e. not overlain by younger rocks). We use exposed coalfields as they were more easily exploited compared to concealed coal (see appendix A.3). Variables for second-nature geography include distance to the nearest top ten largest cities in 1801[27], log population density in 1801, distance to turnpike roads in 1800, distance to inland waterways, including canals and rivers, in 1800, and distance to ports in 1780. The last three are calculated using detailed pre-rail infrastructure data.[28]

Summary statistics for the main variables in our analysis are shown in table 2. Statistics for first and second nature variables are in appendix A.4 table A.4.1. There are several features to note. Despite the total English and Welsh population increase between 1851 and 1891, the average difference in log 1891 and 1851 population was negative because most rural units were declining in population consistent with table 1. In the longer time-span, from 1821 to 1891, the total population change was positive and the unit average log difference was positive. The average difference in the 1881 and 1851 share of male secondary occupations was slightly negative, despite the national trend to slightly higher secondary shares. This suggests that, like population, secondary occupations became more concentrated. Turning to railways, station access increased and distance to nearest station fell with time. For example, 10.7% of units had at least one station open in 1851, rising to 27.6% in 1891.

Table 2: Summary statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
Panel A: Population and occupational change variables					
Diff. Ln. 1891 and 1851 population	9,489	-0.023	0.468	-3.388	4.599
Diff. Ln. 1891 and 1821 population	9,489	0.146	0.609	-3.174	5.655
Diff. 1881 and 1851 male agriculture share	9,488	-0.067	0.153	-0.820	0.928
Diff. 1881 and 1851 male secondary share	9,489	-0.007	0.072	-0.707	0.639

[27] The ten largest cities are London, Manchester, Birmingham, Liverpool, Leeds, Bristol, Newcastle, Plymouth, Portsmouth, and Sheffield (near Nottingham)

[28] Rosevear, Satchell, Bogart, Shaw Taylor, Aidt, and Leon (2017) created a GIS of turnpike roads, Satchell, Shaw-Taylor, and Wrigley (2017) created a GIS of inland waterways, and Alvarez-Palau, Dunn, Bogart, Satchell, Shaw-Taylor (2017) created a GIS of ports.

Diff. 1881 and 1851 male tertiary share	9,489	0.045	0.092	-0.700	0.806
Panel B: Rail station variables & instruments					
At least one Station in unit by 1851	9,489	0.107	0.309	0	1
At least one Station in unit by 1891	9,489	0.276	0.447	0	1
Distance to nearest station in 1851	9,488	10.45	11.06	0.021	73.12
Distance to nearest station in 1891	9,489	3.486	2.686	0.023	26.00
Has LCP in unit	9,489	0.229	0.421	0	1
Has stage coaching inn by 1802	9,489	0.079	0.269	0	1
Has LCP & stage coaching inn by 1802	9,489	0.031	0.174	0	1

Sources: see text.

As a preview of our main result, a two-sided t-test shows that the difference in log 1891 and 1851 population is 0.433 higher for units with a rail station open by 1851 versus all other units (p-value 0.00). Thus, units with stations in 1851 had 54% higher population by 1891 than units without stations on average. The difference in the share of secondary employment increased by an additional 0.0081 for units with an 1851 rail station, and the share of agricultural employment decreased by additional 0.0316. However, endogeneity is clearly a concern in this setting. Our methodology will address this using instrumental variables.

4. Methodology

We employ the commonly used 'changes-on-levels' specification in urban economics. As explained by Duranton and Puga (2014), it analyzes infrastructure levels and their effects on future population changes assuming a gradual adjustment process. Our baseline specification is a cross-section log population change equation shown in (1)

$$\Delta Lnpop_{i,1891-1851} = \beta * Station1851_i + \gamma \cdot x_{i,j} + \varepsilon_i \qquad (1)$$

where the subscript i denotes the unit and j denotes the county containing the unit. The dependent variable $\Delta Lnpop_{i,1891-1851}$ is the difference in log 1891 and log 1851 population for unit i. The main variable, $station1851_i$, is an indicator that equals 1 if unit i has at least one open station within its boundary by 1851 and zero otherwise. In other words, the control group is all units with no open station in 1851. The idea is that rail transport services were so much cheaper and faster that some industrial and commercial firms had to be near stations to be competitive. Consequently, workers were likely to move and live near stations out of considerations for employment opportunities and commuting cost. Hence, having a railway station in a unit is predicted to cause its population to grow more than in units without railway access all else equal.

The control vector $x_{i,j}$ always includes unit first nature characteristics and the natural log of unit population density in 1851, 1841, and 1831 to capture effects of initial population and prior trends. In preferred specifications, unit's second nature characteristics and 59 county fixed effects are added as controls. The standard errors are always clustered on counties.[29]

The instrumental variable for $station1851_i$ is an indicator for having a least cost path (LCP) pass through the unit. Another is an indicator for having coaching inns by 1802 interacted with the LCP indicator. They are explained in detail in the next section.

We focus on the effect of stations in the year 1851 for several reasons. First, we want to be comparable to previous studies, which estimate effects of 'first-wave' rail construction on population change over the following 20 to 50 years.[30] Second, the railway mania took place in the mid-1840s, and it led to the opening of the main trunk lines shortly after. Therefore, having a station in 1851 provides a measure of access to a new network connecting most large towns in the early nineteenth century. A potential concern is that the effects of railway building after 1851 also affected growth. We will check whether omitting units getting stations after 1851 affects the baseline estimates. Also, the impact of getting stations later is examined separately.

As robustness we also use a 'changes-on-changes' specification shown in (2)

$$\Delta Lnpop_{i,1891-1821} = \beta * \Delta\, station_{i,1891-1821} + \pi \cdot x_{i,j} + \varepsilon_i \qquad (2)$$

where the dependent variable is the difference in log 1891 and log 1821 unit population. On the right-hand side $\Delta\, station_{i,1891-1821}$ is the difference in the indicator for having stations in

[29] There is little difference if we correct standard errors for spatial correlation using Conley (2010), Hsiang (2010).
[30] For example, Hornung (2015) estimates the effect of having railway stations open by 1848 on city population growth from 1849 to 1871 in Prussia. Berger and Enflo (2017) use a panel version of (1) to estimate the effects of having a railway line in 1870 on parish population growth from 1850 to 1900 in Sweden.

1891 and 1821. Since the station indicator is zero in 1821 for all units, $\Delta\, station_{i,1891-1821}$ is simply an indicator equal to 1 if a unit had an open station in 1891. The variable $x_{i,j}$ includes the same controls as (1).

One key extension estimates heterogenous effects of station access drawing on insights from NEG models.[31] When railways stations arrived in low population density units, they brought increased competition from more productive units. The greater competition resulted in employment losses and offset some of the positive net-migration effects from getting stations. The prediction is that station effects on population growth will be smaller, and perhaps zero, for low density units. We estimate these heterogenous effects by initial conditions using an interaction between $Station1851_i$ and several variables capturing 1801 population density.

Another related extension focuses on local displacement. Being very close to stations offers the obvious advantage of much reduced transport costs and the resulting concentration of economic resources, while being far away could provide protection from competition and help retaining economic resources. Introducing stations could alter the balance between these agglomeration and dispersion effects. The prediction is that beyond some station distance threshold, population growth could be lower in units closer to stations than those far from stations. The size and range of the 'displacement zone' is estimated with a modified version of equation (1) using station distance-bins.

Finally, we also study occupational change using the difference in 1881 and 1851 male agricultural, secondary, or tertiary shares as the dependent variables in equation (1). The idea is that near stations accessible land had more demand, land rents increased, and less value-added activities are expelled to the periphery. Therefore, the occupational share in agriculture is expected to decline in units with 1851 stations. If so, the occupational shares were likely to rise in secondary, tertiary, or both.[32] It will depend on which sector benefits more from density.

5. The Least cost path network

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[31] See Fujita, Krugman, and Venables (1999), Fujita and Thisse (2002), and Lafourcade and Thisse (2011).

[32] Recall we exclude mining, fishing, and unspecified occupational shares. So technically secondary and tertiary shares need not rise with lower agricultural shares, as they could rise in mining, fishing, or unspecified shares.

5.1 LCP network construction

Our instrumental variable builds on the inconsequential places approach. One early application is Chandra and Thompson (2008).[33] The key idea, applied to our setting, is that some spatial units were selected by railway builders to get stations because of their existing traffic volumes and/or their potential to generate passengers and freight traffic. They are known as consequential places. Good examples for such units are large urban centers. There were also 'inconsequential' places receiving railway stations only because of their geography, which placed them on a cost-minimizing railway route connecting the consequential places. Being near the cost-minimizing route serves as the instrumental variable in this approach. The major challenges are to select consequential places and to create and select routes connecting them. We build on the literature to develop an approach which fits our setting.

Most studies select major or historic cities in the pre-railway era to serve as consequential places (e.g. Hornung 2015). We follow a similar approach as explained below. Supposing that two consequential places are to be connected, then what is the best route? The original approach is to use straight lines, following the notion that railway builders sought to minimize construction costs by choosing the shortest distance between important markets generating the traffic.[34] Subsequent studies use slope and geographic impediments to create LCPs (e.g. Faber 2014 and Berger 2019). We follow this latter approach and use slope and distance to create LCPs linking consequential places.

The next issue is how should a network of LCPs be constructed. Faber (2014) introduced minimum spanning tree algorithms, which identify the subset of LCPs that connect all consequential places on a single continuous network subject to global construction cost minimization. We use the total number of railway miles in 1851 as a global constraint, but we apply different criteria to select candidate LCPs based on the predicted amount of trade between consequential places. Also different, our LCP network can have routes within a few km

[33] Redding and Turner (2014) call this the 'inconsequential places' approach. Aside from Chandra and Thompson (2000), see Michaels (2008) and Lipscombe et. al. (2013) for early applications.
[34] Atack et. al. (2010) is an early application in the railways literature to use straight lines to connect places. It has also been used to study contemporary Chinese transport networks as in Banerjee, Duflo, and Qian (2020).

of one another. This corresponds well to an inefficient feature of British railways whose construction was carried out by private companies in an uncoordinated manner (see Casson 2009).

The first step in our approach is to select consequential places. We use 100 towns with a population greater than 5000 in 1801.[35] Their larger size meant they were likely to get at least one railway line connecting them with another town above 5000. But not all town pairs will be connected. A profit-seeking company would see little value in building a railway to connect distant towns of moderate size. A simple gravity equation is used to approximate the relative value of connecting town pairs i and j. $G_{ij} = (pop_i * pop_j)/dist_{ij}$, where $dist_{ij}$ is the straight line distance and pop_i is population. We ordered G_{ij} from largest to smallest and connect only those 'candidate' town pairs with a value greater than a threshold defined momentarily.

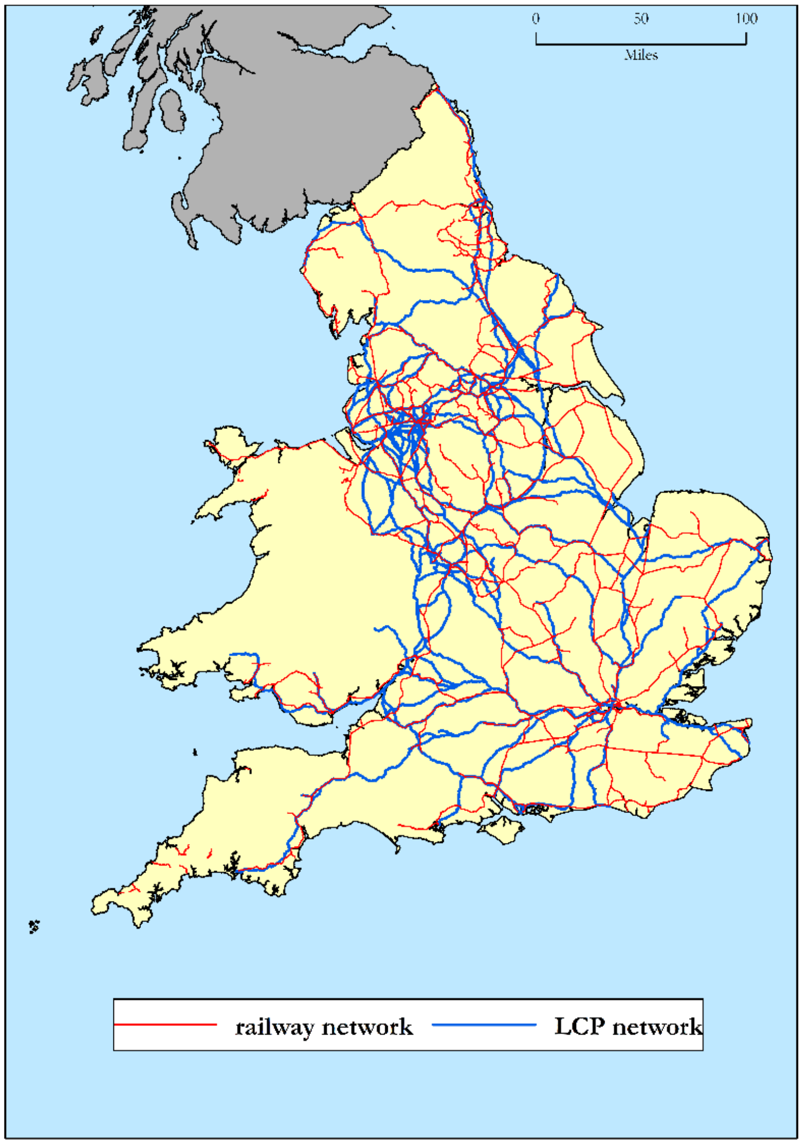
The second step is to identify LCPs connecting our list of candidate town-pairs. Railway companies were assumed to minimize the construction costs considering distance and elevation slope. We use construction cost data for railways in the 1830s and early 1840s and measure the distance of these lines and total elevation changes between the two main towns at the ends. The construction cost is then regressed on the distance and the elevation change (the details are in appendix A.5). Based on this analysis, we find a baseline construction cost per km when the slope is zero and for every 1% increase in slope the construction cost rises by three times the baseline (cost per km=1+3*slope%). This formula and GIS tools identify the LCP connecting each candidate town pair.

The third step is to identify which LCPs are included in the final LCP network. We start with the candidate town pair having the largest gravitational value G_{ij} and include its associated LCP. Second, we add the LCP associated with the candidate town pair having the second largest G_{ij}. If the two routes have overlapping sections, then those are combined. We continue in the same manner adding LCPs until the total mileage of LCP network equals that of the 1851 rail network. Below we call the GIS points representing the 100 large towns in 1801 the 'LCP nodes.' We emphasize that our approach does not depend on network effects or

[35] The town population data come from Law (1967) and Robson (2006) and were digitized by Bennet (2012).

competition between railway operators. It is purely based on identifying the cost minimizing routes to connect the most important markets as identified by the gravitational value G_{ij}.

Figure 3: The Least Cost Path (LCP) network and 1851 rail network compared



Sources: LCP network created by authors, see text.

Figure 3 shows our LCP network (blue) and the actual 1851 railway network (red). The overlap is close in many cases and there is a 0.323 correlation between an indicator variable for having railway lines pass through a unit in 1851 and an indicator for having the LCP pass, which serves as our instrument.[36] While our LCP network does not have its own stations, there is a 0.251 correlation between the indicators for having the LCP pass and for having stations by 1851. The reason behind this close correlation between LCP pass and stations is that stations were so numerous along railway lines in England and Wales. On average there was one station for every 5.9 km of railway line in 1851.

Another instrumental variable is used as a further extension. As railway companies often placed stations near nodes of the pre-existing network, we use an indicator for having a coaching inn in 1802. This comes from *Cary's New Itinerary*, which was a book for travelers identifying routes and inns to rest. There were 1,228 inns throughout England and Wales by 1802 and these have been digitized and linked to GIS.[37] In the extension, we add an interaction term for inns in 1802 with the LCP in a unit as an additional instrument in a robustness check (see table 2 for summary statistics).[38]

5.2 The Exclusion restriction

Our exclusion restriction requires that once we control for potential confounding factors, being in or near the LCP network does not influence a unit's population growth after 1851 except through having 1851 stations nearby. The inclusion of several control variables plays a key role here. Unit population density in 1851, 1841, and 1831 are correlated with population growth from 1851 and they are also correlated with having the LCP in a unit. Some first nature variables, like elevation slope, influence population growth and are also correlated with having the LCP. The same applies to some second nature variables, like distance to inland waterways in 1800. They followed some of the same routes captured in our LCP.[39] Waterways are also thought to be a contributor to the emergence of industrial cities like Manchester with exploding population size (Maw 2013).

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[36] Note that railway lines built after 1851 are close to the LCP too, but the overlap is weaker. For example, there is a 0.279 correlation between having a railway line in 1861 and having the LCP.

[37] We thank Alan Rosevear for digitizing coaching inns from Cary.

[38] We also tried an instrument for the length of LCP divided by land area. But once we condition on having the LCP, this variable did not predict having an 1851 station.

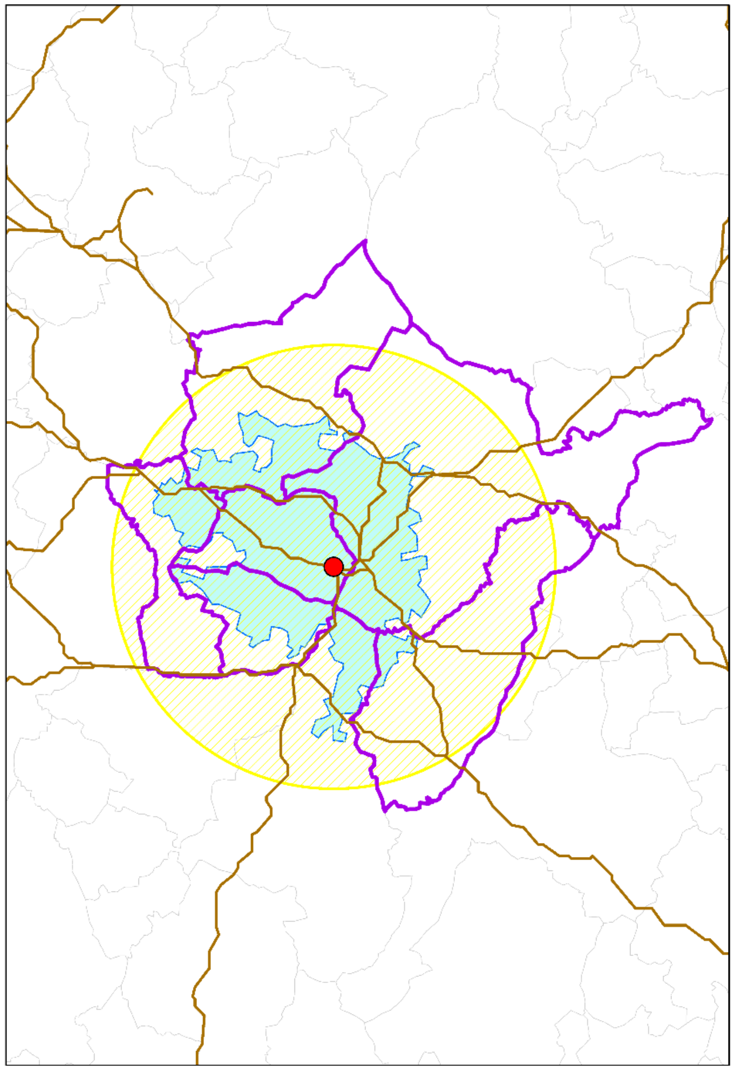
[39] The correlation between distance to 1800 inland waterways and the LCP is -0.188 (p-value 0.00). For comparison, the correlation between distance to 1851 station and distance to waterway is 0.360 (p-value 0.00).

Despite our rich set of controls, the IV exclusion restriction could still fail. One concern is that units containing the 100 LCP nodes are likely to have unobservable urban characteristics, such as better human capital and better exchange of ideas, that would predict growth independent of railways. A similar problem arises from including units in their immediate hinterland. Consider for example units that do not contain an LCP node, but whose center was only a few km away. As they were so close, they might have been part of the built-up area associated with the node and probably shared the same unobserved urban characteristics. Thus, to address this concern we exclude from our sample all units with LCP nodes and those in its hinterland which were effectively part of the urban economy of the node.

Our sample restriction is implemented in two ways. In our baseline, units whose center is less than 7 km from LCP nodes are dropped. We chose 7 km because nineteenth century maps suggest the built-up areas around the center of the largest nodes were less than 7 km. For example, Samuel Lewis' 'Plan of London, 1831' shows its built-up area extended farthest to the west around Hyde Park and was approximately 5.5 km from St. Paul's Cathedral, often considered the center of London. By 1841 London's western built-up area reached into Paddington around 6.5 km from St. Paul's. Of course, London was a special case, so as further illustration figure 4 shows a digitized version of the built-up area c.1891 around the node representing Birmingham, one of the largest industrial towns (light blue shaded area). The yellow line represents the 7 km boundary. The brown lines represent LCPs. The boundaries for the units excluded by their center being less than 7 km from Birmingham are shown in purple. The 7 km boundary works well in omitting units that likely shared the unobservable urban characteristics associated with Birmingham, which is our main concern related to the exclusion restriction. But for nodes with smaller built-up areas, it is likely that we have dropped units that probably did not have nodal urban characteristics. Moreover, our sample decreases by a non-trivial 12%.[40]

Figure 4: LCPs and excluded units less than 7 km from Birmingham and its built-up area in 1891

[40] Nevertheless, we still have observations in the top three deciles of 1801 population density in our restricted sample. For example, 5.1%, 9.7% and 10.3% of units are in the 10^{th}, 9^{th}, and 8^{th} deciles of 1801 population density.



Notes: The red dot represents Birmingham, a node in our LCP. Birmingham's built-up area c.1891 is shown in blue. The brown lines are LCPs. The yellow circle represents a distance of 7 km from the node. The purple lines are boundaries of units that are excluded based on their center being less than 7 km from node.

An alternative sample restriction drops any unit whose boundaries share any area with the built-up area around nodes (i.e. no overlap). As illustrated for Birmingham, we have outlines of the built-up area for all our nodes. [41] The advantage of this restriction is that we do not need to use the 7 km threshold to approximate the reach of urban characteristics. The

[41] The built-up parts of over 100 towns are digitized from the OS first revision 1:2500 or 1:10560 mapping (1891-1914). See Satchell et. al. (2017) 'Candidate towns' for a description of this data. Built up areas are not yet available for dates before 1891.

limitation is that the built-up area is created from maps after 1891 when railways already had impacts.[42] To preview our results, the IV coefficients are similar in the two restricted samples. However, having no sample restriction produces a larger—and less plausible— IV estimate.

6. Estimates for baseline specifications

6.1 Effect of 1851 stations

Ordinary least squares (OLS) and instrumental variable (IV) estimates for the effects of having stations by 1851 on the difference in log 1891 and log 1851 population are shown in the top panel of table 3. The bottom panel shows the first stage coefficient for having an LCP. The baseline sample omits units less than 7 km from nodes. The specifications in (1) and (2) are the most parsimonious in terms of controls, including first nature characteristics and log population density in 1851, 1841, and 1831. Specifications in (3) and (4) add second nature controls, while specifications in (5) and (6) further add county fixed effects. Our preferred IV specification is column (6) because second nature factors and county fixed effects address concerns about the exclusion restriction as discussed above. The IV estimate is 0.349.[43]

It is notable that IV estimates are larger than OLS across all specifications. There are at least two explanations. First, getting stations in 1851 was associated with units having 'worse' 1851 to 1891 growth prospects after accounting for other factors. We find this first explanation less believable given railways were built by private companies with profit maximization motives. Second, our IV estimate may be capturing a local average treatment effect, in which there was a larger impact of getting stations when a unit had an LCP. Why might this be so? The LCPs were more common in units already densely populated in the early nineteenth century.[44] Therefore, it is possible that the effect of getting a railways station because of the LCP is partly

[42] The built-up parts of over 100 towns are digitized from the OS first revision 1:2500 or 1:10560 mapping (1891-1914). See Satchell et. al. (2017) 'Candidate towns' for a description of this data. Built up areas are not yet available for dates before 1891.
[43] Note the Kleibergen-Paap F-stat is above 48, and so weak instruments in the first stage are not a concern.
[44] Having the LCP and 1801 population density are significantly correlated, even in samples that restrict units to be more than 7 km from LCP nodes.

capturing the heterogeneous effect of stations depending on 1801 population density. We will examine this argument more thoroughly in section 7.

Table 3: Estimates for effect of 1851 station on difference in log 1891 and log 1851 population

	Second stage for Δ1891,1851 Ln Pop					
	(1)	(2)	(3)	(4)	(5)	(6)
Estimator	OLS	IV	OLS	IV	OLS	IV
Station in unit by 1851	0.231***	0.956***	0.186***	0.581***	0.166***	0.349*
	(0.029)	(0.175)	(0.024)	(0.181)	(0.021)	(0.206)
County FEs?	N	N	N	N	Y	Y
Second Nature controls?	N	N	Y	Y	Y	Y
Kleibergen-Paap F stat		96.489		66.438		48.939
Observations	8,341	8,341	8,337	8,337	8,337	8,337
R-squared	0.192		0.238		0.304	

	First stage for Station in unit by 1851		
	(7)	(8)	(9)
	OLS	OLS	OLS
LCP in unit	0.100***	0.0831***	0.0737***
	(0.014)	(0.013)	(0.013)
County FE?	N	N	Y
Second Nature controls?	N	Y	Y
Observations	8,341	8,337	8,337
R-squared	0.188	0.200	0.216

Notes: Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include first nature variables and 1851, 1841, and 1831 ln pop density as controls. For definitions of first nature, second nature variables, and County FEs see text. All units less than 7 km from an LCP node are dropped.

Concerning magnitudes, our preferred IV station coefficient, 0.349, is equivalent to 0.75 standard deviations of the dependent variable. In annual growth terms, the coefficient implies an increase in population of 0.875% per year.[45] The effects of 1851 stations are also large relative to estimates for other variables. For example, having coal and being a coastal unit is estimated to increase the difference in log 1891 and log 1851 population by 0.171 and 0.168, respectively.[46] The coefficient on distance to the nearest top ten 1801 city is 1/124 of the IV station effect, meaning getting a railway station in 1851 was equivalent to moving a unit 124 km closer to a major city, or like moving a unit from the Midlands of England to near London.

[45] The total growth effect is 100*(exp(0.349)-1)%. Over 40 years this is equal to 0.875% growth in annual terms.

[46] The estimates for all variables are shown in the appendix table A.4.2. Here a brief summary is provided.

Table 4 shows IV estimates using different sample restrictions. Column (1) uses all units, including those with nodes. The IV estimate, 0.993, is very large. Column (2) excludes units less than 3 km from nodes and again the IV estimate is large. For reasons discussed earlier, we expect upwardly biased estimates in (1) and (2) as the samples have some units in the built-up area of nodes and thus have unobservable urban characteristics associated with higher growth.[47] Column (3) excludes units less than 5 km from nodes. The IV coefficient is not statistically different from our preferred estimate of 0.349 in table 3. This makes sense as the sample excludes more of the units sharing the unobservable characteristics with nodes when we extend the distance threshold. In column (4) units overlapping with the built-up area of nodes are excluded. The IV estimates are larger than our preferred IV estimate, although not statistically different.[48]

Table 4: IV estimates for the effect of 1851 stations under different sample restrictions

	(1) All units, i.e. no sample restriction	(2) Exclude if less than 3 km from LCP nodes	(3) Exclude if less than 5 km from LCP nodes	(4) Exclude if overlap with built up area of LCP nodes
Station by 1851	0.993***	0.733***	0.463***	0.500**
	(0.251)	(0.223)	(0.200)	(0.198)
County FEs?	Y	Y	Y	Y
Second Nature controls?	Y	Y	Y	Y
Kleibergen-Paap F	68.81	61.381	56.991	57.941
Observations	9,480	9,044	8,754	8,860

Notes: The dependent variable is Δ1891,1851 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include 1851, 1841, and 1831 ln pop density, first nature variables, second nature variables, and county fixed effects as controls.

Our main estimates are robust to using a combination of instruments. As noted earlier, we add a second instrument -- the LCP interacted with the indicator for having coaching inns by 1802. The additional instrument does have predictive power, helping to differentiate where

[47] Placebo tests, using pre-railway population growth from 1801 to 1831 as the outcome variable, provide additional evidence that unobservable factors are a concern in the un-restricted sample, or when units less than 3 km are excluded. See appendix A.7, table A.7.1, for more details.

[48] As additional evidence, appendix 7 reports placebo tests which show the LCP does not affect pre-railway population growth in the sample excluding units less than 7km from nodes and overlapping with built-up areas.

along the LCP network 1851 stations were built. Here the IV coefficient for stations is slightly smaller at 0.299 (s.e. 0.174) in our baseline restricted sample (See appendix table A.6.1).

Another robustness check uses propensity score matching with the 1851 station indicator as the treatment and the difference in log 1891 and log 1851 population as the outcome. The results are almost identical to our preferred IV estimates.[49]

The control group in our baseline specification includes units that did not have a station by 1851 but received their first station between 1852 and 1891. To see if this introduces a bias, we estimate our preferred specification in table 3 after dropping the 1,459 units that got their first station between 1852 and 1891. The IV coefficient on 1851 stations is 0.337 (s.e. 0.195), similar to the preferred IV specification.

In closing this section, it is worth pointing out the 'changes-on-changes' specification (equation 2) yields a similar conclusion to the 'changes on-levels' specification we have focused on thus far. Recall it gives an estimate for the change in population between 1821 and 1891 caused by the change in station access over the same 70-year period. To make the estimates comparable, the sample includes all units more than 7 km from an LCP node and the specification includes the full set of controls. The LCP indicator is the instrument for the change in station access. The IV coefficient for change in station access is 0.605 (s.e. 0.274, see appendix table A.6.2). It implies that having a railway station increased population by 0.867% per year between 1821 and 1891.[50] Notice this is nearly identical to the estimated increase in annual population growth implied by the preferred IV coefficient for 1851 stations in table 3.

6.2 Effects of stations opening at different dates

The impact of getting stations at different dates from 1851 to 1871 is worth exploring in more detail. On the one hand, it is possible that opening a station later yielded larger growth

[49] The simplest specification matches on a single variable: the log of 1801 population density. The matched sample is balanced and yields a statistically significant treatment effect of 0.323 (S.E. 0.029), which is very similar to our 0.349 IV estimate in table 4 column 2. Unfortunately, we were unable to achieve balanced matching on many co-variates. But, if we match on all second nature variables or selected first nature variables, the treatment effects are similar. These results are available upon request.

[50] Here we calculate the total growth as 100*(exp(0.605)-1)%. Over 80 years this is equal to 0.867%

effects because the network was more developed, and hence more connections could have been made. On the other hand, there could have been first mover advantages, implying opening a station later yielded smaller growth effects.

The effects of getting stations by 1851 versus later are estimated using specifications like table 3, except now average annual population growth is the dependent variable. In one specification, we estimate the effect of a station first opening in the ten-year period from 1852 to 1861 on annual growth from 1861 to 1881 along with a variable for whether units had an open station by 1851. Here the omitted group are units without stations by 1861. Note we add a control for log population density in 1861 and still control for the same in 1851, 1841, and 1831. Here we must use OLS estimates as our LCP network does not predict which units got stations at different dates. While OLS is biased, our assumption is that the nature and degree of the bias is likely to be the same for stations opening in 1851, 1861, and 1871. Therefore, we can compare OLS estimates for stations opening at different dates.

The results are shown in table 5. Column (1) reveals no difference in the estimated impact of having a station open by 1851 versus the first station opening between 1852 and 1861. Column (2) yields a similar conclusion using average annual growth from 1861 to 1891 as the dependent variable. Column (3) reports estimates to establish the relative effects of having the first station opening between 1862 and 1871. It also includes variables for having stations by 1851 and getting the first station between 1852 and 1861. Again, the annual growth effects of stations first opening by 1851, 1861, or 1871 are similar. Thus, there is no clear difference in the effects from opening stations late or early. One possible explanation is that first mover advantages and denser network advantages at a later stage balance each other out.

Table 5: OLS Estimates for effect of stations on annual population growth using different opening dates

	Ann. Pop. growth in % 1861-81 (1)	Ann. Pop. growth in % 1861-91 (2)	Ann. Pop. growth in % 1871-91 (3)
Station by 1851	0.454***	0.407***	0.417***
	(0.059)	(0.048)	(0.044)
First station opens 1852-61	0.431***	0.428***	0.388***
	(0.083)	(0.066)	(0.056)
First station opens 1862-71			0.417***

			(0.081)
County FEs?	Y	Y	Y
Second Nature controls?	Y	Y	Y
Control for 1861 pop. density	Y	Y	Y
Control for 1871 pop. density	N	N	Y
Observations	8,337	8,337	8,337
R-squared	0.247	0.307	0.299

Notes: Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include 1851, 1841, and 1831 ln pop density, first nature variables, second nature variables, and county fixed effects as controls. All units less than 7 km from an LCP node are dropped.

7. Heterogenous effects based on 1801 population

NEG models, featuring increasing returns, suggest that the population growth effects of getting railway stations should be greater if unit population density was initially high, even back to 1801. Such effects could also explain differences between OLS and IV as discussed earlier.

Column (1) in table 6 shows estimates for the baseline OLS after adding an interaction between 1851 station and log 1801 population density. Column (2) shows IV estimates using the LCP dummy interacted with the log of 1801 density as the second instrument, which is needed since there are now two endogenous variables involving stations. To interpret the IV coefficients in (2), we predict that at the median 1801 density having an 1851 station led to 0.25 higher difference in log 1891 and log 1851 population. At the lower 25th and higher 75th percentiles the increases were significantly different at 0.15 and 0.35.

An alternative specification uses an indicator variable for units below the 60th percentile of 1801 population density. Its interaction with stations in 1851 is the variable of interest, which is endogenous like 1851 stations. Column (4) in table 6 reports estimates using the LCP interacted with the indicator for the 60th percentile as the second instrument. The IV estimates imply the effect of stations was to increase the difference in log 1891 and log 1851 population by 0.059 (0.555-0.497) for units below the 60th percentile, but it is not statistically different from zero. To state differently, units in the bottom 60% of 1801 density distribution got only a 0.1% increase in annual population growth from getting stations, while for units in the top 40% getting stations led to an additional increase in annual population growth of 1.4%.

Table 6: Heterogeneous effects of getting a station by 1851 on population growth from 1851 to 1891

	(1)	(2)	(3)	(4)	(5)
Estimator	OLS	IV	OLS	IV	IV
Station by 1851	-0.035	-0.668	0.214***	0.555***	0.609***
	(0.101)	(0.643)	(0.0248)	(0.195)	(0.227)
Ln 1801 pop density	-0.089**	-0.094**	-0.097**	-0.081**	-0.085**
	(0.037)	(0.038)	(0.037)	(0.037)	(0.037)
Station by 1851* Ln 1801 pop density	0.051**	0.250*			
	(0.024)	(0.132)			
Below 60th pct. pop den. 1801			-0.029**	0.010	0.005
			(0.011)	(0.018)	(0.018)
Station by 1851* Below 60th pct. pop den. 1801			-0.108**	-0.497***	-0.494***
			(0.0414)	(0.172)	(0.221)
Drop units with more than 1 station	N	N	N	N	Y
Kleibergen-Paap F stat		16.918		19.259	12.400
Observations	8,377	8,377	8,337	8,337	8,172
R-squared	0.305		0.307		

Notes: The dependent variable is Δ1891,1851 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include county fixed effects, first nature variables, second nature variables, 1851, 1841, and 1831 ln pop density as controls. All units less than 7 km from an LCP node are dropped. In (2) the instruments are the indicator for LCP and the indicator for LCP interacted with log 1801 density. In (4) and (5) the instruments are the indicator for LCP and the LCP indicator interacted with dummy for unit below 60th percentile 1801 population.

The heterogenous effects are robust to considering different samples and specifications. Column (5) in table 6 restricts the sample to units with zero stations or only 1 station in 1851. The coefficients are similar, indicating getting multiple stations in high density units cannot account for the differences in outcomes. Moreover, using different percentiles, like the 50th or 70th, gives similar results (see appendix table A.6.3). Together, these estimates imply that railways contributed to further divergence between low and high population density units in the nineteenth century. They also support some key predictions from NEG models.

8. Local population displacement effects

While being very close to stations increased population growth, it is theoretically possible that, due to the changing balance between agglomeration and dispersion effect, after some distance threshold, growth becomes lower in units closer to stations compared to units farther from stations. Equation (3) is used to estimate the threshold distance beyond which the direction and scale of growth effects change.

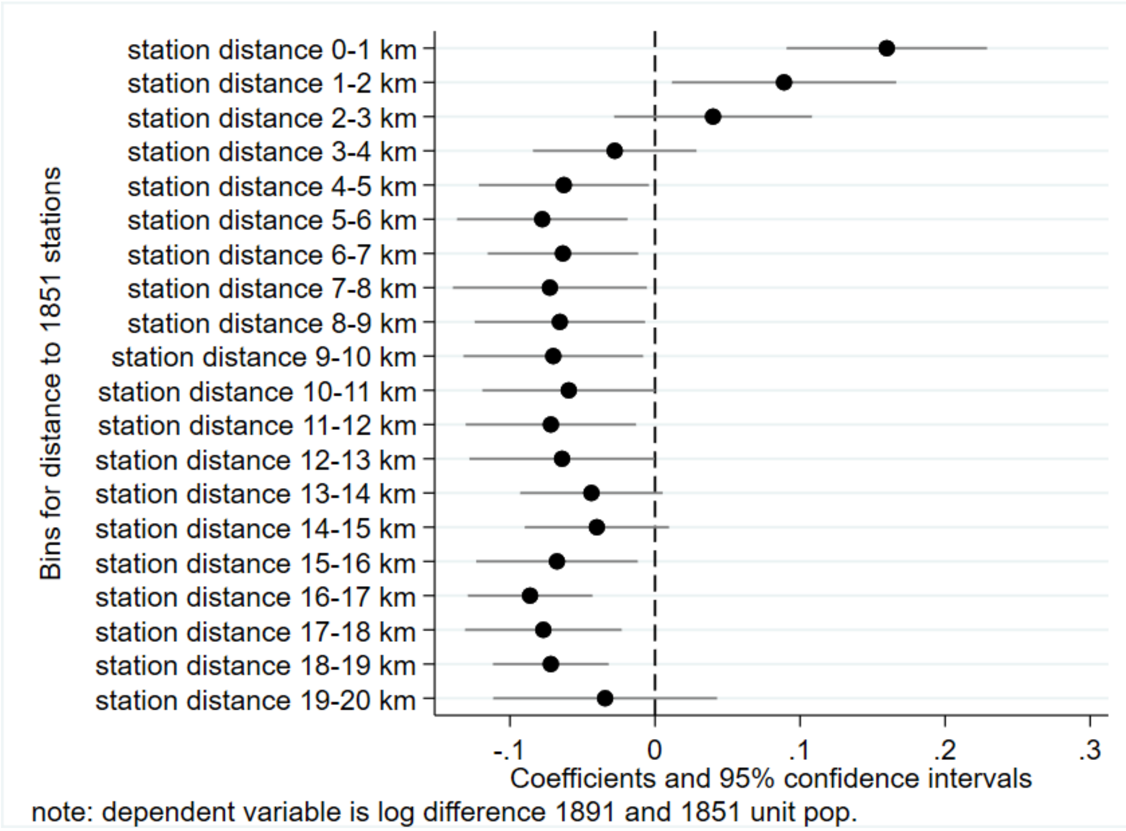
$$\Delta Lnpop_{i,1891-1851} = \sum_{k=0}^{19} \beta_k Station1851distance[k, k+1]_i + \gamma \cdot x_{i,j} + \varepsilon_i \qquad (3).$$

$Station1851distance[k, k+1]_i$ is an indicator variable for being between k and k+1 km from a station in 1851. These distance bins start with 0 to 1 km, 1 to 2 km and go up to 19 to 20 km. The omitted comparison group includes units more than 20 km from an 1851 station. The same control variables are included as in our preferred specification in table 3. Units less than 7 km from an LCP node are also dropped as in the baseline.

The coefficients and their 95% confidence intervals for each distance bin are plotted in figure 5. Between 4 and 19 km the difference in log 1891 and log 1851 population was 0.05 to 0.10 lower compared to units more than 20 km from stations. Thus, these estimates imply there was a 'displacement zone' starting around 4 km from an 1851 station.

One limitation of equation (3) is that station distance was selected, possibly biasing these OLS estimates. The large number of station distance bins makes it impractical to use instruments. To address this issue, we opt for a more parsimonious specification using log distance to the nearest 1851 station and its square as the endogenous variables and log distance to the nearest LCP and its square as the instruments. There are two endogenous variables along with two corresponding instruments, all measured in 1851. The estimating equation is otherwise identical to that reported in column (6) table 3, with all controls.

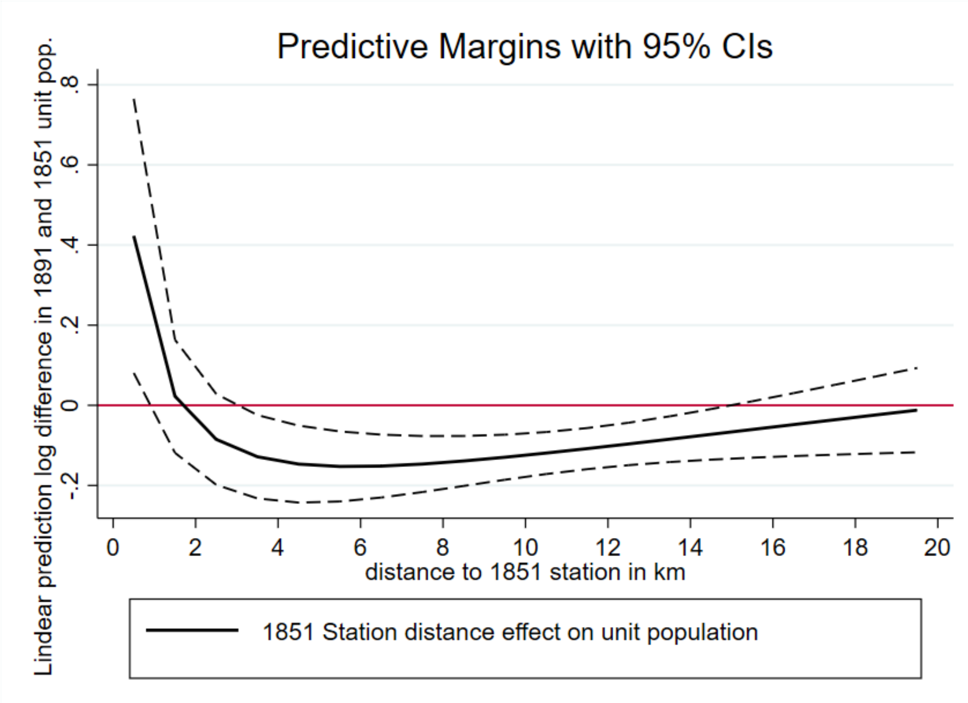
Figure 5. Effects of distance to 1851 stations on difference in log 1891 and log 1851 population



Notes: the coefficients are from specifications that include county fixed effects, first nature variables, second nature variables, 1851, 1841, and 1831 ln pop density as controls. Standard errors are clustered on counties. All units less than 7 km from an LCP node are dropped.

The IV estimates capturing station distance are summarized in Figure 6. The difference in log population is estimated to be positive and large for units less than 1.5 km from stations. It becomes negative and statistically different from zero between 3 to 15 km distance. Thus only a minority of units experienced positive growth effects from railways. Around 60% were in the displacement zone (here 3 to 15 km) and experienced population losses from railways relative to units more than 15 km away.

Figure 6. IV estimates for effect of 1851 station distance on difference in log 1891 and log 1851 population



Notes and Sources: Author's calculation of predicted difference in log 1891 and log 1851 population. The dashed lines represent 95% confidence intervals. See text for more details.

9. Effects of stations on changes in occupational structure

Using the same methodology to study population change, we also briefly analyze the effect of 1851 stations on changes in male occupational structure. The specifications are like table 3, except the difference in the share of 1881 and 1851 male agricultural, secondary, or tertiary occupations are now the dependent variables. We also add controls for 1851 male shares in secondary, tertiary, mining, or unspecified occupations to condition on occupational structure when railways were beginning to open. An alternative specification studies the difference in log shares as the dependent variable, but this is not our preferred specification as it leads to dropping several hundred units with zero shares in some sectors. Nevertheless, the results are similar and reported in appendix table A.6.4.

The coefficients in columns (1) and (2) of table 7 show that getting stations in 1851 led to a significant decline in male agricultural shares. The IV coefficient -0.124 is equivalent to -

0.80 standard deviations in the dependent variable. With respect to the difference in log shares it represents a 33% decline (see appendix table A.6.4). Columns (3) and (4) show that getting stations led to a significant increase in male secondary shares. The IV coefficient 0.066 is equivalent to 0.89 standard deviations, or a 36% increase. Columns (5) and (6) show smaller effects for tertiary. These estimates imply that having railway stations led to significant occupational change from agriculture to secondary.

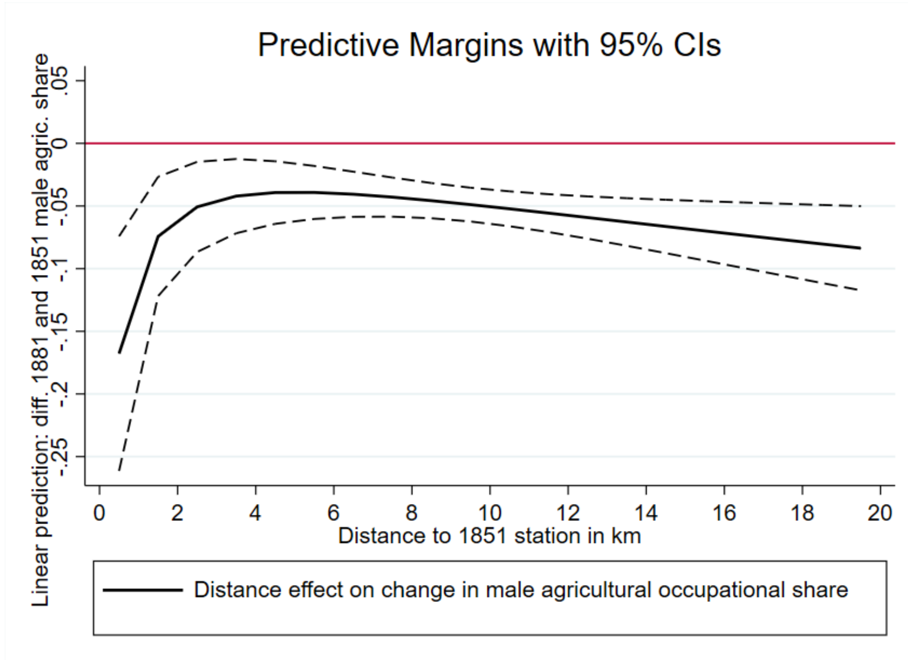
Table 7: Estimates for effect of 1851 station on difference in male occupational shares 1881 and 1851

	(1)	(2)	(3)	(4)	(5)	(6)
Estimator	OLS	IV	OLS	IV	OLS	IV
Dependent variable:	Δ male agriculture occupational share		Δ male secondary occupational share		Δ male tertiary occupational share	
Station in unit by 1851	-0.0422***	-0.124**	0.0114***	0.0667**	0.0253***	0.0384
	(0.00465)	(0.0612)	(0.00286)	(0.0339)	(0.00339)	(0.0447)
Kleibergen-Paap F stat		48.139		48.139		48.139
Observations	8,337	8,337	8,337	8,337	8,337	8,337
R-squared	0.393		0.212		0.341	

Notes: Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include county fixed effects, first nature variables, second nature variables, 1851, 1841, and 1831 ln pop density as controls, and 1851 male shares in agricultural, secondary, tertiary, mining, or unspecified occupations. The instrument for station in unit by 1851 is an indicator if unit has LCP in its boundaries. All units less than 7 km from an LCP node are dropped.

We also find that occupational structure changed in the displacement zone discussed in section 8. A plot for the effect of log 1851 station distance on the change in the share of agricultural occupations between 1881 and 1851 is shown in figure 7. Like figure 6, the log distance to stations and its square are instrumented with log distance to the LCP and its square. The IV estimates imply agricultural shares declined significantly less for all units between 5 to 12 km distance. Similar estimates for changes in the tertiary share reveal they increased significantly less between 5 and 12 km distance (see appendix figure A.6.1). Thus, in the displacement zone occupational structure became more agricultural and less oriented to services.

Figure 7. IV estimates for effect of 1851 station distance on the difference in 1881 and 1851 agricultural shares



Notes and Sources: Author's calculation of predicted difference in 1881 and 1851 male agricultural occupational share. The dashed lines represent 95% confidence intervals. See text for more details.

10. Implications for the distribution of population

We have stressed that in England and Wales there was an increasing geographical concentration of population in urban areas during the second half of the nineteenth century. In this final section we estimate how the population distribution would have been different without railways. The total population increased from 18.05 to 28.74 million between 1851 and 1891, or a change of +10.69 million (59.22%). Over the same period, the total population in units having railway stations by 1851 increased from 8.09 to 15.98 million, or a change of +7.88 million (97.47%). Thus, units having railway stations by 1851 accounted for 74% of all population growth in England and Wales.

As a thought experiment, we assume that the presence and/or absence of railways does not change demographic behaviors such as nuptiality, fertility and mortality. Hence, the total population of England and Wales would have increased by the same amount between 1851 and 1891, even without railways. Now using our preferred IV estimates, having a railway station by 1851 added 41.8 percentage points to an average unit's population growth rate between 1851 and 1891. Assuming that without railways these units would have grown instead by 97.47-41.8%, then their population would have increased less to 12.60 million by 1891 (as opposed to the observed 15.98 million). In other words, their population would have increased by 3.38 million less from 1851 to 1891 than it did. Following our assumption that the total population in 1891 is fixed, that means that the 3.38 million population loss for units with railway stations by 1851 would have been fully offset by population gains in the units without railway stations by 1851. These latter units would have seen their population increase from 9.96 to 16.14 million (as opposed to the observed 12.76 million), meaning they would have grown by an additional 33.9%.

What does this imply for the effect of railway stations on the urban/rural population distribution? We extend the previous thought experiment and estimate the share of the population in the top 5% of units in terms of population size with and without railways. It should be noted here that the top 5% units accounted for 54.4% of population in England and Wales in 1851, while the share of urban population at the same date was 54% (see table 1). So, the top 5% units essentially account for the entirety of urban units. We assume that the population in each unit with stations by 1851 increased by 41.8% less and in each unit without stations by 1851 the population increased by 33.9% more. As shown in the previous paragraph, these numbers maintain the factual total population increase in England and Wales from 1851 to 1891. Then we calculate new (i.e. counter-factual) population for each top 5% unit in 1891 and their new population share.

The new population distributions have some important differences. The factual data show that the share in the top 5% increased from 0.554 in 1851 to 0.676 in 1891, or a +0.122 change in the top 5% share. If no units had railways in 1851, we estimate the population share in these urban units, or the urbanization rate, would have increased less to 0.624, or only a +0.07 change in share. That implies that without railways the change in urban units' population share would have been 0.052 less than it was, suggesting that railways can account for 43% of the increase in the urbanization rate. These are likely to represent lower bound effects. If we use estimates from the heterogenous effects specification (column 4 table 6), then the population share in these urban units would have increased even less to 0.591, suggesting railways can account for 70% of the increase in urbanization rate.

11. Conclusion

In this paper, we study how railways led to population change and divergence in an economy whose urbanization rate increased dramatically from 1800 to 1900. We make use of detailed data on railway stations, population, and occupational shares in 9,489 spatial units. Endogeneity is a major challenge in our context given that private companies built the network. To address this issue, we create a LCP instrument based on major cities in 1801 and the length of the 1851 rail network. Our estimates show that having a railway station in a unit by 1851 caused it to have significantly higher population growth from 1851 to 1891 and shifted the male occupational structure away from agriculture to secondary. Moreover, in extensions, we estimate having stations increased population growth relatively more if units had greater density in 1801. Also, there were relative population losses for units 4 to 15 km from stations compared to more than 20 km, indicating stations created a wide displacement zone.

Overall, we find that railways reinforced the urban hierarchy of the early nineteenth century and contributed to further spatial divergence. The implications for the distribution of population were large. Without railways there would have been significantly less concentration of population in urban areas during the second half of the nineteenth century. Britain's urbanization would have been less exceptional as a result.

References

Alvarez-Palau , Eduard, Xavi Franch, and Jordi Martí-Henneberg. "Evolution of the territorial coverage of the railway network and its influence on population growth: The case of England and Wales, 1871–1931." Historical Methods: A Journal of Quantitative and Interdisciplinary History 46.3 (2013): 175-191.

Alvarez-Palau , Edward, Dunn, O., Bogart, D., Satchell, M., Shaw-Taylor, L. , 'Ports of England and Wales, 1680-1911', 2017. http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html

Armstrong, John. The Vital Spark: The British Coastal Trade, 1700-1930. International Maritime Economic History Association, 2009.

Atack, Jeremy, Fred Bateman, Michael Haines, and Robert A. Margo. "Did railroads induce or follow economic growth?." Social Science History 34, no. 2 (2010): 171-197.

Atack, Jeremy, Michael R. Haines, and Robert A. Margo. Railroads and the Rise of the Factory: Evidence for the United States, 1850-70. No. w14410. National Bureau of Economic Research, 2008.

Atack, Jeremy, and Robert A. Margo. "The Impact of Access to Rail Transportation on Agricultural Improvement: The American Midwest as a Test Case, 1850-1860." Journal of Transport and Land Use 4.2 (2011).

Avery, Brian William. Soil classification for England and Wiles: higher categories. No. 631.44 A87. 1980.

Bairoch, Paul, and Gary Goertz. "Factors of urbanisation in the nineteenth century developed countries: a descriptive and econometric analysis." Urban Studies 23.4 (1986): 285-305.

Baldwin, Richard E., and Philippe Martin. "Agglomeration and regional growth." Handbook of regional and urban economics. Vol. 4. Elsevier, 2004. 2671-2711.

Banerjee, Abhijit, Esther Duflo, and Nancy Qian. "On the road: Access to transportation infrastructure and economic growth in China." Journal of Development Economics 145 (2020): 102442.

Baum-Snow, Nathaniel. "Did highways cause suburbanization?." The Quarterly Journal of Economics 122.2 (2007): 775-805.

Baum-Snow, N., Brandt, L., Henderson, J. V., Turner, M. A., & Zhang, Q. (2017). Roads, railroads, and decentralization of Chinese cities. Review of Economics and Statistics, 99(3), 435-448.

Baum-Snow, N., Henderson, J. V., Turner, M. A., Zhang, Q., & Brandt, L. (2020). Does investment in national highways help or hurt hinterland city growth?. Journal of Urban Economics, 115, 103124.

Beach, Brian, and W. Walker Hanlon. "Coal smoke and mortality in an early industrial economy." The Economic Journal 128.615 (2018): 2652-2675.

Bennett, Robert J (2012). "Urban population database, 1801-1911". In: UK Data Service. SN: 7154.

Berger, Thor. "Railroads and rural industrialization: Evidence from a historical policy experiment." Explorations in Economic History 74 (2019): 101277.

Berger, Thor, and Kerstin Enflo. "Locomotives of local growth: The short-and long-term impact of railroads in Sweden." Journal of Urban Economics (2015).

Bolton, Diane K., H. P. F. King, Gillian Wyld and D. C. Yaxley, 'Harrow, including Pinner : Suburban development', in A History of the County of Middlesex: Volume 4, Harmondsworth, Hayes, Norwood With Southall, Hillingdon With Uxbridge, Ickenham, Northolt, Perivale, Ruislip, Edgware, Harrow With Pinner, ed. T F T Baker, J S Cockburn and R B Pugh (London, 1971), pp. 198-203. British History Online http://www.british-history.ac.uk/vch/middx/vol4/pp198-203 [accessed 29 July 2021].

Bogart, Dan. "The Transport Revolution in Industrializing Britain," in Floud, Roderick, Jane Humphries, and Paul Johnson, eds. The Cambridge Economic History of Modern Britain: Volume 1, Industrialisation, 1700–1870. Cambridge University Press, 2014.

Boyer, George R., and Timothy J. Hatton. "Migration and labour market integration in late nineteenth-century England and Wales." Economic History Review (1997): 697-734.

Büchel, Konstantin, and Stephan Kyburz. "Fast track to growth? Railway access, population growth and local displacement in 19th century Switzerland." Journal of economic geography 20.1 (2020): 155-195.

Buxton-Dunn, Oliver and Alvarez-Palau, Eduard and Bogart, Dan and Shaw-Taylor, Leigh (2020). *Historical light aids to navigation 1514-1911.* [Data Collection]. Colchester, Essex: UK Data Service. 10.5255/UKDA-SN-854172

Cameron, R. Concise Economic History of the World (New York: O.U.P., 1993) p. 193.

Campbell, Gareth, and John D. Turner. "Dispelling the Myth of the Naive Investor during the British Railway Mania, 1845–1846." Business History Review 86.01 (2012): 3-41.

Campbell, Gareth, and John D. Turner. "Managerial failure in mid-Victorian Britain?: Corporate expansion during a promotion boom." Business History 57.8 (2015): 1248-1276.

Cary, John. *Cary's New Itinerary: Or an Accurate Delineation of the Great Roads, Both Direct and Cross Throughout England and Wales; with Many of the Principal Roads in Scottland. From an Actual Admeasurement by---; Made by Command of His Majesty's Postmaster General, for Official Purposes. Under the Direction and Inspection of Thomas Hasker (etc.)*. Gosnell, 1802.

Casson, Mark. The world's first railway system: enterprise, competition, and regulation on the railway network in Victorian Britain. Oxford University Press, 2009.

Casson, Mark. "The determinants of local population growth: A study of Oxfordshire in the nineteenth century." Explorations in Economic History 50.1 (2013): 28-45.

Casson, Mark, A.E.M. Satchell, Leigh Shaw-Taylor, and E.A. Wrigley, "Railways and local population growth: Northampton and Rutland, 1801-1891" in Casson, Mark, and Nigar Hashimzade, eds. Large databases in economic history: research methods and case studies. Routledge, 2013.

Chandra, Amitabh, and Eric Thompson. "Does public infrastructure affect economic activity?: Evidence from the rural interstate highway system." Regional Science and Urban Economics 30.4 (2000): 457-490.

Church, Roy, Alan Hall, and John Kanefsky. History of the British Coal Industry: Volume 3: Victorian Pre-Eminence. Vol. 3. Oxford University Press, USA, 1986.

Clayden, Benjamin, and John Marcus Hollis. Criteria for differentiating soil series. No. Tech Monograph 17. 1985.

Cobb, M. H. "The Railways of Great Britain: A Historical Atlas at the Scale of 1 Inch to 1 Mile. 2 vols." *Shepperton: Allen* (2006).

Conley, Timothy G. "Spatial econometrics." Microeconometrics. Palgrave Macmillan, London, 2010. 303-313.

Cormen, Thomas H., Charles E Leiserson, Ronald L Rivest and Clifford Stein: Introduction to Algorithms, Cambridge, MA, MIT Press (3rd ed., 2009) pp.695-6.

Crafts, Nicholas, Timothy Leunig, and Abay Mulatu. "Were British railway companies well managed in the early twentieth century? 1." The Economic History Review 61.4 (2008): 842-866.

Day, Joseph. "The Process of Internal Migration in England and Wales, 1851-1911: Updating Ravenstein and the Step-Migration Hypothesis." *Comparative Population Studies* 44 (2019).

Desmet, Klaus, and Esteban Rossi-Hansberg. "Spatial development." The American Economic Review 104.4 (2014): 1211-1243.

Donaldson, Dave. "Railroads of the Raj: Estimating the impact of transportation infrastructure." American Economic Review 108.4-5 (2018): 899-934.

Donaldson, Dave, and Richard Hornbeck. "Railroads and American economic growth: A “market access” approach." The Quarterly Journal of Economics 131.2 (2016): 799-858.

Duranton, Gilles, and Matthew A. Turner. "Urban growth and transportation." The Review of Economic Studies 79.4 (2012): 1407-1440.

Duranton, G., & Puga, D. (2014). The growth of cities. In Handbook of economic growth (Vol. 2, pp. 781-853). Elsevier.

Esteves, Rui, and Gabriel Geisler Mesevage. "The Rise of New Corruption: British MPs during the Railway Mania of 1845." (2017).

Faber, Benjamin. "Trade integration, market size, and industrialization: evidence from China's National Trunk Highway System." Review of Economic Studies 81.3 (2014): 1046-1070.

Foreman-Peck, James. Railways and late Victorian economic growth. Cambridge University Press, 1991.

Fujita, Masahisa, and Jacques-François Thisse. Economics of agglomeration: Cities, Industrial Location, and Regional Growth Cambridge University Press, 2002.

Fujita, Masahisa, Paul R. Krugman, and Anthony Venables. The spatial economy: Cities, regions, and international trade. MIT press, 1999.

Garcia-López, Miquel-Àngel, Adelheid Holl, and Elisabet Viladecans-Marsal. "Suburbanization and highways in Spain when the Romans and the Bourbons still shape its cities." Journal of Urban Economics 85 (2015): 52-67.

Ghani, Ejaz, Arti Grover Goswami, and William R. Kerr. "Highway to success: The impact of the Golden Quadrilateral project for the location and performance of Indian manufacturing." The Economic Journal 126.591 (2016): 317-357.

Gibbons, Stephen, Teemu Lyytikainen, Henry G. Overman, Rosa Sanchis-Guarner. "New road infrastructure: the effects on firms." Journal of Urban Economics 110 (2019): 35-50.

Gourvish, Terence Richard. Railways and the British economy, 1830-1914. Macmillan International Higher Education, 1980.

Gregory, Ian N., and Jordi Martí Henneberg. "The railways, urbanization, and local demography in England and Wales, 1825–1911." Social Science History 34.2 (2010): 199-228.

Hanlon, W. Walker. "Coal smoke, city growth, and the costs of the industrial revolution." The Economic Journal 130.626 (2020): 462-488.

Hsiang, Solomon M. "Temperatures and cyclones strongly associated with economic production in the Caribbean and Central America." Proceedings of the National Academy of sciences 107.35 (2010): 15367-15372.

Hawke, Gary Richard. Railways and economic growth in England and Wales, 1840-1870. Clarendon Press, 1970.

Heblich, Stephan, Stephen J. Redding, and Daniel M. Sturm. "The making of the modern metropolis: evidence from London." *The Quarterly Journal of Economics* 135.4 (2020): 2059-2133.

Hodgson, Charles. "The effect of transport infrastructure on the location of economic activity: Railroads and post offices in the American West." Journal of Urban Economics 104 (2018): 59-76.

Holl, Adelheid. "Highways and productivity in manufacturing firms." Journal of Urban Economics 93 (2016): 131-151.

Hornung, Erik. "Railroads and growth in Prussia." Journal of the European Economic Association 13.4 (2015): 699-736.

Jedwab, Remi, Edward Kerby, and Alexander Moradi. "History, path dependence and development: Evidence from colonial railroads, settlers and cities in Kenya." The Economic Journal (2015).

Jarvis A., H.I. Reuter, A. Nelson, E. Guevara (2008). Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from http://srtm.csi.cgiar.org.

Kellett, John R. The impact of railways on Victorian cities. Routledge, 2012.

Kitson, P. M., Shaw-Taylor, L., Wrigley, E. A., Davies, R. S., Newton, G., & Satchell, A. M. (2012). The creation of a 'census' of adult male employment for England and Wales for 1817. *Work in Progress. For details of the wider project see http://www. geog. cam. ac. uk/research/projects/occupations*.

Lafourcade, Miren, and Jacques-François Thisse. "New economic geography: the role of transport costs." A handbook of transport economics. Edward Elgar Publishing, 2011.

Law, Christopher M. "The growth of urban population in England and Wales, 1801-1911." Transactions of the Institute of British Geographers (1967): 125-143.

Leunig, Timothy. "Time is money: a re-assessment of the passenger social savings from Victorian British railways." The Journal of Economic History 66.3 (2006): 635-673.

Lipscomb, Molly, Mushfiq A. Mobarak, and Tania Barham. "Development effects of electrification: Evidence from the topographic placement of hydropower plants in Brazil." American Economic Journal: Applied Economics 5.2 (2013): 200-231.

Long, Jason. "Rural-urban migration and socioeconomic mobility in Victorian Britain." The Journal of Economic History 65.1 (2005): 1-35.

Maw, Peter. Transport and the Industrial City: Manchester and the Canal Age, 1750 1850. Manchester University Press, 2013.

Martí-Henneberg, J., Satchell, M., You, X., Shaw-Taylor, L., Wrigley E.A., 'England, Wales and Scotland railway stations 1807-1994 shapefile' (2017). http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html

Michaels, Guy. "The effect of trade on the demand for skill: Evidence from the interstate highway system." The Review of Economics and Statistics 90.4 (2008): 683-701.

Michaels, Guy, Ferdinand Rauch, and Stephen J. Redding. "Urbanization and structural transformation." The Quarterly Journal of Economics 127.2 (2012): 535-586.

Mitchell, Brian R. Economic development of the British coal industry 1800-1914. Cambridge University Press, 1984.

Mitchell, Brian R. British Historical Statistics, Cambridge University Press, 1988.

Odlyzko, Andrew. "Collective hallucinations and inefficient markets: The British Railway Mania of the 1840s." University of Minnesota (2010).

Pascual Domènech, P. (1999). Los caminos de la era industrial: la construcción y financiación de la red ferroviaria catalana, 1843-1898 (Vol. 1). Edicions Universitat Barcelona.

Pogonyi, Csaba G. and Graham, Daniel J. and M. Carbo, Jose, Metros, Agglomeration and Firm Productivity. Evidence from London (March 11, 2019). Available at SSRN: https://ssrn.com/abstract=3350505 or http://dx.doi.org/10.2139/ssrn.3350505

Pooley, Colin, and Jean Turnbull. Migration and mobility in Britain since the eighteenth century. Routledge, 2005.

Pope, Alexander, and D. Swann. "The pace and progress of port investment in England 1660–1830." Bulletin of Economic Research 12.1 (1960): 32-44

Poveda, G. (2003). El antiguo ferrocarril de Caldas. Dyna, 70 (139), pp. 1-10.

Purcar, Cristina. "Designing the space of transportation: railway planning theory in nineteenth and early twentieth century treatises." Planning Perspectives 22.3 (2007): 325-352.

Redding, Stephen J., and Matthew A. Turner. "Transportation costs and the spatial organization of economic activity." Handbook of regional and urban economics. Vol. 5. Elsevier, 2015. 1339-1398.

Redford, Arthur. *Labour migration in England, 1800-1850*. Manchester University Press, 1964.

Riley, S. J., S. D. Gloria, and R. Elliot (1999). A terrain Ruggedness Index that quantifies Topographic Heterogeneity, Intermountain Journal of Sciences, 5(2-4), 23-27.

Robson, Brian T. Urban growth: an approach. Vol. 9. Routledge, 2006.

Rosevear, A., Satchell, M., Bogart, D., Shaw Taylor, L., Aidt, T. and Leon, G., 'Turnpike roads of England and Wales, 1667-1892', 2017.
http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html

Satchell, M. and Shaw-Taylor, L., 'Exposed coalfields of England and Wales' 2013.
http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html

Satchell, M., Shaw-Taylor, L., Wrigley E.A., '1830 England and Wales navigable waterways shapefile' (2017).
http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html

Satchell, M., Potter, E., Shaw-Taylor, L., Bogart, D., 'Candidate Towns of England and Wales, c.1563-1911', 2017.A description of the dataset can be found in M. Satchell, 'Candidate Towns of England and Wales, c.1563-1911 GIS shapefile'
http://www.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html

Schurer, K., Higgs, E. (2014). Integrated Census Microdata (I-CeM), 1851-1911. [data collection]. UK Data Service. SN: 7481, http://doi.org/10.5255/UKDA-SN-7481-1.

Schürer, K., and Joe Day. "Migration to London and the development of the north–south divide, 1851–1911." Social History 44.1 (2019): 26-56.

Shaw-Taylor, L. and Wrigley, E. A. "Occupational Structure and Population Change," in Floud, Roderick, Jane Humphries, and Paul Johnson, eds. The Cambridge Economic History of Modern Britain: Volume 1, Industrialisation, 1700–1870. Cambridge University Press, 2014.

Shaw-Taylor, Leigh, E.A. Wrigley, Peter Kitson, Ros Davies, Gill Newton and Max Satchell. The occupational structure of England and Wales c.1817-1881. Working Paper, 2010.

Simmons, Jack. The railway in town and country, 1830-1914. (1986).

Storeygard, Adam. "Farther on down the road: transport costs, trade and urban growth in sub-Saharan Africa." The Review of Economic Studies 83.3 (2016): 1263-1295.

Tang, John P. "Railroad expansion and industrialization: evidence from Meiji Japan." The Journal of Economic History 74.03 (2014): 863-886.

Wellington, A.M. The Economic Theory of the Location of Railways: An Analysis of the Conditions Controlling the Laying Out of Railways to Effect the Most Judicious Expenditure of Capital. Ed. J. Wiley & sons, 1877.

Wrigley, Edward Anthony, and Satchell, A.E.M.. The early English censuses. Oxford University Press, 2011.

You, Xuesheng and Shaw-Taylor, Leigh. "The development of the railway network in Britain 1825-19111." 2020.

Appendix A.1: Linking population and occupational data across space

The English administrative units display highly inconsistent features. Several different hierarchal systems can coexist at the same time; different regions can use different nomenclature; different systems can exist at different time slices; and boundaries of individual units within each system can change over time. Even though boundaries were never redrawn from scratch, different administrative system over time and boundary changes of individual units within any given systems over time mean that it would be difficult to carry out any analysis, either econometrically or cartographically, without having the data in a set of consistent geographical units.

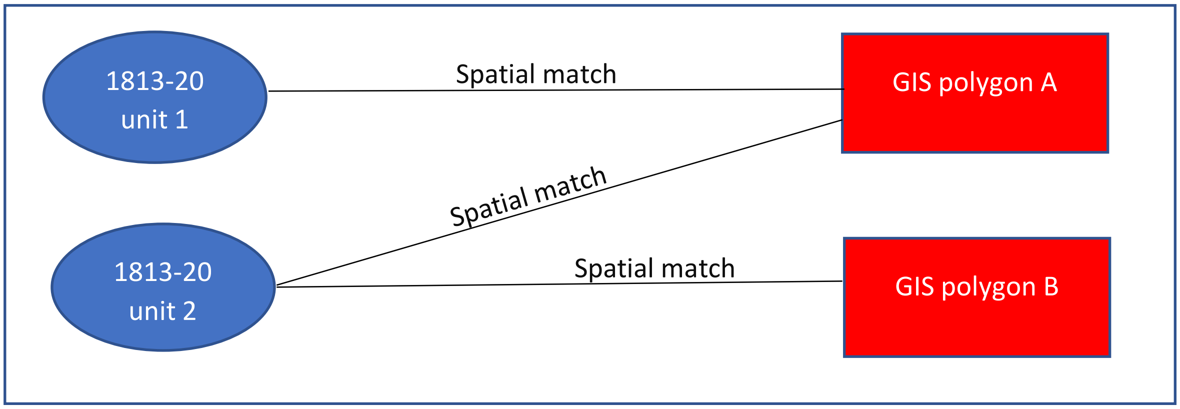
This problem becomes even more apparent drawing on evidence from several datasets at different slices: the baptism data between 1813 and 1820, the 1851 census data, the 1881 census data, and the population data between 1801 and 1891. Each of these datasets have data at different geographical unit. The name and the number of geographical units in each dataset are presented in the table below.

	Name of the geographical unit	**Number of the geographical unit**
1813-20 Baptism data	Ancient parish	11,364
1851 census data	Civil parish	16,397
1881 census data	Civil parish	15,299
1801-91 population data	Continuous unit	12,750

The method of creating a set of consistent geographical units based on the units in each dataset involves two steps. Firstly, we made spatial match between parish level Geographical

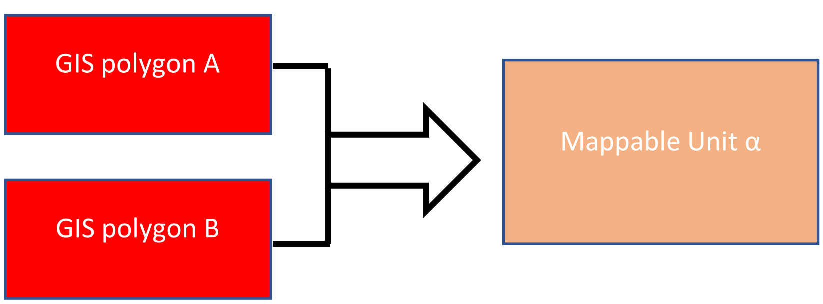
Information System (GIS) polygons and geographical unit from each dataset. The spatial match essentially made connections between the parish level GIS polygons and administrative units from each dataset through nominal linkage. The parish level GIS has c. 23,000 polygons. A separate note on the parish level GIS polygons can be found elsewhere. Part of spatial match process can be carried out automatically, but there are cases where spatial matches cannot be made automatically and require manual linkage. Ms Gill Newton and Dr Max Satchell, both of the Cambridge Group for the History of Population and Social Structure (Cambridge Group), University of Cambridge, managed the process of spatial matching based on an approach suggested by Dr Peter Kitson, previously of the Cambridge Group. A number of students from the University of Cambridge also provided research assistance during the process. A brief account of the spatial match process can be found in Kitson, P., et al, 'The creation of a 'census' of adult male employment for England and Wales for 1817', http://www.econsoc.hist.cam.ac.uk/docs/CWPESH%20number%204%2017th%20December%202013,%20March%202012.pdf It should be noted that the nominal link between GIS polygons and administrative units from each dataset generated by the spatial match process cannot be used directly for mapping purpose. This is due to the fact that a particular GIS polygon can be linked to more than one administrative units from each given dataset. But the spatial match process is essential for the second step we need to create a set of consistent geographical units over time.

The second step is called Transitive Closure. Imagine the following situation using just 1813-20 baptism dataset as an example:

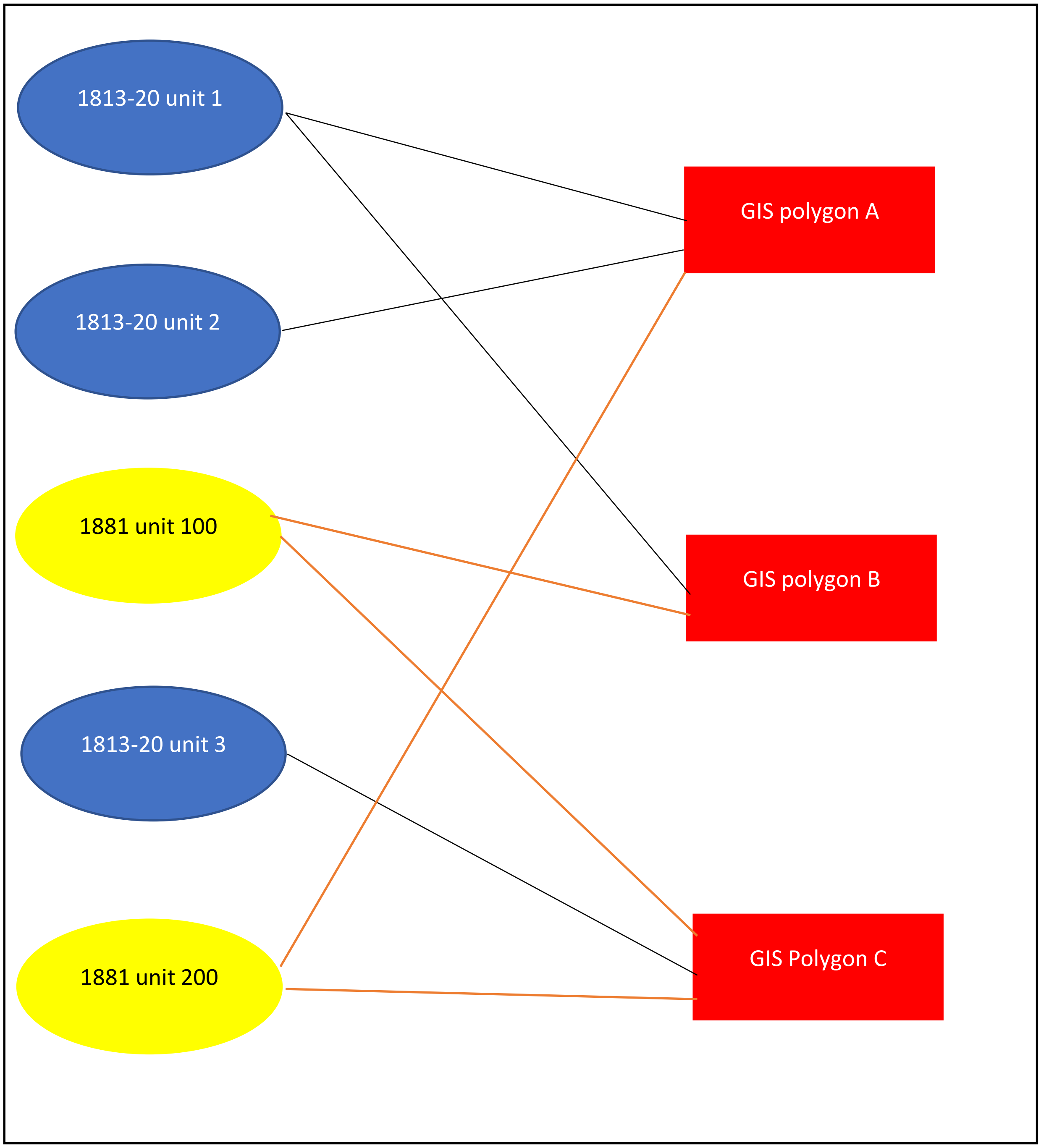


In this case, unit 1 from 1813-20 baptism dataset has a spatial match with the GIS polygon A, and polygon A only. And It does not have direct match with the GIS polygon B. But unit 2 from1813-20 baptism dataset has spatial matches with both GIS polygons A and B. Namely, part of the land enclosed by polygon A belonged to unit 1 with the other part belonging to unit 2. The problem is we do not know where exactly the divide within polygon A is:

So GIS polygon A is left undivided, and both polygon A and polygon B were grouped together to form a 'mappable unit', say mappable unit α, to present units 1 and 2:



The process presented above is the main function of Transitive Closure. When more datasets are added to the study, the situation becomes more complicated. But the basic idea remains the same. For example, imagine the following hypothetical situation:



If we are only dealing with 1813-20 baptism dataset, we can group polygons A and B together to form one mappable unit to represent units 1 and 2; and polygon C becomes a mappable unit on its own to represent unit 3. But once we add more datasets with different geographical units, in this case 1881 census data, we need to generate mappable units that are consistent across different datasets, i.e. over time as well. In this hypothetical case, Transitive Closure will group polygons A, B, and C together to form a single mappable unit. When dealing with 1813-20 baptism dataset, this mappable unit will draw data from units 1, 2 and 3. When dealing with 1881 census dataset, this mappable unit will draw data from units 100 and 200. In this way, the Transitive Closure process makes sure we are presenting and comparing observations from the same geographical units over time.

Transitive closure is a concept widely used in graph theory; for a formal definition and how to compute it, see for instance: Thomas H Cormen, Charles E Leiserson, Ronald L Rivest and Clifford Stein: Introduction to Algorithms, Cambridge, MA, MIT Press (3rd ed., 2009) pp.695-6. Ms Gill Newton, of the Cambridge Group, developed the Python code for Transitive Closure as part of the research project 'The occupational structure of Britain, 1379-1911' based at the Cambridge Group. Dr Xuesheng You, also of the Cambridge Group, implemented this code for this particular paper.

Appendix A.2: Elevation, slope, and ruggedness variables

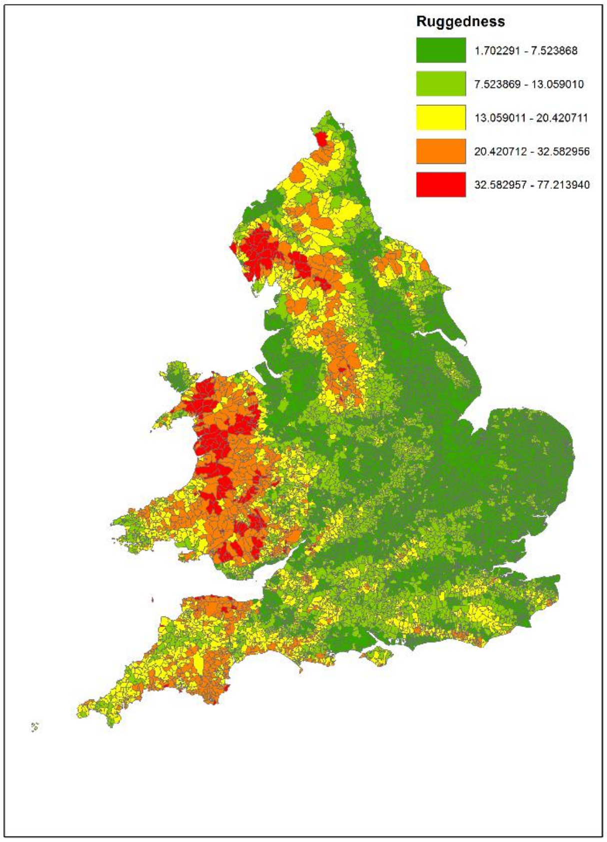
The aim of this appendix is to explain the creation of the elevation variables, including the original sources and method we followed to estimate them. There are several initiatives working on the provision of high-resolution elevation raster data across the world. The geographical coverage, the precision of the data and the treatment of urban surroundings concentrate the main differences between databases.

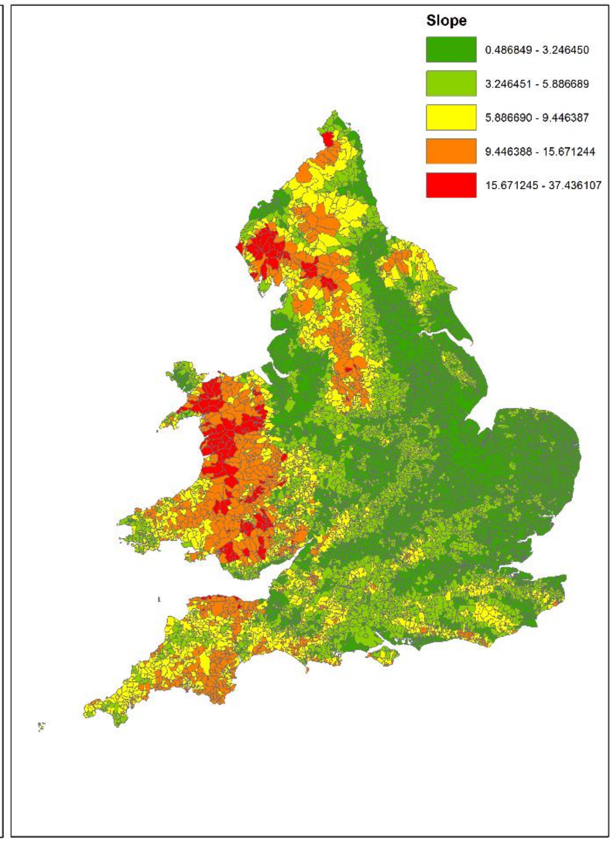
We obtained several elevation DEM rasters, preferably DTM , covering the entire England and Wales. In decreasing order in terms of accuracy, the most precise one database was LIDAR (5x5m.), Landmap Data set contained in the NEODC Landmap Archive (Centre for Environmental Data Archival). In second instance, we used EU-DEM (25x25m.) from the GMES RDA project, available in the EEA Geospatial Data Catalogue (European Environment Agency). The third dataset was the Shuttle Radar Topography Mission (SRTM 90x90m), created in 2000 from a radar system on-board the Space Shuttle Endeavor by the National Geospatial-Intelligence Agency (NGA) and NASA. And finally, we have also used GTOPO30 (1,000x1,000m) developed by a collaborative effort led by staff at the U.S. Geological Survey's Center for Earth Resources Observation and Science (EROS). All those sources have been created using satellite data, which means all of them are based in current data. The lack of historical sources of elevation data obligate us to use them. This simplification may be considered reasonable for rural places but it is more inconsistent in urban surroundings where the urbanization process altered the original landscape. Even using DTM rasters, the construction of buildings and technical networks involved a severe change in the surface of the terrain. Several tests at a local scale were conducted with the different rasters in order to establish a balance between precision and operational time spend in the calculations. Total size of the files, time spend in different calculations and precision in relation to the finest data were some of the comparisons carried on. After these, we opted for SRTM90.

As stated in the text, the spatial units used as a basis for the present paper were civil parishes, comprising over 9000 continuous units. In this regard, we had to provide a method to obtain unique elevation variables for each unit, keeping the comparability across the country. We estimated six variables in total: elevation mean, elevation std, slope mean, slope std., ruggedness mean and ruggedness std. Before starting with the creation of the different variables, some work had to be done to prepare the data. In order to obtain fully coverage of England and Wales with SRTM data, we had to download 7 raster tiles. Those images were merged together, projected into the British National Grid and cut externally using the coastline in ArcGIS software.

Having the elevation raster of England and Wales, we proceed to calculate the first two variables: the elevation mean and its standard deviation. A python script was written to split the raster using the continuous units, to calculate the raster properties (mean and standard deviation) of all the cells in each sub-raster, and to aggregate the information obtained in a text file. These files were subsequently joined to the previous shapefile of civil parishes, offering the possibility to plot the results.

Appendix Figure A.2.1: Slope and ruggedness measures





The second derivative of those results aimed to identify the variability of elevation between adjacent cells. In this regard, two methods were developed to measure this phenomenon: ruggedness and slope. Ruggedness is a measure of topographical heterogeneity defined by Riley et al (1999). In order to calculate the ruggedness index for each unit, a python script was written to convert each raster cell into a point keeping the elevation value, to select the adjacent values using a distance tool, to implement the stated equation to every single point, to spatially join the points to their spatial units and to calculate aggregated indicators (mean and standard deviation) per each continuous units.

In order to calculate the slope variable for each unit, a python script was written to convert the elevation into a slope raster, to split the raster using the continuous units, to calculate the raster properties (mean and standard deviation) of all the cells in each sub-raster, and to aggregate the information obtained in a text file. The obtained results for both ruggedness and slope are displayed at the end of this note. As the reader will appreciate, the scale of the indices is different (1 - 2 times) but the geographical pattern is rather similar. In this regard, we used for the paper those variables derived from slope measures because the time spend in calculations was rather lower.

Appendix A.3: Exposed coal

The shapefile of exposed coalfields of England and Wales c. 1830 was created by Max Satchell using the Digital Geological Map Data of Great Britain 1: 625,000 bedrock produced by the British Geological Survey (BGS). Exposed coalfields can be defined as those sections of coalfields where coal-bearing strata are not concealed by geologically younger rocks. They may, however, be overlain by natural (and man-made) sediments of the Quaternary period where they would form overburden in the exposed coalfield. Quaternary deposits are often unconsolidated sediments comprising mixtures of clay, silt, sand, gravel, cobbles and boulders. Exposed coalfields are of major historical importance because they were places where coal seams crop out at or near the ground surface making coal easiest to both discover and mine. For more details

https://www.campop.geog.cam.ac.uk/research/occupations/datasets/catalogues/documentation/exposedcoalfieldsenglandandwales1830.pdf

Appendix A.4: Summary statistics and estimates for control variables

Summary statistics for first and second nature variables are shown in the following table. Variables are divided into groups to make it clear when they enter regressions.

Table A.4.1: Summary statistics for control variables

Variable	Obs.	Mean	Std. Dev.	Min	Max
Population and occupational control variables					
Ln pop density 1851	9489	4.242	1.367	0.808	11.625
Ln pop density 1841	9489	4.209	1.346	0.805	11.537
Ln pop density 1831	9489	4.145	1.334	0.734	11.622
1851 male secondary occupational share	9,488	0.196	0.123	0	0.8
1851 male tertiary occupational share	9,488	0.149	0.109	0	0.941
1851 male mining & forestry occupational share	9,488	0.025	0.076	0	0.745
1851 male unspecified occupational share	9,489	0.074	0.090	0	0.760
First-nature controls					
Indicator exposed coal	9489	0.080	0.271	0	1
Indicator coastal unit	9489	0.147	0.355	0	1
Elevation	9489	89.72	74.02	-1.243	524.3
Average elevation slope within unit	9489	4.767	3.615	0.484	37.42
SD elevation slope within unit	9489	3.432	2.717	0	23.17
Rainfall in millimeters	9484	755.7	191.7	555	1424
Temperature index	9484	8.958	0.658	5.5	10
Wheat suitability (low input level rain-fed)	9484	2188.1	273.25	272	2503
Latitude	9484	259871	115236	13522	652900
Longitude	9484	443389	112073	136232	654954
Land area in sq. km.	9484	15.63	22.18	0.003	499.8
Perc. of land with Raw gley soil	9489	0.084	1.327	0	76.49
Perc. of land with Lithomorphic soil	9489	8.615	19.83	0	100
Perc. of land with Pelosols soil	9489	8.203	20.63	0	100
Perc. of land with Podzolic soil	9489	4.624	14.32	0	99.56

Perc. of land with Surface-water gley soil	9489	24.63	29.46	0	100
Perc. of land with Ground-water gley soil	9489	10.187	20.11	0	100
Perc. of land with Man made soil	9489	0.363	3.262	0	94.99
Perc. of land with Peat soil	9489	1.187	5.279	0	91.44
Perc. of other soil	9489	0.535	1.966	0	65.15
Perc. of brown soil is omitted group					
Second nature controls					
Ln 1801 population per sq. km	9489	3.877	1.310	0.483	11.43
Distance to inland waterway in 1800 in km	9489	8.121	7.063	0.006	48.67
Distance to turnpike road in 1800 in km	9489	2.431	3.185	0.00	27.95
Distance to port in 1780 in km	9489	33.39	22.33	0.078	99.71
Distance to top 10 city in 1801 in km	9487	68.29	38.69	0	184.14

Sources: see text.

Table A.4.2 shows the estimates for control variables drawn from our preferred specification in columns (5) and (6) in table 3. The county fixed effects are omitted from the table.

Table A.4.2: Coefficient estimates for all variables corresponding to specifications in table 3 columns (5) and (6)

Dependent var.: Δ1891,1851 Ln Pop	(1) OLS	(2) IV
Station in unit by 1851	0.166***	0.349*
	(0.0213)	(0.206)
Ln pop density 1851	0.188***	0.150*
	(0.0678)	(0.0908)
Ln pop density 1841	0.106	0.107
	(0.0673)	(0.0675)
Ln pop density 1831	-0.205***	-0.183***
	(0.0594)	(0.0623)
Indicator exposed coal	0.183***	0.171***
	(0.0498)	(0.0487)
Indicator coastal unit	0.173***	0.168***
	(0.0338)	(0.0344)
Elevation	-0.000263	-0.000227
	(0.000195)	(0.000198)
Average elevation slope within unit	0.00240	0.00355
	(0.00455)	(0.00480)
SD elevation slope within unit	0.00355	0.00251
	(0.00484)	(0.00517)

Rainfall in millimeters	0.000161	0.000143
	(0.000184)	(0.000172)
Temperature index	0.0127	0.0126
	(0.0244)	(0.0249)
Wheat suitability (low input level rain-fed)	1.25e-05	-2.93e-06
	(6.80e-05)	(6.63e-05)
Latitude	1.57e-08	-9.79e-08
	(4.59e-07)	(4.85e-07)
Longitude	1.47e-06***	1.47e-06***
	(4.59e-07)	(4.42e-07)
Land area in sq. km.	6.56e-05	-0.000437
	(0.000212)	(0.000611)
Perc. of land with Raw gley soil	-0.00205	-0.00139
	(0.00386)	(0.00402)
Perc. of land with Lithomorphic soil	0.000186	0.000190
	(0.000296)	(0.000292)
Perc. of land with Pelosols soil	-0.000457	-0.000423
	(0.000318)	(0.000319)
Perc. of land with Podzolic soil	0.00197**	0.00190**
	(0.000769)	(0.000764)
Perc. of land with Surface-water gley soil	0.000212	0.000177
	(0.000349)	(0.000350)
Perc. of land with Ground-water gley soil	-0.000333	-0.000449
	(0.000711)	(0.000746)
Perc. of land with Man made soil	0.00719**	0.00730**
	(0.00332)	(0.00314)
Perc. of land with Peat soil	-0.00248***	-0.00214**
	(0.000919)	(0.00106)
Perc. of other soil	0.00426	0.00397
	(0.00313)	(0.00313)
Ln 1801 population per sq. km	-0.0867**	-0.0793**
	(0.0377)	(0.0374)
Distance to inland waterway in 1800 in km	-0.00276**	-0.00233*
	(0.00129)	(0.00132)
Distance to turnpike road in 1800 in km	0.000700	0.00176
	(0.00325)	(0.00321)
Distance to port in 1780 in km	-0.000922	-0.000881
	(0.000583)	(0.000576)
Distance to top 10 city in 1801 in km	-0.00293***	-0.00283***
	(0.000767)	(0.000795)
Constant	0.228	-0.750**
	(0.387)	(0.378)
Observations	8,337	8,337
R-squared	0.304	0.291

Notes: Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include county fixed effects as additional controls. All units less than 7 km from an LCP node are dropped.

Appendix A.5: The least cost path instrument

In this appendix, we describe how we identify the LCP connecting our nodes. The main criteria used to plan linear projects is usually the minimization of earth-moving works. Assuming that the track structure (composed by rails, sleepers and ballast) is equal for the entire length, it is in the track foundation where more differences can be observed. Thus, terrains with higher slopes require larger earth-moving and, in consequence, construction costs become higher (Pascual 1999, Poveda 2003, Purcar 2007). The power of traction of the locomotives and the potential adherence between wheels and rails could be the main reason. Besides, it is also important to highlight that having slopes over 2% might imply the necessity of building tunnels, cut-and-cover tunnels or even viaducts. The perpendicular slope was also crucial. During the construction of the track section, excavation and filling have to be balanced in order to minimize provisions, waste and transportation of land. Nowadays, bulldozers and trailers are used, but historically workers did it manually. It implied a direct linkage between construction cost, wages and availability of skilled laborers. In fact, it is commonly accepted in the literature that former railways were highly restricted by several factors. The quality of the soil, the necessity of construction tunnels and bridges or the interference with preexistences (building and land dispossession) were several. Longitudinal and perpendicular slope were the more significant ones and we focus on these below.

Slopes are determined using elevation data. Several DEM rasters have been analyzed in preliminary tests, but we finally chose the Shuttle Radar Topography Mission (SRTM) obtained in 90 meter measurements (3 arc-second). Although being a current raster data set, created in 2000 from a radar system on-board the Space Shuttle, the results offered in historical perspective should not differ much from the reality. The LCP tool calculates the route between an origin and a destination, minimizing the elevation difference (or cost in our case) in accumulative terms. The method developed was based on the ESRI Least-Cost-Path algorithm, although additional tasks were implemented to optimize the results and to offer different scenarios. The input data was the SRTM elevation raster, converted into slope. This conversion was necessary in order to input different construction costs.

The next step is to specify the relationship between construction costs and slope. One approach is to use the historical engineering literature. Wellington (1877) discusses elevation slope (i.e. gradients), distance, and operational costs of railways, but this is not ideal as we are interested in construction costs. We could not find an engineering text that specified the relationship between construction costs and slopes. As an alternative we use historical construction cost data. The following details our data and procedure.

A select committee on railways in 1844 published a table on the construction costs of 54 railways. See the Fifth report from the Select Committee on Railways; together with the minutes of evidence, appendix and index (BPP 1844 XI). The specific section with the data is appendix number 2, report to the lords of the committee of the privy council for trade on the statistics of British and Foreign railways, pp. 4-5. There were 45 with a clear origin and destination, to which we can measure total elevation change along the route (details are available). For these 45 railways we calculate the distance of the railway line in meters and the total elevation change (all meters of ascent and descent). We then ran the following regression of construction costs on distance in 100 meters and the elevation change in meters. This regression produces unsatisfactory results, with total elevation change having a negative sign.

We think the main reason is that the sample includes railways with London as an origin and destination. Land values in London were much higher than elsewhere and thus construction costs were higher there. Therefore, we omit railways with a London connection. We also think it is important to account for railways in mining areas as they were typically built to serve freight traffic rather than a mix with passenger.

Our extended model uses construction costs for 36 non-London railways. We regress construction costs on a distance in 100 meters, elevation change, and dummy for mining railways. The results imply that for every 100 meters of distance construction costs rise by ₤128.9 (st. err 45.27) and holding distance constant construction costs rise by ₤382.6 (st. err. 274.5) for every 1 meter increase in total elevation change. Construction costs for mining railways are ₤340,418 less (st. err. 179,815). For our LCP model we assume a non-mining railway, re-scale the figures into construction costs per 100 meters, and normalize so that costs per 100 meters are 1 at zero elevation change. The formula becomes: NormalizedCostper100meters=1+2.96*(ElevationChangeMeters/Distance100meters). The elevation change divided by distance can be considered as the slope in percent, in which case our formula becomes Cost=1+2.96*%slope. We think this is a reasonable approximation of the relationship between construction costs, distance, and elevation slope.

The LCP algorithm is implemented using ESRI python, using as initial variables the elevation slope raster, the reclassification table of construction costs, and the node origin-destination nodes. We implemented the least-cost-path function to obtain the LCP corridors. These corridors were converted to lines, exported, merged and post-processed. Maps of our preferred LCP are shown in the text.

Appendix A.6: Additional results on effects of railway stations

Following from section 6, we report IV estimates using two instruments, the LCP and the LCP interacted with 1802 coaching inns. The IV coefficient for 1851 stations is slightly smaller at 0.300 (S.E. 0.174) but similar to our main result. See table A.6.1.

Table A.6.1: Estimates for effect of 1851 station on population growth from 1851 to 1891 using coaching inns as a second instrument.

	(1)
Estimator	IV
Station in unit by 1851	0.299*
	(0.174)
County FEs?	Y
Second Nature controls?	Y
Kleibergen-Paap F stat	24.978
Observations	8,337
R-squared	
First stage: Station in unit by 1851	
	(2)
	OLS
LCP in unit	0.0637***
	(0.0126)
LCP in unit* 1802 Coaching inn	0.0865**
	(0.0365)
County FE?	Y
Second Nature controls?	Y
Observations	8,337
R-squared	0.216

Notes: The dependent variable is Δ1891,1851 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include 1802 coaching inns, first nature variables, second nature variables, county fixed effects, and 1851, 1841, and 1831 ln pop density as controls. All units less than 7 km from an LCP node are dropped.

Next, we report results for our 'change on change' specification as explained in section 4. They show a positive and significant effect of the change in station access and the log change in population from 1821 to 1891. See table A.6.2.

Table A.6.2: Estimates for effect change in 1891 and 1821 stations on difference in log 1891 and log 1821 population

	Dependent var.: Δ1891,1821 Ln Pop	
	(1)	(2)
Estimator	OLS	IV
Change in Station 1891, 1821	0.324***	0.605**
	(0.023)	(0.274)
Kleibergen-Paap F stat		29.716
Observations	8,337	8,337
R-squared	0.345	
First stage: Change in Station 1891, 1821		(3)
		OLS
LCP in unit		0.0720***
		(0.0146)
Observations		8,337
R-squared		0.223

Notes: Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include first nature variables, second nature variables, and county fixed effects as controls. All units less than 7 km from an LCP node are dropped.

Next, we use different percentiles of 1801 population density like the 50th or 70th to test for heterogenous effects. The results are very similar as table A.6.3 shows.

Table A.6.3: Heterogeneous effects of getting a station by 1851 on population growth from 1851 to 1891 using different percentiles for 1801 population density

	(1)	(2)	(3)	(4)
Estimator	OLS	IV	OLS	IV
Station by 1851	0.214***	0.497**	0.186***	0.522***
	(0.101)	(0.192)	(0.026)	(0.187)
Below 50th pct. pop den. 1801	-0.006	0.0188		
	(0.011)	(0.016)		
Station by 1851* Below 50th pct. pop den. 1801	-0.131***	-0.451***		
	(0.039)	(0.166)		
Below 70th pct. pop den. 1801			-0.061**	-0.017
			(0.016)	(0.024)
Station by 1851* Below 70th pct. pop den. 1801			-0.041	-0.350**
			(0.037)	(0.165)
Kleibergen-Paap F stat		19.689		20.279

Observations	8,377	8,377	8,337	8,337
R-squared	0.306		0.307	

Notes: The dependent variable is Δ1891,1851 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include county fixed effects, first nature variables, second nature variables, 1851, 1841, and 1831 ln pop density as controls. All units less than 7 km from an LCP node are dropped. In (2) the instruments are the indicator for LCP and the indicator for LCP interacted with dummy for unit below 50th percentile 1801 population. In (4) we add the instrument indicator for LCP interacted with dummy for unit below 70th percentile 1801 population.

Next, we report results using the difference in log 1881 and 1851 occupational shares. The text reports results using the difference in 1881 and 1851 occupational shares without taking logs. The results in table A.6.4 give similar conclusions.

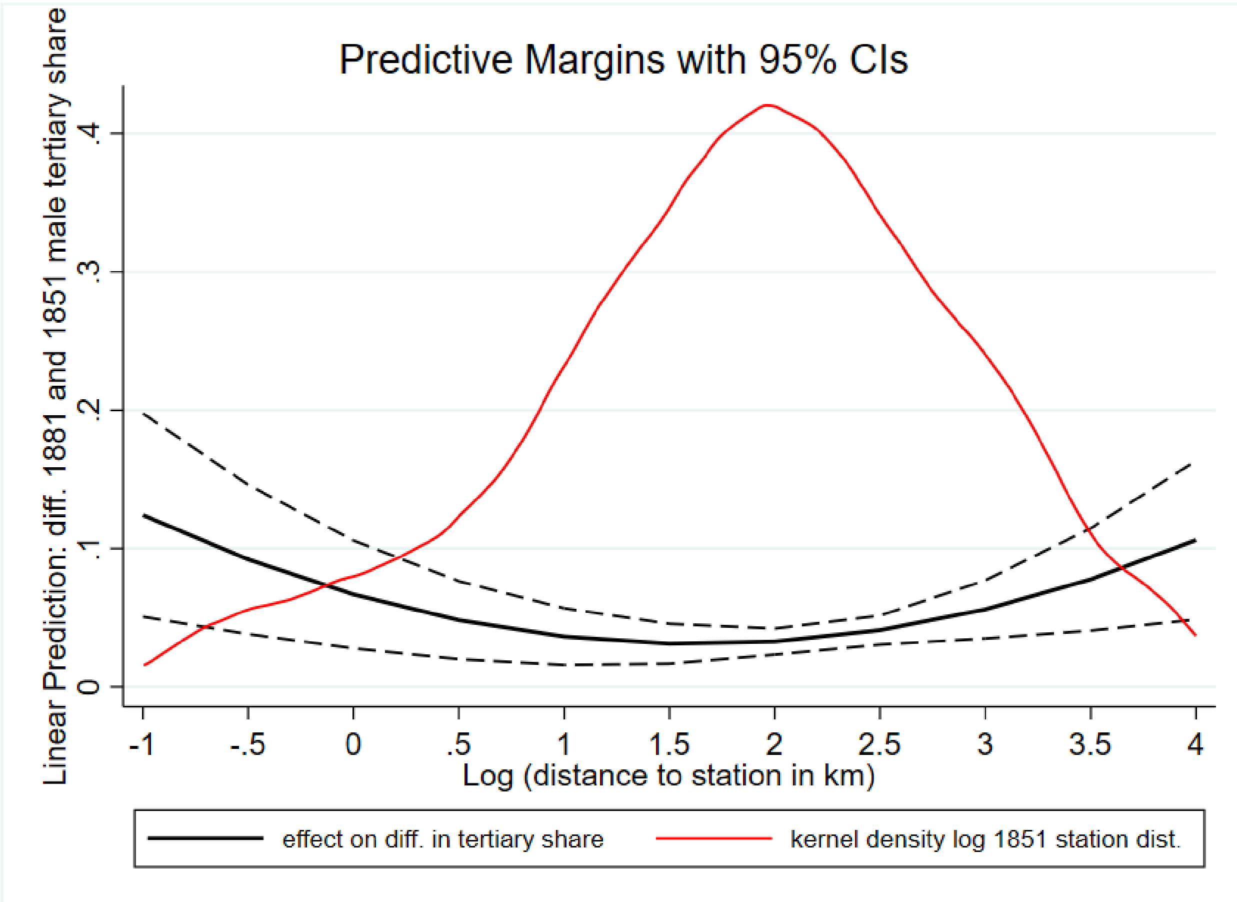
Table A.6.4: Estimates for effect of 1851 station on difference in log male occupational shares 1881 and 1851

	(1)	(2)	(3)	(4)	(5)	(6)
Estimator	OLS	IV	OLS	IV	OLS	IV
Dependent variable:	Δ log male agriculture occupational share		Δ log male secondary occupational share		Δ log male tertiary occupational share	
Station in unit by 1851	-0.117***	-0.336*	0.0645***	0.365**	0.120***	0.3002
	(0.0138)	(0.185)	(0.0139)	(0.169)	(0.0178)	(0.282)
Kleibergen-Paap F stat		48.146		47.026		47.770
Observations	8,333	8,333	7935	7935	8,178	8,178
R-squared	0.343		0.143		0.403	

Notes: Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All specifications include county fixed effects, first nature variables, second nature variables, 1851, 1841, and 1831 ln pop density as controls, and 1851 male shares in agricultural, secondary, tertiary, mining, or unspecified occupations. The instrument for station in unit by 1851 is an indicator if unit has LCP in its boundaries. All units less than 7 km from an LCP node are dropped.

Next, we show the IV estimates for effects of log station distance on the difference in tertiary shares. The IV estimates imply tertiary shares increased significantly less for all units between a log distance of 1.5 and 2.5, or 5 to 12 km.

Figure A.6.1:. IV estimates for effect of 1851 station distance on the difference in 1881 and 1851 tertiary shares


Predictive Margins with 95% CIs
Linear Prediction: diff. 1881 and 1851 male tertiary share
0
.1
.2
.3
.4
-1
-.5
0
.5
1
1.5
2
2.5
3
3.5
4
Log (distance to station in km)
effect on diff. in tertiary share
kernel density log 1851 station dist.

Appendix A.7: Placebo tests using different sample restrictions

Following from section 6, we show results for placebo tests, which focus on population growth before railways. We begin with a specification that regresses the difference in log 1831 and log 1801 population on an indicator for having the LCP plus control variables. The aim is to see whether the LCP has a significant effect on the difference in log 1831 and log 1801 population when there are no sample restrictions and under the various sample restrictions. If there is a significant effect, then that raises concerns the LCP is capturing factors which explain growth that are not associated with railways.

Appendix table A.7.1 shows results with no sample restriction or when we exclude units less than 3 km from nodes. In these samples, having the LCP pass through a unit has a significant effect on population growth between 1801 and 1831, before railways arrived. In (1) and (2) this holds with and without second nature and county fixed effects as controls. In (4) the LCP effect is significant in (4) with these added controls. These results raise the concern that in the un-restricted sample, or when units less than 3 km are excluded, the LCP is capturing factors which explain growth that are not associated with railways.

Table A.7.1: Placebo test I: Effects of LCP on difference in log 1831 and log 1801 population with no sample restrictions or excluding units less than 3 km from nodes

	No sample restrictions		Exclude units less than 3 km from nodes	
	(1)	(2)	(3)	(4)
Estimator	OLS	OLS	OLS	OLS
LCP in unit	0.031	0.025	0.015	0.013
	(0.009)***	(0.008)***	(0.009)	(0.008)*
County FE?	N	Y	N	Y
Second Nature controls?	N	Y	N	Y
Observations	9,480	9,480	9,044	9,044
R-squared	0.0638	0.144	0.0637	0.1206

Notes: The dependent variable is Δ1831,1801 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All models include first nature variables and ln pop 1801 density as controls. For definitions of first and second nature variables see text.

Appendix table A.7.2 shows results when we exclude units less than 7 km from nodes and when units overlap with the built-up area of nodes. In these samples, having the LCP pass through a unit does NOT have a significant effect on population growth between 1801 and 1831, before railways arrived. Thus, in these samples, there is no obvious concern the LCP is capturing factors which explain growth that are not associated with railways.

Table A.7.2: Placebo test II: Effects of LCP on difference in log 1831 and log 1801 population, excluding units less than 7 km from nodes and units overlapping with built up area of LCP nodes

	Exclude units less than 7 km from nodes		Exclude units overlapping with built up area of LCP nodes	
	(1)	(2)	(3)	(4)
Estimator	OLS	OLS	OLS	OLS
LCP in unit	0.0002	0.0054	0.0001	0.0043
	(0.0087)	(0.0080)	(0.0083)	(0.0079)
County FE?	N	Y	N	Y
Second Nature controls?	N	Y	N	Y
Observations	8,337	8,337	8,860	8,860
R-squared	0.062	0.116	0.0557	0.1015

Notes: The dependent variable is Δ1831,1801 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All models include first nature variables and ln pop 1801 density as controls. For definitions of first and second nature variables see text.

Finally, we use placebo tests to show that a variable for the LCP interacted with coaching inns by 1802 is not significantly related to the difference in log 1831 and log 1801 population. Here we exclude units less than 7 km from nodes. See table A.7.3 for results. Thus, in this sample, there is no obvious concern that having inns and the LCP are capturing factors which explain growth that are not associated with railways.

Table A.7.3: Placebo test III: Effects of LCP and its interaction with coaching inns on difference in log 1831 and log 1801 population

	(1)	(2)
Estimator	OLS	OLS
LCP in unit	0.0005	0.0071
	(0.0083)	(0.0076)
LCP in unit* 1802 Coaching inn	-0.0319	-0.02371
	(0.0224)	(0.0221)
County FE?	N	Y
Second Nature controls?	N	Y
Observations	8,337	8,337
R-squared	0.072	0.1228

Notes: The dependent variable is Δ1831,1801 Ln Pop. Standard errors in parentheses are clustered on counties. *** p<0.01, ** p<0.05, * p<0.1. All models include first nature variables and ln pop 1801 density as controls. For definitions of first and second nature variables see text. All units less than 7 km from an LCP node are dropped.