Railways, endowments, and population change in 19th century England and Wales[1]

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Abstract

Railways transformed inland transportation during the nineteenth century. In this paper, we test whether population increased near railway stations in an already urbanized economy, England and Wales. Our analysis shows that being near railways led to significantly higher population even after addressing endogeneity. We also examine three important issues related to railways and population change. First, we test whether population gains near stations coincided with population losses a short distance from stations. Our results show that population increased significantly within 2 or 3 km of a station, but more surprisingly population did not decline at distances 10 or 15 km from stations. Second, we test how local endowments changed the impact of railways. Our results show that having coal and being coastal substantially increased the population gains from being close to railways. Third, we test how initial population density changed the impact of railways. Our results show the most dense locations in 1801 gained less from railways than middle density locations. All together, we find that railways grew population near stations without leading to depopulation farther away, the impact was larger with favorable endowments, and railways contributed to some population convergence across space.

Keywords: Urbanization, railways, transport, reorganization, endowments

JEL Codes: N7, O1, R4

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I. Introduction

The effects of transport infrastructure on urbanization and regional economic development are issues of long-standing importance. Many studies use historical contexts to examine the long-run impacts of infrastructure. Railways feature prominently in these studies and several show that population increased significantly in a town or county once it got a railway station nearby.[7] Such findings raise further questions. Did locations near railways gain significant population in economies that were already urbanized? Did population growth near stations come at the expense of population declines farther from stations? Did railways' population impact differ depending on initial population size or endowments? All these questions are important from policy and theoretical perspectives.[8]

In this paper, we estimate how the introduction of a railway station changed the population of a local area in England and Wales, whether population increases came at the expense of nearby areas, and whether its impact depended on endowments or pre-existing agglomeration. The English and Welsh economy provides a good context to study these issues. First, the urbanization rate was already high before railways arrived (Shaw-Taylor and Wrigley 2014). This provides a context to test whether railways led to further or new agglomeration. Second, mobility and migration were high, so railways could easily attract population (Boyer and Hatton 1997, Long 2005). Third, natural endowments, such as coal, played an important role in English industrialization and urbanization before railways (Wrigley 2010, Fernihough and

[7] For some examples see Hornung (2015), Berger and Enflo (2017), Atack, Bateman, Haines, and Margo (2010).
[8] See Redding and Turner (2015) for an overview of the literature, and where these issues are discussed.

O'Rourke 2014), and therefore provide a context to test how transport change enhanced natural resource advantages.

Our analysis of railways in England and Wales uses a new dataset with local populations in every decennial census year from 1801 to 1881. Our spatial 'units' are constructed from parishes and townships, the smallest places reported in the British Census.[9] We define a unit center based on a large dataset of market squares and churches. We also incorporate GIS data on railway lines and stations in each decade from 1831 to 1881. Finally, our data also includes geographic characteristics, like coastline and coal, and pre-rail infrastructure networks like turnpike roads, ports, and inland waterways.

In the empirical analysis, we use a panel regression exploiting the variation in population density and railway access across 9489 units in nine census years from 1801 to 1881. In the baseline specification, we define a treatment indicator for all units having railway stations within 2 km of their center, following contemporaries who emphasized the importance of being very close to stations. The results from our baseline fixed effects (FE) model show the opening of a railway station within 2 km increased unit population by approximately 18% relative to all other units.

Endogeneity is a key concern in our estimation. However, using an instrumental variables (IV) strategy based on least cost paths, we show that differences between IV and FE estimates are not significant. Thus, our estimates confirm that population increased near railway stations in England and Wales, even though it was already urbanized to a large degree.

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

Next, we address three subsidiary questions. First, did railways in England and Wales cause population to decline some distance away from stations? In this analysis, railway treatment is defined in 1 km bins up to 20 km from a station with units more than 20 km distant serving as the control group. We find population changed little for units between 3 and 20 km from a station compared to units beyond 20 km. Similar results are found using control groups up to 70 km from stations. Strikingly, there is no evidence railways caused population declines in the hinterland of a station. There was still hinterland-to-station migration, but it was not so significant as to absolutely depopulate such areas.

Second, did the effect of railways differ depending on local endowments? Our results show that getting stations within 2 km increased population by an additional 13 to 15% if units had coal or if they were coastal. Our interpretation is that having coal and being coastal led to an initial advantage that was further exploited by the wider market brought by railways. Also being coastal was associated with more competition between railways and steamships.

Third, did railways have different effects across the distribution of 1801 population density? Our results show getting stations within 2 km increased population by 6 to 10% more for units in the 3^{rd} to 9^{th} deciles of 1801 density versus the 10^{th} or top decile. These results suggest that railways contributed to some population convergence. We think the top density units had smaller prospects for population growth because there was no vacant land to convert into new housing and it was very costly to build vertically in the nineteenth century. Units in the middle to upper part of the 1801 distribution (the 3^{rd} to 9^{th} decile) did not face this problem.

Our results contribute to a large literature on railways and nineteenth century growth. [10] For England and Wales, there have been qualitative assertions suggesting the importance of railways on population growth and preliminary quantitative investigations of such issues.[11] This paper goes further by considering different mechanisms behind railways' impact with a much enriched empirical basis. In terms of methodology, the most closely related papers are Hornung (2015), Berger and Enflo (2017), and Buchel and Kyburz (2018), who study railways and population change in Prussia, Sweden, and Switzerland respectively. We differ by studying a more advanced economic context. Some of our results are similar, but others are different. Bucel and Kyburz and Berger and Enflo find that railways caused population losses away from stations, whereas we do not. We think railways in England and Wales did not confer such a large locational advantage as in economies less developed when railways arrived. Concerning initial density, Hornung finds that in Prussia railways had larger effects for small and medium towns compared to the largest towns. Like in England, we think the more limited supply of land in the most dense areas probably explains why railways had smaller effects there. Finally, Berger and Enflo find no coastal interaction effect with railways, whereas we do. Again, since England was more developed around coastal areas before railways, we think it makes sense that railways fostered growth more in coastal areas than in Sweden.

[10] See Tang (2014) for Japan, Atack, Bateman, Haines, and Margo (2010), Attack and Margo (2011), Donaldson and Hornbeck (2016), and Hodgson (2018) for the US, Jedwab, Kerby, and Moradi (2015) for Kenya, and Donaldson (2018) for India.

[11] See Simmons (1986), Hawke (1970), Dyos and Aldcroft (1974), Gourvish (1986), Kellet (2012) for qualitative studies and Hawke (1974), Leunig (2006), Gregory and Martí Henneberg (2010), Casson (2013), Casson et. al. (2013), Alvarez et. al. (2013), and Heblich, Redding, and Sturm (2018) for quantitative studies.

Our results also contribute to a broader literature studying the effects of transport infrastructure and regional development.[12] Many articles focus on local and regional outcomes in recent decades. Historical contexts, like the one studied in this paper, complement this literature by providing a long-run perspective. For example, one can usefully learn whether infrastructures lead to 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 an already developed economy.

The paper is organized as follows. Section II provides background. Section's III and IV introduce data and methods. Section V describes the baseline results. Section VI addresses endogeneity. Sections VII, VIII, and IX analyze population losses and heterogeneity.

II. Background

II.A Urbanization

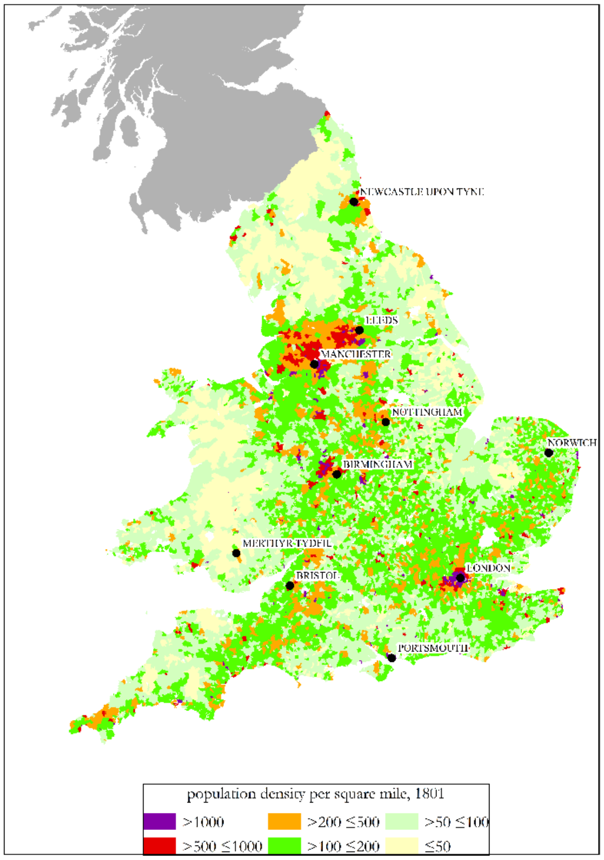
The nineteenth century was a period of significant population increase in England and Wales. Census figures show the population increased from 8.6 million in 1801 to 17.0 million in 1851 and 22.3 million in 1881. Employment also changed. Shaw-Taylor and Wrigley (2014) document that 36% of adult males worked primarily in agriculture in 1817, but in 1871 it was only 19%. The secondary sector absorbed a small share of the male labor force leaving agriculture. From 1817 to 1871 the percentage of male secondary employment rose from 44% to 46%. Male tertiary employment experienced the most change, increasing from 18% to 28%.

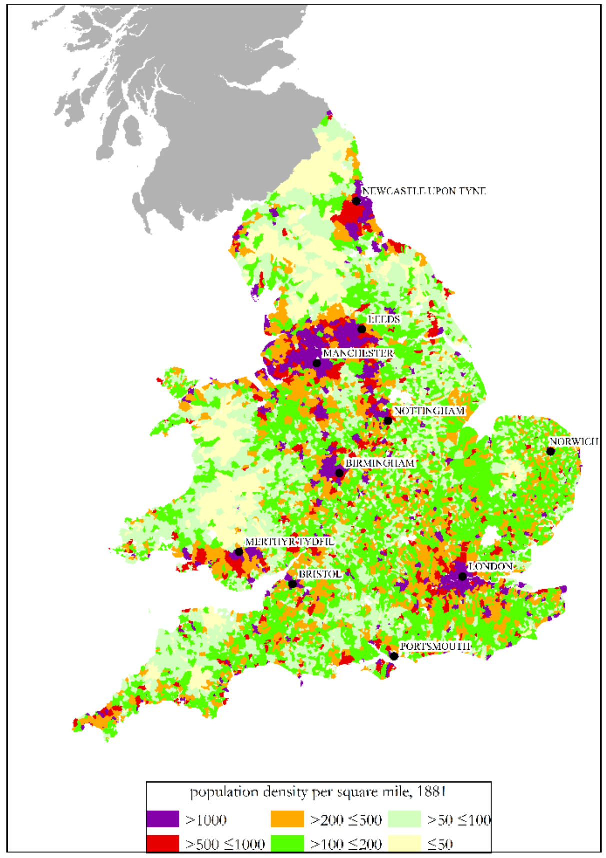
[12] See Baum-Snow (2007), Duranton and Turner (2012), Faber (2014), Jedwab et. al. (2015), Garcia-Lopez et. al. (2015), Storeygard (2016), Ghani (2016), Holl (2016), Baum-Snow et. al. (2017), and Gibbons et. al. (2019).

With structural change there was an increased concentration of population in urban areas. The percentage in towns of 5000 or more was already high in 1801 at 29.5% of the population. But it increased further to 56.7% in 1871 (Shaw-Taylor and Wrigley 2014). In rural areas, population generally stagnated or declined. Essentially all population growth was urban growth, indicating a migration from rural to urban.

While most urban areas grew, the rate differed across them. London kept growing over the nineteenth century but at a rate not much greater than the national average. The highest growth rates were observed in major industry towns, mining areas, and ports such as Manchester, Leeds and Liverpool, though their growth rates were far away from being uniform. Further down the hierarchy, there was still a substantial proportion of population living in small-medium sized towns. They experienced a wide spectrum of population growth rates. There was also a spatial pattern to growth near historical urban centers. As demonstrated by figure 1, areas a short distance from the centers, or what Kellet (2012) calls inner districts and suburbs, appear to have experienced the fastest population expansion. Historians have argued that railways were a key factor leading to these different urban growth experiences, but the magnitude of their effects and interaction with initial conditions are unclear (Simmons 1986).

Figure 1: Population density in 1801 and 1881





II.B Development of railways

England and Wales had a well-developed transport network before railways. It had many good roads suitable for coaches and large wagons and it had a large inland waterway network for barges. Even so, railways were far superior in both speed and cost. For example, rail freight rates in 1870 were one-tenth road freight rates in 1800 in real terms (Bogart 2014). However, road transport remained competitive with railways in short distance. For example, carts dominated within ten miles of London even though they were more expensive (Kellet 2012, p. 288). Shipping was another transport mode that remained competitive. Steamships transformed coastal and international shipping and complemented railways (Armstrong 2009).

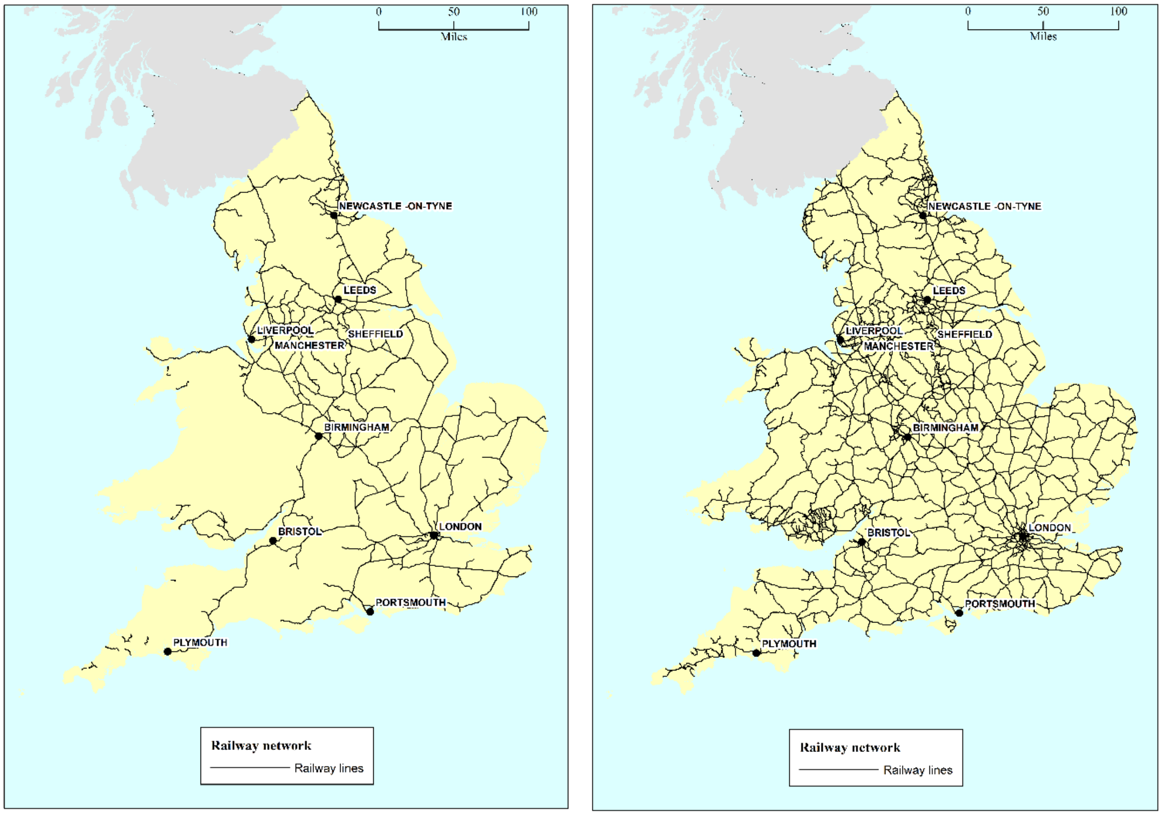
The first public, steam powered rail service opened in 1825 in the coal mining region between Stockton and Darlington. Then in 1830, the Liverpool and Manchester railway opened, followed by several other railways connecting large towns. By 1841, 9 of the 10 largest cities had railway connections. Along these trunk lines, the average distance between stations was 4 to 5 miles, so some smaller towns got stations nearby because of connections between larger cities (Simmons 1986, p. 98, 232).

Several factors influenced the routes of the early railways. The first and main consideration was to connect large cities by the most direct route in order to save construction costs (Simmons 1986, pp. 169-171). Land acquisition costs were another consideration. When railway companies approached urban areas, they often built lines through slums and working-class neighborhoods because there was less opposition (Kellet 2012, p. 306, 335).

The 'railway mania' of the mid-1840s was the period with the biggest expansion of the network. It was partly driven by the early railway company's strategy to maintain their position. It was also driven by politicians who wanted railway stations in their constituencies.[13] The significance of the railway mania can be seen in the growth of track mileage. Between 1839 and 1844, railway km grew from 1560 to 3456 and between 1845 and 1851 it grew to 10,082 km. The rail network in 1851 is shown in the left-hand panel of figure 2. By this year, regional networks had formed around the large towns in addition to connections via the trunk lines.

Figure 2. The railway network in 1851 and 1881

[13] For the literature on the railway mania see Casson (2009), Odlyzko (2010), Campbell and Turner (2012, 2015)



A substantial growth in traffic came with network expansion. The growth rate in passenger services was largest in the early years when railways displaced coaches. Passenger miles increased at annual rate around 20% in the 1840s and 10% in the 1850s. It fell to 5% or less by the 1860s and 70s (Hawke 1974, p. 50). Railway freight traffic also grew at its highest rate in the 1840s and 1850s, although it continued to increase well into the 1900s.

Extensions to the rail network in the 1860s and 70s facilitated traffic growth. The network in 1881 is shown in the right-panel of figure 2. By then railway lines reached all parts of England and Wales. Few towns lacked a railway station and many rural areas had stations too.

III. Data

Our population data come from British censuses, available every decade starting in 1801. Individuals are counted at a place, usually the parish or township. The census was taken on a Sunday, so that census takers could identify where people lived, not where they worked. The census population counts have been digitized at the smallest census place level for nine 'census years' from 1801 to 1881.[14] One challenge is that census places are not always the same across time. To address boundary changes, we have created consistent spatial units between 1801 and 1881 and linked them with census population and occupation data.[15] Our sample size is 9489 and spans all counties in England and Wales. Using GIS, we also associate each unit with a 'center.' The center corresponds to a town central point, if the unit had a town within its boundary at some point between 1600 and 1850.[16] If there was no town within the boundary, the centroid is used. The centroid arguably makes sense for a rural unit without a marketplace. Regardless, little error is introduced by using the town center or centroid since our units are only 15 square km on average.

Our railway data includes GIS shapefiles for railway lines and stations in every census year starting in 1831. The rail networks are created using historical maps and are highly accurate.[17] To analyze railways, a straight line is drawn from the center of each unit to its nearest station. That allows us to create several railway access variables. For example, we know

[14] The digitization of the population data is described in Wrigley (2011). Later data comes from the Integrated Census Microdata (I-CeM), 1851-1911. See Schurer and Higgs (2014).

[15] We create 9489 consistent units mapping population from 1801 to 1891 and male occupations in 1817, 1851, and 1881. We thank Gill Newton, of the Cambridge Group for History of Population and Social Structure, who developed the Python code.

[16] Satchell, Potter, Shaw-Taylor, Bogart (2017) provide a dataset on 1746 towns and their centers. 746 of our units have at least one town in them. If there is a single town, we choose its center. If there are multiple, the town center with the largest 1801 population is used.

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

that in 1841, 4.6% of units had a railway station within 2 km. By 1881, 29.9% of units had one. 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. We address this below.

Other variables include indicators for being on exposed coalfields and being on the coast, ruggedness measures, average rainfall and temperature, wheat suitability, latitude, longitude, and the share of land in 10 different soil types.[18] We call these 'first-nature' variables following the literature in economic geography (see Fujita et. al. 2001). Coastal is identified using an intersection of the seacoast with unit boundaries. The ruggedness measures include average elevation within units, the average elevation slope, and the standard deviation in elevation slope (see appendix 2 for details). Annual rainfall and temperature (both averaged from 1961 to 1990) and wheat suitability come from FAO.[19] Of special significance, Satchell and Shaw-Taylor (2013) identify those areas with exposed coal bearing strata (i.e. not overlain by younger rocks). Exposed coalfields were more easily exploited compared to concealed coal (see appendix A.3 for details).

Another set of unit-level variables are called 'second-nature' factors, meant to capture initial agglomeration. These variables include distance to one of the ten largest cities in 1801[20],

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[18] 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.
[19] 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.
[20] The ten largest cities are London, Manchester, Birmingham, Liverpool, Leeds, Bristol, Newcastle, Plymouth, Portsmouth, Sheffield

log population density in 1801, and distance to pre-railway infrastructures like turnpike roads in 1800, inland waterways in 1800, and ports in 1780.[21] Summary statistics are shown in table 1.

Table 1: Summary statistics

Variable	Obs.	Mean	Std. Dev.	Min	Max
Main panel variables					
Ln unit population per sq. km	85,396	6.334	1.238	1.609	12.128
Station 2 km (Indicator dist. to rail station <2km)	85,401	0.103	0.304	0	1
Distance to rail station in km	56,934	33.135	58.77	0.0214	415.68
Instrument					
Distance to LCP in km	9489	12.67	16.511	7.28e-06	116.39
First-nature controls (cross-sectional)					
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

[21] 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, Dunn, Bogart, Satchell, Shaw-Taylor (2017) created a GIS of ports.

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
Second nature controls (cross-sectional)					
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 major city in 1801 in km	9487	136.3	67.98	0	418.7

Sources: see text.

IV. Empirical specification

Our first goal is to estimate how the introduction of a railway station nearby changed the population of a unit. We use a panel regression exploiting the variation across the 9489 units in nine census years from 1801 to 1881. The baseline specification is

$$y_{it} = unitFE_i + yearFE_t + \beta station2km_{it} + \ county_i * yearFE_t + \varepsilon_{it} \qquad (1)$$

where y_{it} is log population density for unit i in year t, $unitFE_i$ are the unit fixed effects, $yearFE_t$ are the census year fixed effects, $station2km_{it}$ is an indicator equal to 1 if unit i gets its first station within 2 km in year t and zero otherwise, $county_i$ are county fixed effects, and ε_{it} is the error term. All units belong to one of 59 county administrations and so the interactions between $county_i$ and $yearFE_t$ control for county-specific population changes across each decade. In some specifications, we also add interactions between the first and second nature control variables listed in table 1 and year fixed effects.

There are several reasons why 2 km distance is our main treatment indicator for having railways nearby. First, related studies like Buchel and Kyburz (2018) use 2 km distance as their treatment, so it eases comparison. Second, the railway historian, Kellet (2012), gives repeated examples of Victorian business owners, who emphasized the value of being very close to stations.[22] Third, it is thought that most English workers lived close to their work (Pooley and Turnbull 2005, p. 173), so if firms chose to locate near stations, then most of their workers would live nearby too. All that said, the station distance most relevant for firms and workers is not exactly known. In a later section, we also consider treatment beyond 2 km, and more specifically spillover effects onto neighboring units 5 or 10 km from a station.

Before turning to the estimates, it is important to acknowledge that the baseline specification assumes treated and untreated units have the same population trends prior to treatment. The 'parallel trends' assumption may not hold in our context for many reasons, but mainly because railways could have been built in areas more likely to grow. We will test for pre-trends and use an instrumental variable strategy to examine potential bias.

V. Baseline results

The results for specification (1) are shown in table 2. The coefficient for stations within 2 km is expressed in log points, or approximately the percentage difference in population between units within 2 km of stations versus others. The standard errors are clustered on the unit in all specifications. As there is a potential for spatial correlation, we also calculated Conley standard errors. The latter were very similar to clustered standard errors.[23] The results in

[22] One claimed if they were to establish a warehouse, they would prefer a location one-half mile from a station rather than one mile away (p. 308). In another case, it was noted that locations beyond half a mile from a station could become 'derelict' (Kellet p. 324). In another, land values rise within a half-mile radius of a station (p. 309).
[23] For all specifications in table 2, we calculated Conley standard errors using 10 km as the uniform distance cutoff. We also allowed for serial correlation across two periods using the code provided by Hsiang (2010). The resulting standard errors are similar and even smaller than in table 2. Estimates are available upon request.

column (1) imply that population increased by 20% in units after they gained stations within 2 km when compared to units that did not gain stations within 2 km in the same year. The estimated effects are reduced somewhat after accounting for first and second nature factors that might influence trends over the nineteenth century. Notice the coefficient in columns 2 and 3 is approximately 0.176 versus 0.202 in column 1. The last specification (4) shows the estimates are not affected by dropping the 82 units where station closures meant they lost a station within 2 km (see column 4).

Table 2. Baseline results

Dependent variable: Ln unit pop. density	(1)	(2)	(3)	(4)
Station 2 km	0.202***	0.178***	0.176***	0.180***
	(0.008)	(0.008)	(0.008)	(0.008)
Unit FE, Year FE, County*Year FE	Y	Y	Y	Y
First Nature*Year FE	N	Y	Y	Y
Second Nature*Year FE	N	N	Y	Y
Drop units where station closure increased distance beyond 2 km	N	N	N	Y
Observations	85,396	85,351	85,320	84,582
R-squared	0.399	0.439	0.443	0.443

Notes: Standard errors in parentheses are clustered on the unit. *** p<0.01, ** p<0.05, * p<0.1. For definitions of first and second nature variables see table 1.

In terms of magnitude, an 18% increase in population (the estimate in 4) represents a sizeable effect. The mean unit population growth between 1831 and 1881 was 1% and the standard deviation was 16.3%. Therefore, the effects of getting a station were equal to 1.10 standard deviations of population growth. Later, we provide a detailed counterfactual estimate of how population would have changed without railways, but first we examine parallel trends.

The specification in equation (2) uses an 'event study' analysis

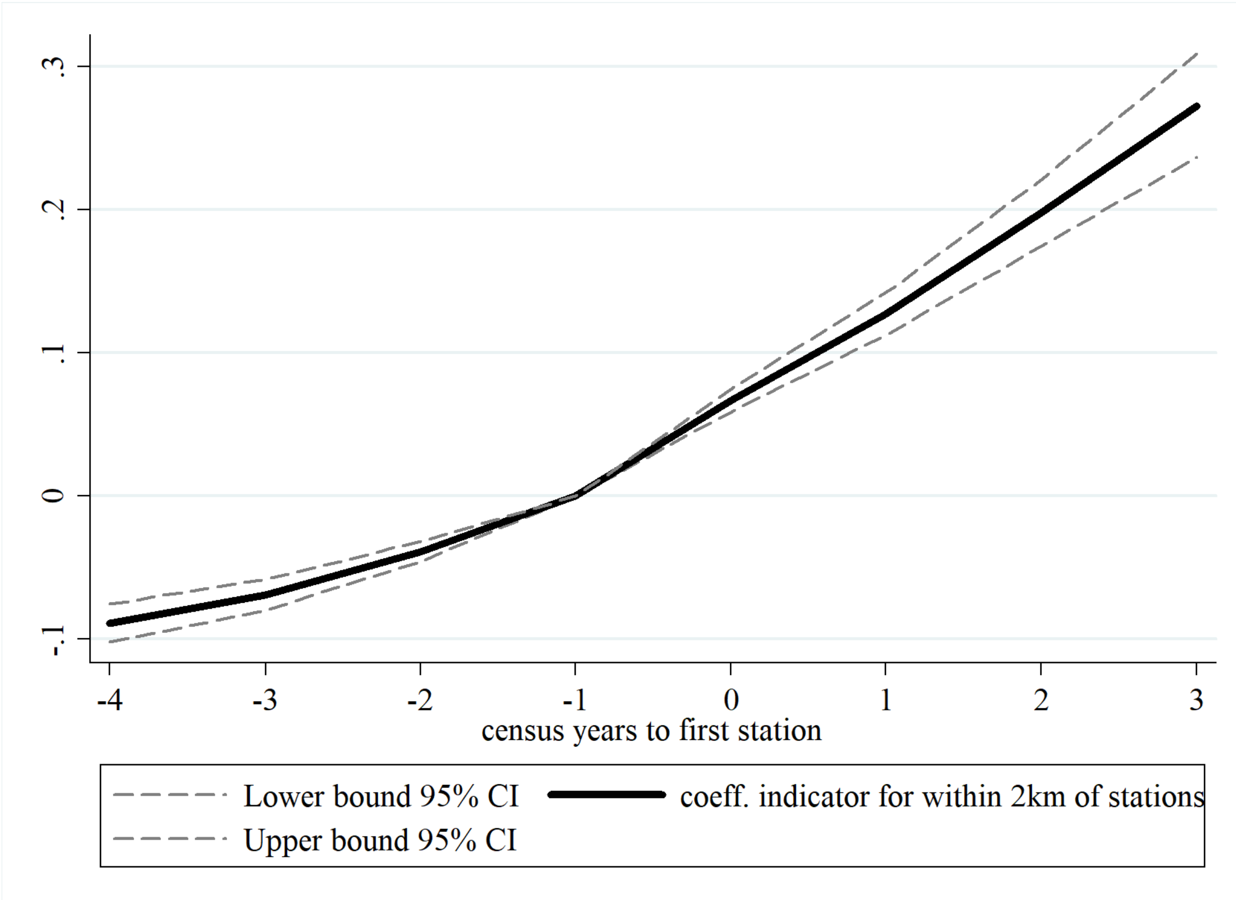
$$y_{it} = unitFE_i + yearFE_t + \sum_{j=-8,\neq -1}^{j=5} \beta_j I\{station2km\}_{it+j} + \gamma x_i \cdot yearFE_t + \varepsilon_{it} \qquad (2)$$

where $I\{station2km\}_{it+j}$ is an indicator equal to one if the unit get treated with its first railway t + j census years from year t and zero otherwise. The omitted variable $I\{station2km\}_{it-1}$ is an indicator equal to one if the unit will get treated in the next census year. Notice that we identify how population is different for units up to 8 census years before (t- 8) they got their first station and 5 census years after (t+5) they got their first station.

Figure 3 shows coefficient estimates from the event study specification with 95% confidence intervals.[24] We focus on the four census years prior and the three census years after to make the magnitudes easier to see. The estimates show that population is 6.6% higher in the first census year after opening. By the second, third, and fourth census years it is 12.7, 19.7%, and 27.2% higher. Thus, the relative population difference from being near a station increased over time. However, the estimates also show that population trended up prior to units getting their first railway. For example, population is 3.8% higher one census year before getting the first station compared to two census years before getting the first station. This last finding implies the parallels trends assumption does not hold. As a result, the baseline specification is potentially biased. Fortunately, we have an IV strategy to investigate whether endogeneity leads to a large bias in this setting. The next section develops the approach.

[24] Note this model includes the full set of controls, like the interactions between year fixed effects and first and second nature variables. Note the sample does not include the 82 units where station closures meant they lost a station within 2 km because the event of getting a station nearby is more complicated.

Figure 3: Event Study estimates for railway station effects with 95% confidence intervals



Notes: This solid line is estimated log point population change from being within 2 km of a station four census years before and three census years after. Dashed lines are 95% confidence intervals.

VI. Instrumental variable estimates

Our instrumental variable is derived from the 'inconsequential places' approach.[25] The key idea is that some units became close to railway stations simply because they were on the route designed to connect larger towns at a low capital cost. The first step in creating the instrument

[25] See Chandra and Thompson (2000), Michaels (2008), Faber (2014), and Lipscombe et. al. (2013) for foundational papers.

is to select town-pairs that will be connected by railways. We start with all English and Welsh towns having a population greater than 5000 in 1801.[26] Their larger size meant they were almost certain to get at least one railway line connecting them with another town above 5000. But not all large town-pairs would be connected. A profit-seeking promoter would see little value in building a railway to connect distant towns of a moderate size. We use a simple gravity model to calculate the relative value of connecting all town-pairs each with a population above 5000. The gravitation value G_{ij} for town pairs i and j is $G_{ij} = (pop_i * pop_j)/dist_{ij}$, where $dist_{ij}$ is the straight line distance between town i and j. We ordered G_{ij} from largest to smallest and connect all pairs with a value greater than a threshold defined momentarily.

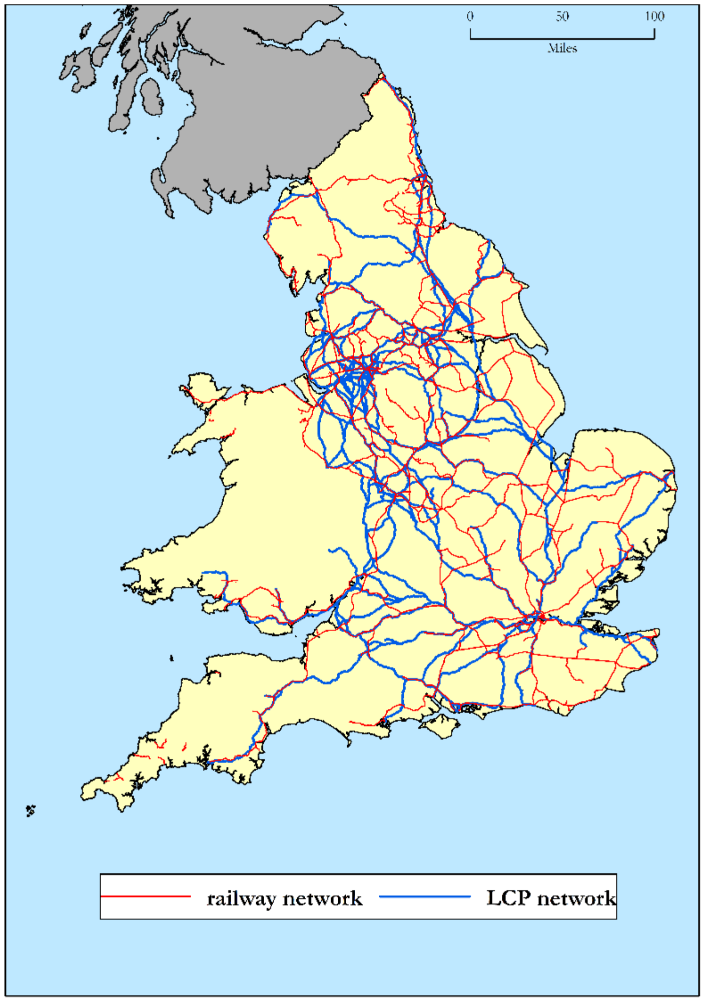
The second step is to identify routes connecting the selected town-pairs. We assume that in considering their routes, railway companies tried to minimize the construction costs considering distance and elevation slope. We use construction cost data for railways built in the 1830s and early 1840s. We also measure the distance of the lines and total elevation changes between towns at the two ends of the line. The construction cost is then regressed on the distance and the elevation change to identify the parameters (the details are in appendix A.1). 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%). We use this formula and GIS tools to identify the least cost path (LCP) connecting each town pair with a population above 5000 in 1801.

[26] The town population data come from Law (1967) and Robson (2006).

The third step is to identify the routes included in the rail LCP network. Our method is as follows. First, we start with the LCP route associated with the largest gravitational value *G*. Second, we add the LCP route associated with the second largest *G*. If the two routes are close to one another we combine duplicate sections. We continue in the same manner adding LCP routes until the total LCP network size equals the size of the 1851 network. We think 1851 is a useful ending point because most trunk lines were constructed by this date and it follows the railway mania. For clarity, we label as 'LCP nodes' all town points selected to construct the LCP based on their gravitational value. In GIS, the nodes are points and thus the nodes will be within 2 km of our unit centers in some cases. We address this below.

The LCP network and actual 1851 railway network are shown in figure 4. The overlap is almost exact in some cases. Overall many locations close to the LCP appear very close to railway lines. More importantly, since stations were so numerous along the railway line in England and Wales, distance to LCP and distance to the station are very similar.

Figure 4: The LCP network and 1851 rail network compared



Sources: see text.

To further illustrate, we regress the indicator for being within 2 km of a rail station in each census year on an indicator for being within 2 km of the LCP. In these regressions, we drop 350 units within 2 km of the LCP nodes. They are near stations by construction. The results are shown in table 3. In all specifications, being close to the LCP implies a higher probability of being close to a station. In column 2, for example, being within 2 km of the LCP implies a 18.0%

higher chance of being within 2 km of a railway station in 1851. The R-squares are under 0.05 in all models, which is not bad considering we have no other control variables predicting stations.

Table 3: Bivariate regression showing predictive power of the instrumental variable

Dependent variable: 1 if unit is within 2 km of station in year t				
	(1) 1841	(2) 1851	(3) 1861	(4) 1871
Within 2 km of LCP	0.065*** (0.006)	0.180*** (0.011)	0.202*** (0.012)	0.213*** (0.012)
Constant	0.0143*** (0.001)	0.0751*** (0.003)	0.133*** (0.004)	0.190*** (0.005)
Control variables	N	N	N	N
Drop units within 2 km of LCP nodes	Y	Y	Y	Y
Observations	9,139	9,139	9,139	9,139
R-squared	0.025	0.051	0.044	0.039

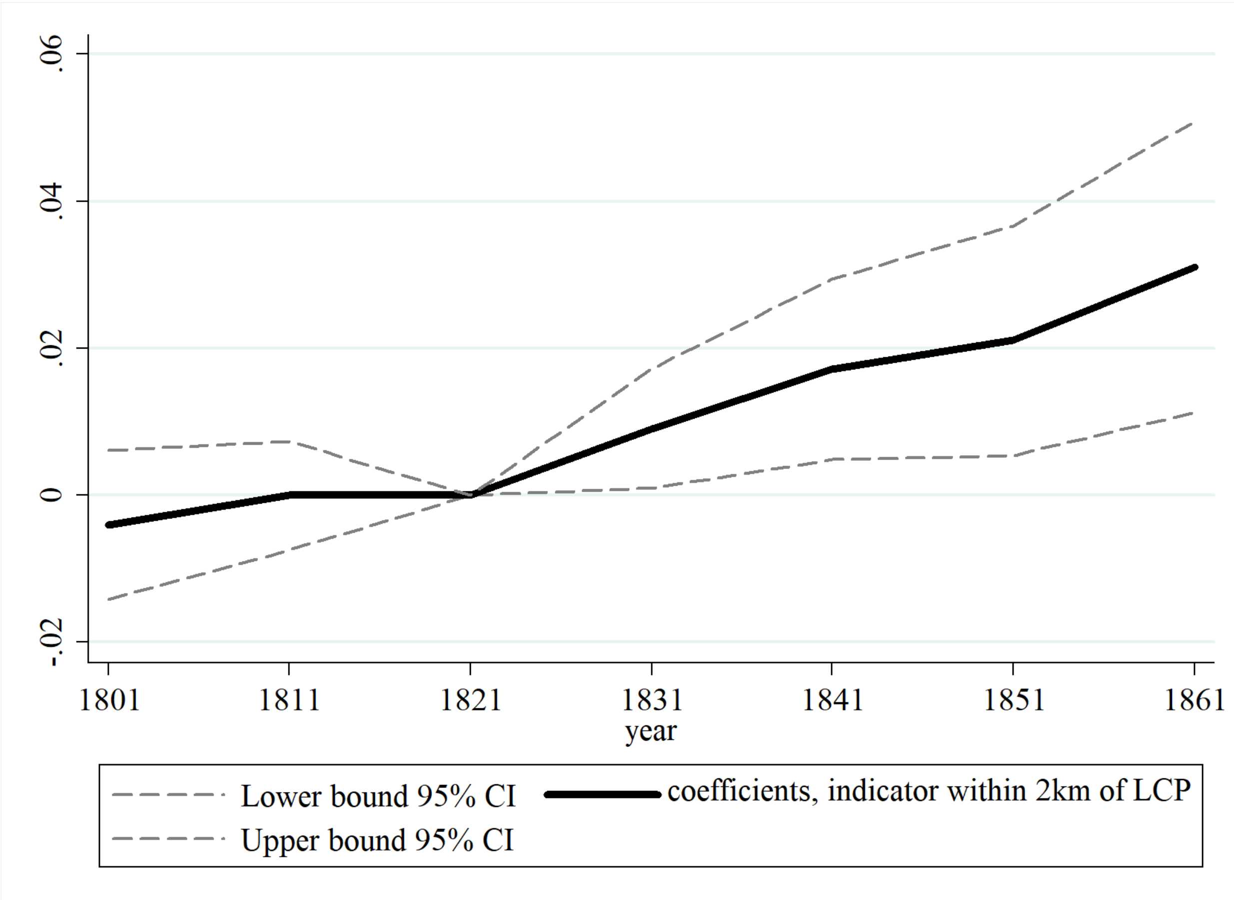
Note: Robust standard errors are reported in parentheses. *** p<0.01, ** p<0.05, * p<0.1

The more crucial issue is whether the instrument is associated with population change through channels other than railway stations. As a test for the exclusion restriction, we examine whether being within 2 km of the LCP influenced early population change. The specification in equation (3) uses all the same variables as the baseline (1), but it includes interactions between the indicator for being within 2 km of the LCP and year FEs. The omitted interaction applies to the census year 1821, before railways arrived.

$$y_{it} = unitFE_i + yearFE_t + \sum_{t=01,\neq 21}^{81} \delta_t LCP2km_i \cdot yearFE_t + x_i \cdot yearFE_t + \varepsilon_{it} \qquad (3)$$

Importantly, we exclude units within 2 km of the LCP nodes as they were selected on potential.

Figure 5: Distance to the LCP and population change over time



Notes: This graph shows the coefficient for being within 2 km of the LCP interacted with year FEs as defined in specification (3). 95% confidence intervals are shown.

The estimates for the LCP-year FE interactions up to 1861 are plotted in figure 5. It shows population in 1801 and 1811 are not statistically different from population in 1821 for units within 2 km of the LCP.[27] Once the railway era begins in 1831, units near the LCP begin to diverge. We should expect this since the LCP is associated with getting railways. From these

[27] Note if we do not exclude the LCP nodes, the population in 1801 and 1811 are statistically different for units within 2 km of the LCP. The magnitude implies it was between 1 and 2 percent lower.

estimates, there is additional reason to be confident that our instrument is valid because it does not predict population trends in the pre-railway era.

Table 4: Instrumental variable estimates for the effect of nearby stations

Dependent variable: ln unit pop. density				
	1831-1881		1831-1871	
	(1)	(2)	(3)	(4)
VARIABLES	FE	IV	FE	IV
Station 2 km	0.126***	0.346***	0.101***	0.245***
	(0.006)	(0.085)	(0.006)	(0.073)
Kleibergen-Paap rk Wald F statistic		22.11		27.66
Unit FE, Year FE, County*Year FE	Y	Y	Y	Y
First Nature*Year FE	Y	Y	Y	Y
Second Nature*Year FE	Y	Y	Y	Y
Drop units within 2 km of LCP nodes	Y	Y	Y	Y
Observations	54,330	54,330	45,275	45,275
R-squared	0.258	0.197	0.240	0.209

	1831-1861		1831-1851	
	(5)	(6)	(7)	(8)
VARIABLES	FE	IV	FE	IV
Station 2 km	0.101***	0.155**	0.0662***	0.112*
	(0.006)	(0.063)	(0.007)	(0.059)
Kleibergen-Paap rk Wald F statistic		34.60		44.53
Unit FE, Year FE, County*Year FE	Y	Y	Y	Y
First Nature*Year FE	Y	Y	Y	Y
Second Nature*Year FE	Y	Y	Y	Y
Drop units within 2 km of LCP nodes	Y	Y	Y	Y
Observations	36,220	36,220	27,165	27,165
R-squared	0.227	0.218	0.248	0.245

Notes to table 4: Standard errors in parentheses are clustered on the unit. *** $p<0.01$, ** $p<0.05$, * $p<0.1$. For definitions of control variables see table 1. The instrument is an indicator if units are within 2 km of the LCP interacted with year FEs.

The IV estimates using data from four time periods are shown in table 4. As we use panel data, the instrumental variable is the indicator for being within 2 km of the LCP interacted with year FEs. The first set of estimates in each set is the baseline FE estimate excluding nodes within 2 km of the LCP. The IV model follows. The Kleibergen-Paap Wald F-statistics are all above 22. The largest F-stat is found for the period 1831-1851, when our LCP fits the rail network best. The IV estimates show sizeable and significant effects from being close to railway stations. The IV estimates are also larger than FE. For example, in the 1831 to 1861 period, being within 2 km of stations is estimated to have increased population by 15.5% in the IV and 10.1% in FE. However, the difference between the IV and FE is not large, and they are not statistically different in a hypothesis test for the equality of the two coefficients.[28]

Our takeaway from this section is that being within 2 km of railway stations caused population to increase by *at least* 10% in England and Wales. Our estimates are in line with what has been found in other countries. For example, studying the period from 1840 to 1861, and using a similar specification to ours, Hornung finds that towns with railroad access had 6.8 to 7.7% higher population. Hornung's estimates are similar to our IV and FE estimates in (7) and (8) for the period 1831 to 1851. Having confirmed that population increased near stations, even in an economy that was already urbanized, we now address our three subsidiary questions.

VII. Railways and population decline away from stations

Several previous studies find that population increases near a station came at the cost of absolute population declines some distance from stations. For example, in Switzerland Bucel and Kyburz (2018) estimate that between 1850 and 1900 there was a 12 to 17% population decline for Swiss villages 4 to 8 km from a railway line. Did the same occur in England and

[28] For example, the p-value is 0.44 for the test that the IV coefficient in column (8) equals the FE coefficient in (7). The p-value is 0.39 for the same test of the IV coefficient being equal to FE in columns (5) and (6).

Wales? To answer this question, we first create 20 indicator variables for station distances 0 to 1 km, 1 to 2 km, and so on up to 19 to 20 km. The specification is shown in equation (4)

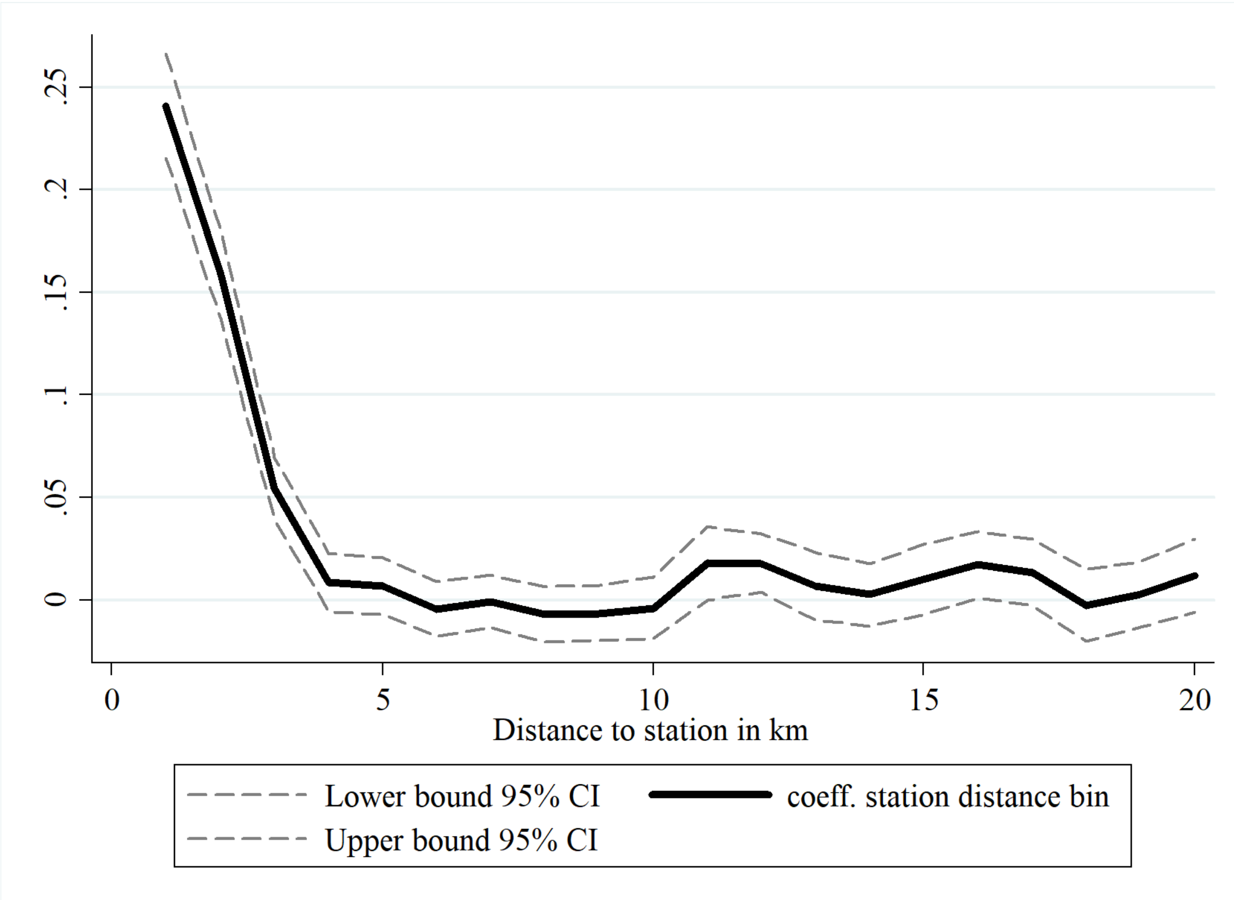
$$y_{it} = unitFE_i + yearFE_t + \sum_{j=0}^{j=19} \beta_j I\{stationjtoj + 1km\}_{it} + \gamma x_i \cdot yearFE_t + \varepsilon_{it} \qquad (4)$$

where $I\{stationjtoj + 1km\}_{it}$ equals 1 if unit i is between j and j+1 km from a station in year t. Each coefficient indicates whether the population in units between j and j+1 km from a station increased or decreased relative to units more than 20 km.

Figure 6 plots the coefficients on the station distance bins. There is a large population increase in units less than 1 km equal to around 24%. Between 1 to 2 and 2 to 3 km, population is also larger at 16% and 6% respectively. For more than 3 km, there is little difference with units more than 20 km, and there no evidence for a significant population loss.

In the previous specification, we use a distance cutoff of 20 km to create our control group. This seems reasonable because historical evidence suggests many goods were shipped to stations by wagon at distances up to 5 miles (Hawke 1970, p. 180). However, one could argue that the 20 km cutoff is too short to evaluate the treatment effect of stations. For Swedish railways, Berger and Enflo (2017) show that population differences between towns in treatment and control groups are insignificant if the control group is 70 km from a station. In the English case, few units were so far from stations by 1881. In fact, the maximum distance was 26 km in 1881. However, by 1851 the maximum distance to a station was 73 km and in 1841 it was 146 km. Therefore, we use our pre-1861 data to estimate a similar specification to (4) but include indicators for station distances 0 to 5 km, 5 to 10 km, and so on up to 65 to 70 km. The omitted group are units more than 70 km from a station.

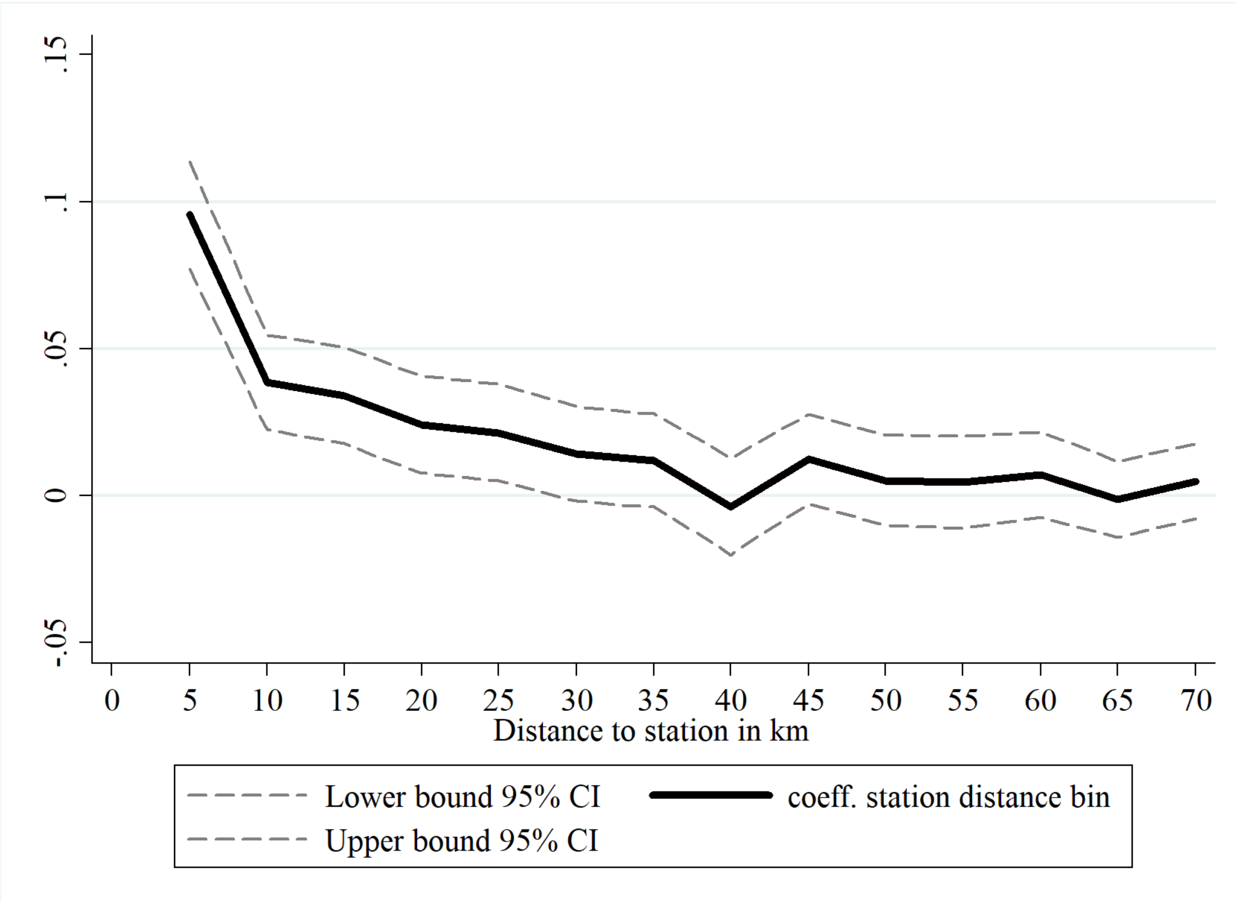
Figure 6: The estimated effect on population at varying station distances up to 20 km



Notes: Solid lines are the coefficient estimates on station distance indicators as defined in equation (4). The dashed lines are 95% confidence intervals.

The coefficient estimates are plotted in figure 7. The effect of being 0 to 5 km distance is large and significant, equal to a 9% population difference with units more than 70 km. Distances 5 to 10 km and 10 to 15 km also have larger population, but the magnitudes are smaller around 3%. Beyond 25 km there is no significant difference with units more than 70 km. In sum, we find no evidence for population increase near stations coinciding with absolute population decline farther away from stations.

Figure 7: The estimated effect on population at varying station distances up to 70 km



Notes: Solid line are the coefficient estimates from a modification of equation (4). The dashed lines are 95% confidence intervals.

Given the high fertility rates at the time (see Shaw-Taylor and Wrigley 2014), the different population changes by distance to railway stations suggests some population 'reorganization' from rural (less connected) to urban (better connected) areas. But unlike the reorganizational effect found in Switzerland and Sweden, what was unique about nineteenth century England and Wales is that railways did not lead to absolute depopulation or population decline in areas farther away from stations. While it is difficult to identify all the reasons, we think that England's advanced prior development offers part of the explanation. Areas farther from stations often had good infrastructure, like roads and inland waterways, before railways.

In fact, the coefficients from our full baseline model show that being closer to turnpike roads and inland waterways in 1800 also led to population increases over the nineteenth century.[29] Therefore, we think units farther from stations had some developmental characteristics which helped them retain some of their population.

VIII. Railways and geographic endowments

We now turn to our second subsidiary question: did having good geographic endowments change the effects of being close to railway stations? Our analysis of endowments focuses on having coal and being coastal. Both played a large role in England's urbanization and development prior to railways. The importance of coal is illustrated by the following fact in our data: population density in 1801 was 194% higher in units that had exposed coal versus those that did not. There are several reasons. First, coal provided cheap energy for home heating, which was a major cost for households (Wrigley 2010). Second, coal also provided cheap energy to fire steam engines, which helped make England's manufacturing sector so productive. Consistent with this point, male secondary employment in the early nineteenth century tended to be higher near exposed coal (Sugden, Keibeck, and Shaw-Taylor 2018).

The importance of being coastal is illustrated by another fact in our data: population density in 1801 was 57% higher in coastal units versus non-coastal units. England's coastal communities have long been noted for their success in domestic and international trade. London, Liverpool, Bristol, and Hull are famous examples of dense trading centers, but there are many others (see Armstrong 2009). Consistent with this point, coastal units generally had

[29] These are not shown to save space but are available upon request.

higher male tertiary employment in the early nineteenth century, especially in occupations related to shipping (Shaw-Taylor et. al. 2010).

We now test whether railways increased population more in coastal units and those that had exposed coal as identified in GIS data. We use interaction variables as in equation (5)

$$y_{it} = unitFE_i + yearFE_t + \beta_1 station2km_{it} + \beta_2 station2km_{it} * geography_i + \gamma x_i \cdot yearFE_t + \varepsilon_{it} \quad (5)$$

where $geography_i$ includes two indicator variables: (1) exposed coal and (2) being coastal. Note that the geographic variables are included in x_i and therefore interacted with the census year FEs to allow for population trend effects independent of railways (they are not reported to save space).

Table 5. Heterogenous effects of stations: coal and coastal

Dependent variable: ln unit pop. density	(1)	(2)	(3)
Station 2km	0.160***	0.156***	0.135***
	(0.008)	(0.008)	(0.008)
Station 2km*exposed coal	0.152***		0.159***
	(0.028)		(0.028)
Station 2km*coastal		0.134***	0.140***
		(0.0254)	(0.025)
Unit FE, Year FE, Cty*Year FE	Y	Y	Y
First Nature*Year FE	Y	Y	Y
Second Nature*Year FE	Y	Y	Y
Observations	84,582	84,582	84,582
R-squared	0.444	0.444	0.446

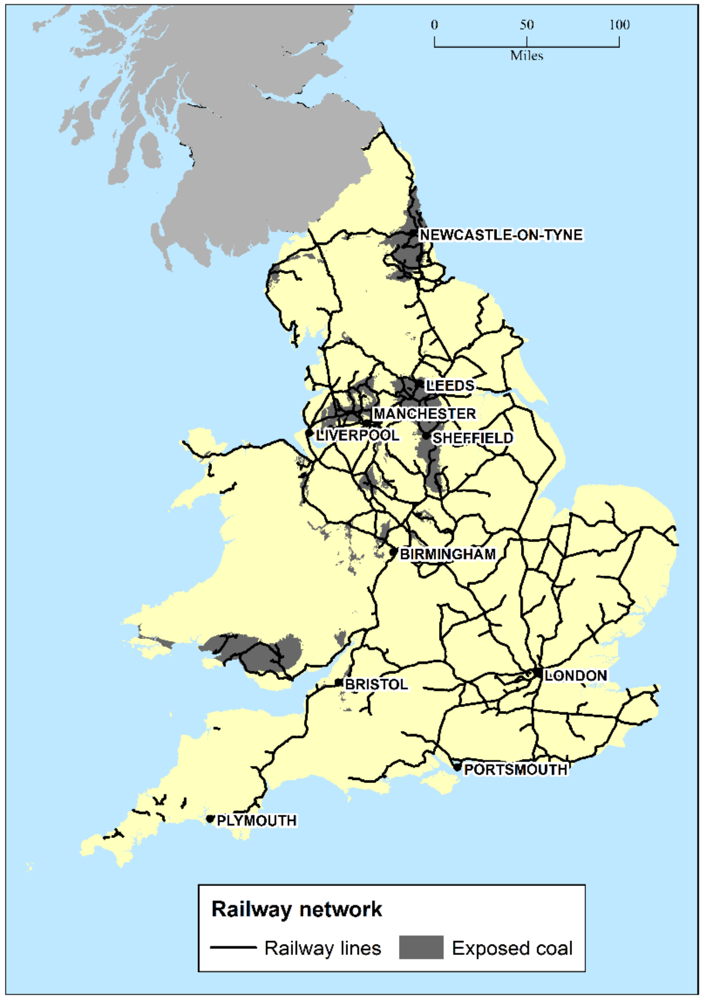
Notes: Standard errors in parentheses are clustered on the unit. *** p<0.01, ** p<0.05, * p<0.1. For definitions of variables see table 1.

The estimates for equation (5) are shown in table 5. In column (1) having coal doubles the effect of having stations (compare 0.160 with 0.152). Similarly, in column (2) being coastal almost doubles the effect of having stations. Including both interactions (column 3) does not change the overall conclusion that being near stations increased population more if units had coal or were coastal.

The preceding effects have not been documented in other countries and the explanation may be unique to England and Wales. Our findings are consistent with the fact that minerals, like coal, were the most important freight category for English and Welsh railways in terms of weight (Hawke 1970, p. 71). Many railway lines were also built to serve areas with coal. The close association between railway lines in 1851 and coalfields is shown in figure 8.

Our findings are also consistent with an argument that railways helped further develop the inland coalfields. As one illustration, Hawke (1970, pp. 166-168) reports that 98.4% of coal imported into London came by sea and 1.6% by rail in 1850. By 1870, most of the coal into London (55.7%) came by rail, mainly from the inland coalfields of Derbyshire and Yorkshire, more than 200 km away. Between 1801 and 1913, the increase in coal output in Great Britain was over 2,500%. Mitchell (1984, p. 3) argues it was a consequence of the new-found effectiveness of the railways in the distribution of coal over substantial distances. In sum, our estimates suggest that in units with coal, railways especially increased the labor force in mining and relating manufacturing activities, leading to even greater population change.

Figure 8: railway lines in 1851 and exposed coalfields



Finally, our result that coastal areas benefited more from railways is also consistent with the literature. It is often noted that railways and steamships competed with one another, and as a result, railway freight rates were more competitive near the coast (Church 1986, pp. 47). This argument suggests it would have been more attractive for firms and workers to locate near stations along the coast. Notably some railways also built their own docks to compete with shipping (Church 1986, pp. 40). In these cases, railways would be associated with additional infrastructure that provided more incentives to locate near stations along the coast.

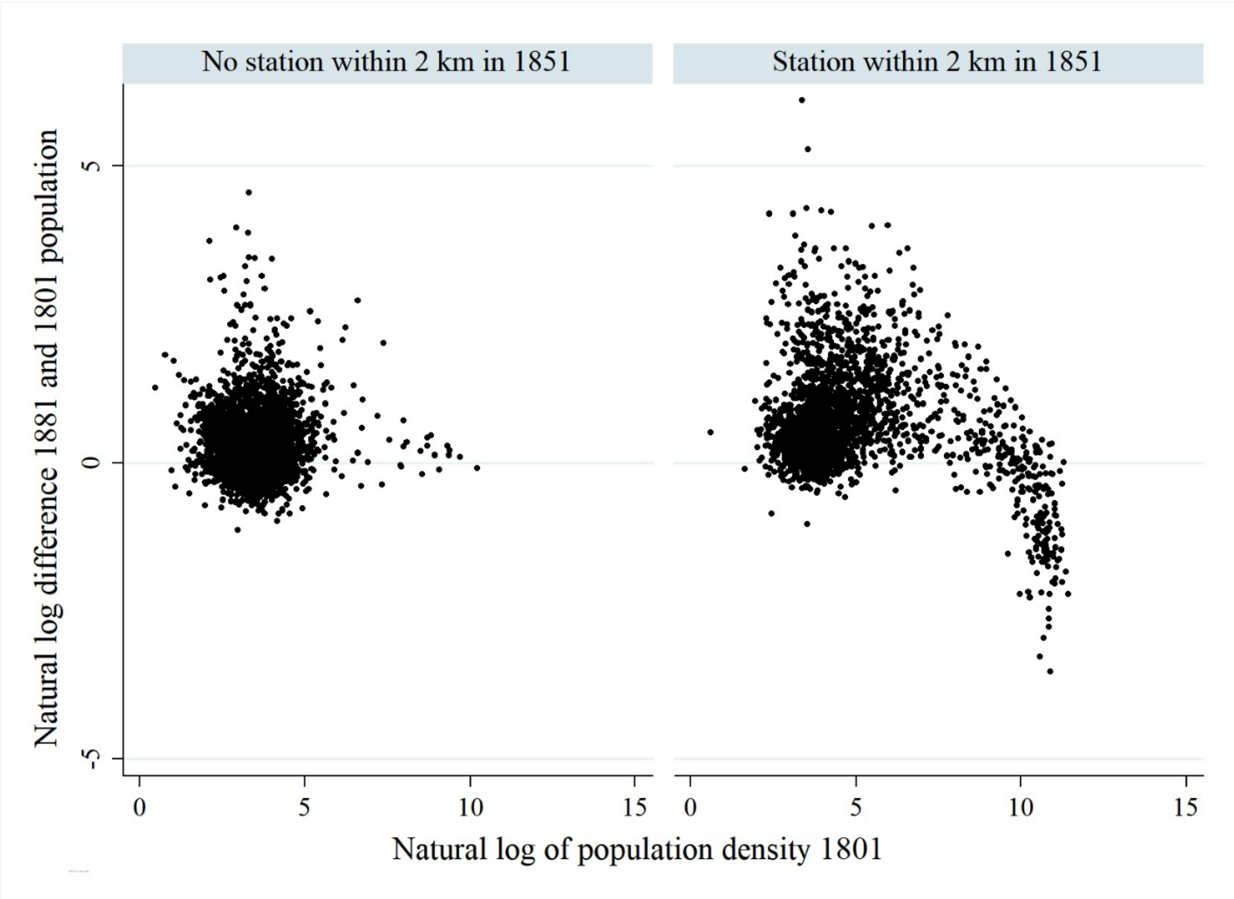
IX. Railways and initial population density

Our third and final subsidiary question examines how railways interact with initial population density. There is a wide range of theoretical models showing how transport costs and agglomeration interact. The models do not always have the same prediction. In theory, lower transport costs can contribute to further agglomeration and hence divergence, or they can work for convergence.[30]

The patterns of population convergence in nineteenth century England and Wales can be quickly summarized. A bivariate regression of unit population growth between 1801 and 1881 on log of population density in 1801 shows that lower population density units in 1801 grew faster between 1801 and 1881. However, the rate of convergence is greater for units that had stations nearby in 1851. This can be seen in figure 9. Very high-density units grew less between 1801 and 1881 if they had an 1851 railway station within 2 km, while medium density units seem to have grown more if they had an 1851 railway station within 2 km.

[30] See Fujita et. al. (2001), Baldwin and Martin (2004), and Desmet and Rossi-Hansberg (2014).

Figure 9: Scatter plot population growth and initial population density by railway status



Notes: The graph uses all 9489 units with population and station data between 1801 and 1881.

We formally test for an interaction between railways and initially population density using interaction variables for 1801 population deciles. The specification is the following:

$$y_{it} = unitFE_i + yearFE_t + \sum_{j=1}^{j=9} \beta_j station2km_{it} * I\{popdecilej\}_j + \gamma x_i \cdot yearFE_t + \varepsilon_{it} \qquad (6)$$

where all the variables are as before and $I\{popdecilej\}_j$ is an indicator for decile j (the 10th decile is omitted). The coefficient estimates in table 6 show being near stations increased population by 6 to 10% more for units in the 3rd to 7th deciles of 1801 density versus the 10th or top decile. Also, stations increased population density by 8% more in the 9th decile versus the

10th. In other words, we find being near railway stations contributed to convergence in medium to upper density units. The coefficients are broadly similar in column (2), which eliminates units within 20 km of the ten largest cities in 1801, including London. Thus, the patterns are not unique to areas very close to the largest cities.

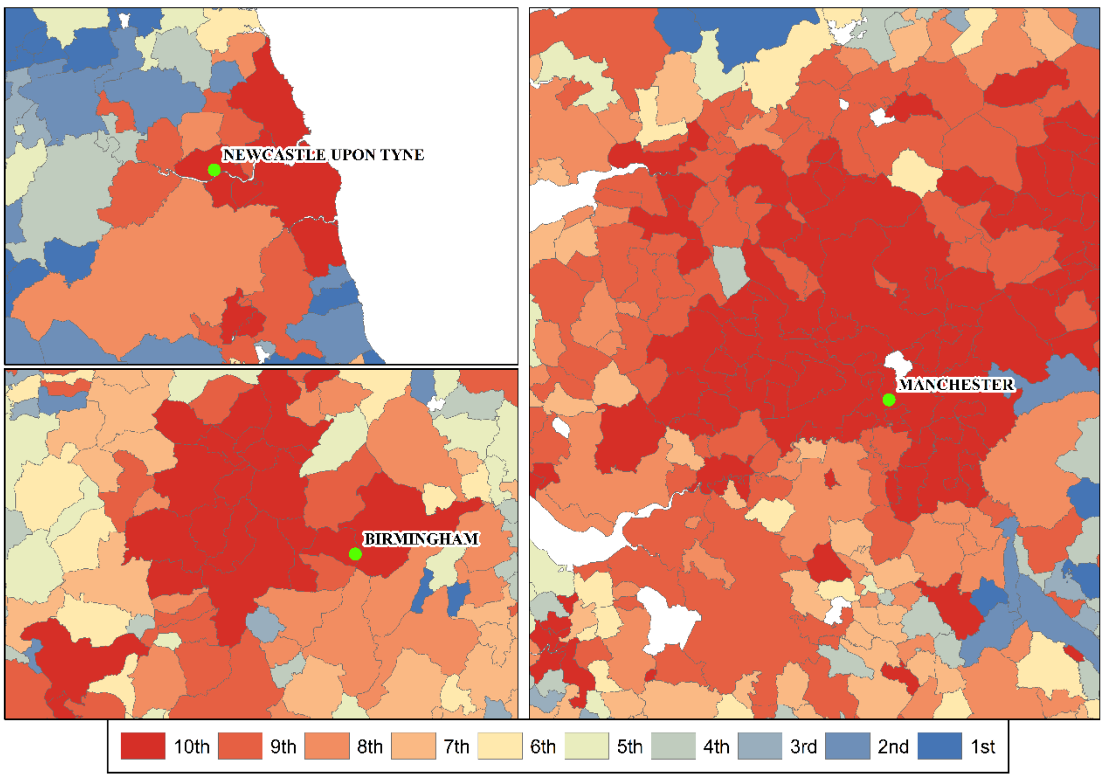
Table 6. Heterogenous effects: initial population density

Dependent variable: ln unit pop. density		
	(1)	(2)
Station 2 km	0.096***	0.105***
	(0.018)	(0.017)
Station 2km*1801 pop decile 1	0.058	0.045
	(0.046)	(0.046)
Station 2km*1801 pop decile 2	0.020	0.017
	(0.039)	(0.039)
Station 2km*1801 pop decile 3	0.062*	0.057
	(0.037)	(0.037)
Station 2km*1801 pop decile 4	0.100**	0.090**
	(0.044)	(0.045)
Station 2km*1801 pop decile 5	0.058*	0.051
	(0.034)	(0.035)
Station 2km*1801 pop decile 6	0.101***	0.090***
	(0.033)	(0.032)
Station 2km*1801 pop decile 7	0.063**	0.059**
	(0.030)	(0.030)
Station 2km*1801 pop decile 8	0.033	0.024
	(0.027)	(0.027)
Station 2km*1801 pop decile 9	0.082***	0.075***
	(0.027)	(0.027)
Only units more than 20 km from largest cities in 1801	N	Y
Unit FE, Year FE, Cty*Year FE	Y	Y
First Nature*Year FE and Second Nature*Year FE	Y	Y
1801 decile indicators*Year FE	Y	Y
Observations	84,582	83,529
R-squared	0.441	0.441

Notes: Standard errors in parentheses are clustered on the unit. Station 2km* 1801 pop decile 10 is omitted. *** p<0.01, ** p<0.05, * p<0.1. For definitions of first and second nature variables see table 1.

In interpreting these results, it is important to note that the physical boundaries of our geographical units are time-invariant by design. Also, units in the 1801 top decile were already densely populated and had little room left for further housing expansion. But over time, and as railways arrived, the physical footprint of growing towns expanded to previously fringe areas with a bit less population density.

Figure 10: 1801 Population deciles near Newcastle, Birmingham, and Manchester



Notes: The graph calculates deciles across 9489 units with population in 1801.

As an illustration, the spatial distribution of 1801 population deciles are shown near Newcastle, Birmingham, and Manchester in figure 10. The 10^{th} decile was at or very near city centers represented by the green circles. Here land was very scarce and the potential to grow was less. The 9th decile is more common a bit farther from the center. In these inner and suburban districts, railways had more potential to contribute to population growth.[31] A similar interpretation could apply in units between the 3rd and 7th deciles, which were farther from city centers.

X. Conclusion

In this paper, we estimate how the introduction of a railway station changed the population of a local area in England and Wales, whether population increases came at the expense of nearby areas, and whether railways' impact depended on endowments or pre-existing agglomeration. The English and Welsh economy provides a good context to study these issues because urbanization was high before railways and natural resources were a major factor in its development.

Our results confirm that population grew significantly more near stations in England and Wales, effectively adding new or further agglomeration. This finding is robust including in specifications which address endogeneity using instruments based on least cost paths. Perhaps more surprising, we find no evidence of significant population declines farther from stations. Specifically, population increased within 2 or 3 km of a station, but did not decline at distances 5, 10, or 15 km from stations. This stands in contrast to other countries, where population declined in the hinterland of stations. We think that being close to a railways station offered

[31] Early pollution could provide another explanation. There is a literature showing that pollution was a serious problem in the nineteenth century (Beach and Hanlon 2017, Hanlon 2019) and would be consistent with ours.

advantages over other locations, but it was less dramatic in England and Wales because of the good prior infrastructure associated with roads and inland waterways.

We also find that endowments mattered. Having coal and being coastal substantially increased the effects of being close to stations versus not. This finding matches with the importance of natural resources in England's development. Our interpretation is that railways helped areas on the inland coalfield grow and that competition with shipping provided an additional inducement to locate near stations and along the coast. Moreover, railways helped middle and upper density units gain relative to the most densely populated units in 1801. The explanation is related to the limited supply of land in city centers.

As a final exercise, we provide a quantitative assessment for the aggregate effects of railways. We use the estimates from a regression including the direct effect of being within 2 km of stations and interactions with coal, coastal, and deciles of 1801 population. We calculate the predicted population *loss* to units in 1881 if they did not have railway stations within 2 km. This exercise is more credible because we find no evidence of population declines farther from stations. The counterfactual shows an average unit population loss in 1881 of 1,850 without railways. Summing across all units in 1881 implies a total population loss of 5.14 million people or 20.0% of the 1881 population. The aggregate effects of railways were large in England and Wales. Future research should examine other economies to shed more light on how railways affected urbanization differently depending on initial conditions.

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Appendix A.1: 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.2: Elevation, slope, and ruggedness variables

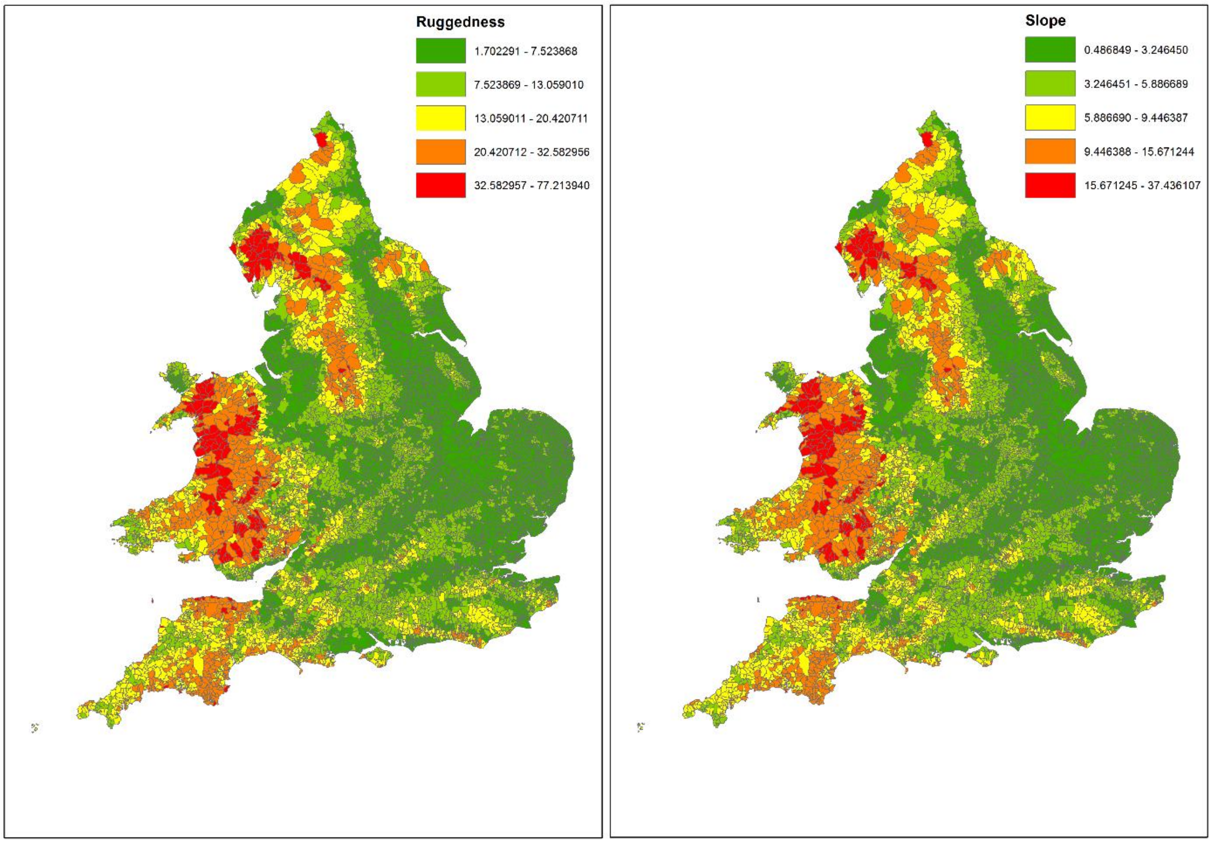
The aim of this appendix is to explain the creation of the elevation variables, including the original sources and method we followed to estimate them. There are several initiatives working on the provision of high-resolution elevation raster data across the world. The geographical coverage, the precision 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 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 see https://www.campop.geog.cam.ac.uk/research/occupations/datasets/catalogues/documentation/exposedcoalfieldsenglandandwales1830.pdf