Turnpikes, canals, and economic growth in England and Wales, 1800-1850

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Abstract

Improvements to roads and rivers and the construction of canals were the largest infrastructure investments in England during the industrial revolution. This paper estimates their effects on local population and employment growth using new GIS data covering all parishes in England and Wales or more than 9000 units. The main results show that greater access to the turnpike and inland waterway network around 1800 increased parish population growth from 1801 to 1851. Greater access to infrastructure also increased secondary and tertiary employment growth from 1817 to 1851. Greater access had the opposite effect on agriculture employment growth, we think because it was more land intensive. In a final exercise, we show that English and Welsh population growth would have been 3.9% lower between 1801 and 1851 if road and inland waterways were equal to the late 17th century. As this represents about 8% of the total, it appears that turnpike roads, rivers, and canals were one of several contributors to growth during the industrial revolution.

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Improvements in transport and communications have been one of the main drivers of economic growth throughout history. For most countries, the transport revolution began with railways and steamships. But in some western economies, like England, the transport revolution gained speed prior to railways and steamships. Improvements to roads, rivers and the construction of canals were two key developments. From 1680 to 1830 more than 20,000 miles of road were improved, 500 miles of river were made navigable, and 4000 miles of canal were constructed in England and Wales. Collectively, they made inland transport by wagon, coach, and barge far more efficient compared to the late 17th century. Also remarkable is that most of these infrastructure investments were financed by turnpike trusts and joint stock companies. A permissive parliament allowed local landowners and business interests to establish new organizational forms, which bundled financing and organization tools. By mobilizing capital, turnpike roads, river navigation, and canal companies created a transport revolution that ran side by side with the industrial revolution.

Turnpike roads and canals have been studied extensively, however, there has never been a rigorous empirical analysis on their contribution to economic growth across England and Wales. Insufficient data is a key reason. Scholars have not had accurate geographic data on the locations of all turnpike roads, rivers, and canals. Scholars have lacked high quality data on local economic outcomes before the mid-19th century. This paper uses such data in of its first applications. It studies new GIS data on the locations of turnpike roads, rivers, and canals.[2] It also studies data on parish population and employment levels from the late 1700s and early 1800s. Parishes are one of the smallest jurisdictions in England and Wales and they offer a

[2] For an overview of this data and more background on turnpikes and inland waterways see Bogart (2017) and Satchell (2017).

unique opportunity to study transport infrastructure at very local level. Lastly, this paper uses a new data set on endowments at the parish-level, including having coal.

Our first main hypothesis is that population will fall with greater distance to infrastructure. The second set of hypotheses are that secondary and tertiary employment will fall with greater distance to infrastructure, while agricultural employment will rise. The third hypothesis is that the effects of infrastructure were greater for parishes with medium to large initial population or employment density. Our baseline model tests these hypotheses by regressing population or employment growth from 1801 to 1851 on variables for distance to turnpike roads and distance to canals in 1800 plus controls. The endogeneity of turnpikes and canals is addressed using the location of historic infrastructures, like main roads and natural rivers in 1680. They served as the corridors for the improved networks of the 1700s and early 1800s and were either exogenous or they were created long before the transport revolution began. Thus, we believe their locations are not likely to drive economic growth except through later improvements to infrastructure.

The main results show that distance to turnpikes and canals affected parish population and employment growth. The estimates imply that a 50% increase in distance to turnpike roads decreased annual population growth by 0.02%, decreased annual secondary employment growth by -0.081%, and increased annual agricultural employment growth by 0.018%. A 50% increase in the distance to inland waterways reduced annual population growth by -0.023% and reduce annual secondary employment growth -0.134%. There is some heterogeneity in these effects depending on the initial employment or population density. For example, we find that distance to inland waterways is more significant for parishes with the largest population density in 1801. This suggests that canals contributed to greater concentration in population density.

The estimates are also used to quantify the amount of population growth that would have occurred if turnpike and inland waterway networks in 1801 were the same as the main road and river network in 1680. We find that population growth from 1801 to 1851 would be 3.9 percentage points lower, or put differently, the annual population growth rate would have been -0.079% lower. Based on these estimates, it is clear that turnpike roads and canals were a contributor to growth during the industrial revolution. But their impact is small compared to the total. Overall population grew by 49 percentage points between 1801 and 1851. Moreover, compared to railways turnpike roads and inland waterways had a smaller effect. In a companion paper, we estimate that a 50% increase in distance to railway stations should reduce annual population growth by -0.09% (Bogart et. al. 2017a). Therefore, we find evidence that the growth effects of the transport revolution increased as speeds and technology in transport accelerated.

This paper adds to a large historical literature on turnpike roads, rivers, and canals.[3] This paper is an advance over previous studies because it uses new and highly accurate GIS data on turnpike roads, rivers, and canals from across England and Wales. It also studies outcomes like employment growth, which have never been analyzed with turnpikes and canals.

This paper also adds to a large literature studying infrastructure networks, growth, and structural change.[4] This paper is the first paper to apply standard empirical models to the study of pre-railway transport networks. All previous studies have analyzed the steam or automobile era. By turning the focus to an earlier era of wagons and coaches, one can see how modern and more

[3] See Jackman (2016), Willan (1964), Freeman (1980), Turnbull (1987), Szostak (1991), Bagwell (2002), Bogart (2005a, b, 2009), Gerhold (1996, 2014), Crompton (2004), Maw (2013).

[4] See Baum Snow (2007), Duranton and Turner (2012), Duranton, Morrow, and Turner (2015), Faber (2014), Pascali (2016), Donaldson (2015).

sophisticated transport improvements compare. One lesson from this paper and related studies is that the effects of transport have been growing with time.

The paper is organized as follows. Sections I, II, and III give background on turnpike roads, inland waterways, and economic growth in England and Wales from 1700 to 1850. They include a preview of the novel data used in this paper. Section IV describes the empirical framework. Section V provides details on the data sources. Section VI presents the results.

I. Background on turnpike trusts

England and Wales had a large network of roads and pathways going back to the Middle Ages. Responsibility for maintenance was placed upon local governments known as parishes. Parishes financed road improvements by forcing their residents to work without pay and by levying property taxes. The public and local method of road financing became unsatisfactory during the 17th and 18th centuries. There was a growing use of large wagons and carriages, which caused damage to roads. The problem was especially acute in the southeast around London.

Turnpike trusts emerged as a solution to this problem. Turnpike trusts were created through a legislative process shared by many types of private and local bills. A bill to create a turnpike trust almost always began with a petition to the House of Commons, often from landowners and commercial interests. The petitions normally stressed the need for road improvement, and the inadequacy of the law. Once turnpikes bills were written and passed by the Commons, Lords, and Monarch they became known as a 'turnpike act.'

Each act established a body of trustees with authority over the road. They were usually composed of the promoters and other local elites. Trustees were given the right to levy tolls and issue bonds. As an added bonus, trusts could also claim statute labor from the parishes along their route. Turnpike acts also placed restrictions on trustees. For example, they could not charge tolls above a maximum schedule, and they could not earn direct profits. Turnpike acts did not give permanent powers. They were only valid for 21 years, at which point the trustees had to apply for what became known as a 'renewal act.' The vast majority of renewal acts were approved by parliament. In this manner, turnpike trusts became a fixture in England and Wales transportation system through the mid-19th century.

Importantly, the main function of turnpike trusts was not to build new roads, but rather to improve the quality of existing roads. The usual official rationale for creating turnpikes was that the 'ordinary' laws for repairing a particularly highways needed to be amended if a particular group of roads were to be improved. Did turnpike trusts meet these goals? Bogart (2005) has analyzed the road spending of parishes in the five years before a turnpike trust was established in their jurisdiction. The evidence shows less than 5% of parishes levied highway rates (i.e. taxes on property owners) in those five years, implying that the only spending that was occurring through other means like unpaid labor. The same study also estimated average turnpike trust road spending during their first 20 years of operation. They spent between 10 and 20 times more than the parishes they replaced.[5]

Importantly, this paper uses new GIS data accurately identifying the location of every turnpike road and the data associated with them, like their date of establishment. The data

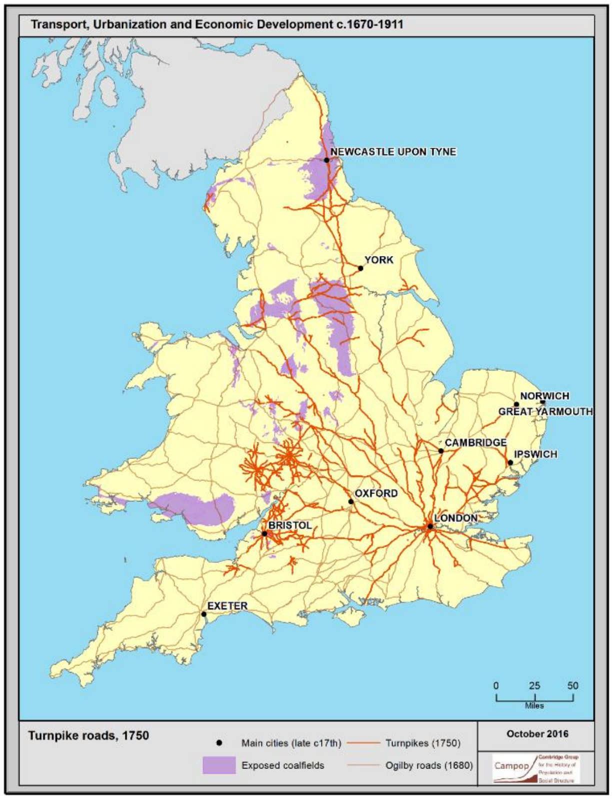
[5] Additional evidence comes from an assessment of each trusts' road condition in 1838. A parliamentary committee asked all trusts to describe their road. They used terms like "Bad", "Good", "Tolerable", "Good" or "Very good". Over 60% were characterized as "Good" or "Very good." A relatively small number, 15%, were classified as "Bad" or "Not Good". While a assessment of turnpike road quality by the trustees themselves is subject to bias, it provides more evidence that greater expenditures by turnpike trusts generally resulted in a good road network.

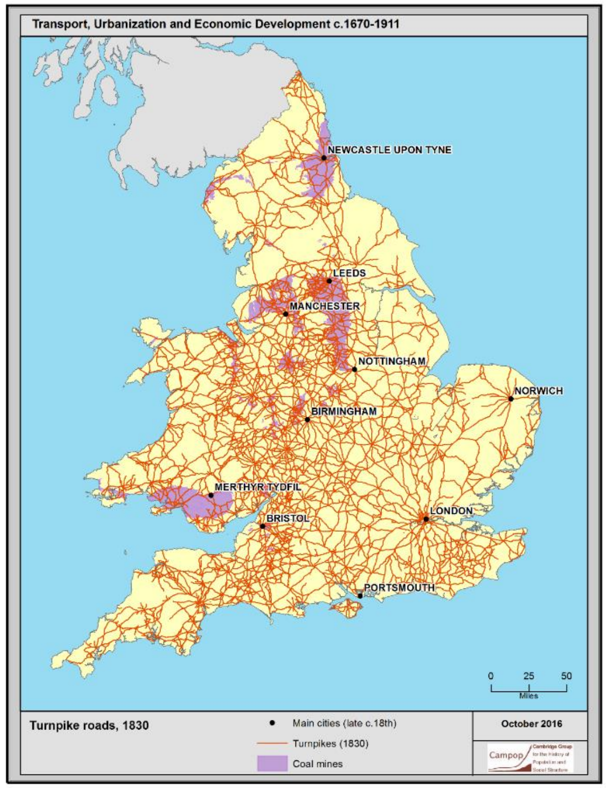
features and sources will be explained below. Figure 1 uses the data to map all turnpike roads in 1750 along with the largest cities of 1700. It also shows the main roads in 1680 using Ogilby's maps. [6] By the mid-eighteenth century, turnpikes were established on major roads leading into London and most of the major towns even as far north as Newcastle. Many were established on principal roads mentioned in Ogilby. Also notable is the cluster of turnpike roads in the west of England near Bristol. Albert called them 'town-centered' trusts. They were designed to foster trade between a town and its hinterland. It also appears that were a competitive element in which towns were more likely to form trusts if their neighboring towns did the same.

Between 1750 and 1770 turnpike roads diffused widely across England and Wales. Approximately 10,000 miles of road were placed under trust authority in these two decades. As a result, tolls became commonplace on all roads near major towns. The establishment of turnpike roads continued through the first quarter of the nineteenth century. The rate of adoption was slower, but many areas added significant turnpike roads. Panel B in figure 1 shows turnpike roads in 1830 and the ten largest towns according to the 1801 census. Large cities like London, Leeds, Birmingham, and Bristol all had many turnpike roads. A particularly dense network of turnpike roads also formed in the West Midlands and West Yorkshire, especially near the coalfields. This development is notable because these areas were beginning to industrialize. Turnpike trusts also reached areas like the Southwest and Wales. Turnpike roads were in every part of England and Wales.

[6] For details on the mapping of 1680 roads see http://www.campop.geog.cam.ac.uk/research/projects/transport/data/roadnetwork1680.html

Figure 1: Turnpike roads and major cities in 1750 and 1830





II. Background on inland waterways

The importance of travel by inland waterway was recognized by contemporaries as early as the Middle Ages and by many scholars since.[7] Transport historians term rivers with sufficient depth and width for vessels to travel unimpeded *natural rivers*. Rivers where it proved necessary to extend width and depth to make them navigable, a factor which potentially can dramatically increase cost, are termed *improved rivers*. Canals were fundamentally different navigable waterways in that their routes were chosen by people, whereas hydrology dictated the route of rivers.

[7] See Satchell (2017b) for a more complete background on the inland waterways of England and Wales.

In terms of organization, river navigations were financed and implemented by a variety organizations, including partnerships, trusts and municipal government. They received their authority from an act of parliament similar to turnpike trusts. The act authorized levying of tolls and powers to purchase land. Canals were generally built by joint stock companies. The capital requirements for building a canal were considerable. Collectively canals were the largest infrastructure investment in England by 1830. Much of the financing for canals came from local landowners and business interests.

The technology of a pound lock was fundamental to improving rivers and constructing canals. Elevation changes made it difficult to haul or sail a barge through a waterway. Locks were chambers that filled with water and equaled elevation on a slope. They required enormous amounts of water so in many circumstances purpose-built reservoirs had to be built to supply them which added further to the expense. The most spectacular examples are called *lock flights* - sets of locks which ran staircase like up a hillside.

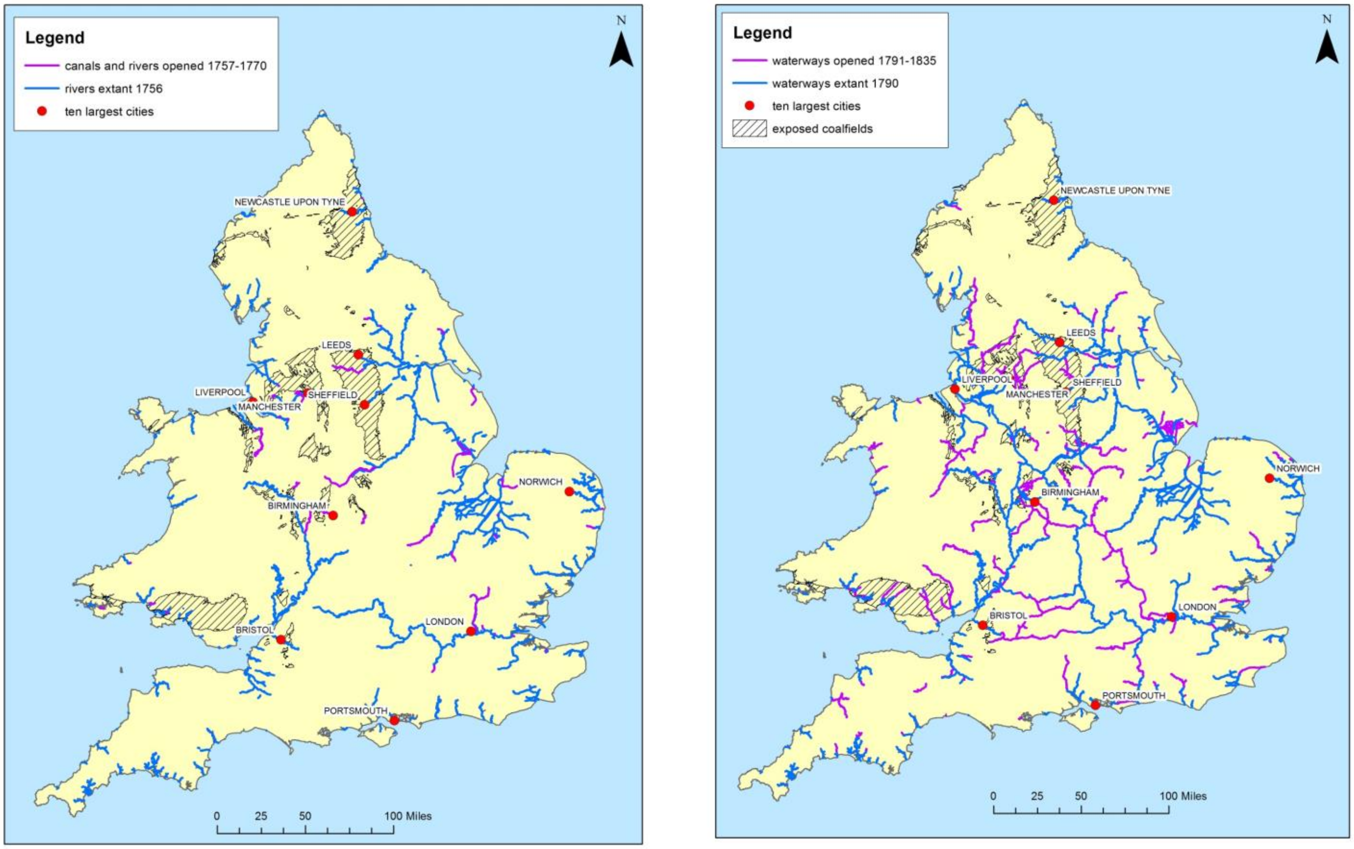
Compared to roads, inland waterways were a more efficient way to carry low value non-perishable bulky goods such as coal and grain. If comparison is made between the weight that could be typically carried by one horse wagons on the pre-turnpike roads of the seventeenth century, and loads that could be hauled by a single-horse barge on a broad canal of the eighteenth century it can be seen that 96 horses pulling wagons would be needed to carry the same load as that drawn by one horse on a broad canal. Or put another way a single horse barge could move almost eighty times as much freight as a one-horse wagon.

In 1600 England and Wales had about 950 miles of navigable waterway. By c.1760 it had increased to 1400 miles, nearly all of which were navigable rivers. When the last significant addition to the waterways network, the Birmingham and Liverpool Junction Canal, was completed in 1835 the total network was about 4,000 miles, the great majority of the post-1760 mileage being canals.

The evolution of the inland waterway network can be mapped in a high degree of detail thanks to a new GIS data set created by Satchell (2017). The details of the data are discussed below. The first panel in Figure 2 shows the extent of the river network to 1756 the year before first proper canal was constructed. Natural and improved rivers connected much of the interior with the coast. Most significant were the river navigations that connected burgeoning industrial towns to coastal and international shipping networks. Of major importance was the extension of the Aire and its tributary the Calder to Leeds and Wakefield (West Riding). Both towns were situated on the Yorkshire coalfield and Leeds was a major textile center.

Canals changed the inland waterway network radically from 1757 to 1830. The second panel in figure 2 illustrates the network along with the coal fields. Several important canals linked coal mines to manufacturing towns in the Midlands, including Coventry and Birmingham. The movement of goods and raw material between the northern industrial centers in Lancashire and the West Riding was made practicable by the completion of three trans-Pennine canal routes. Also significant, the grand junction canal connected London to Birmingham and the industrial centers of the northwest.

Figure 2: Evolution of the inland waterway network



III. Regional perspective on turnpike roads and canals

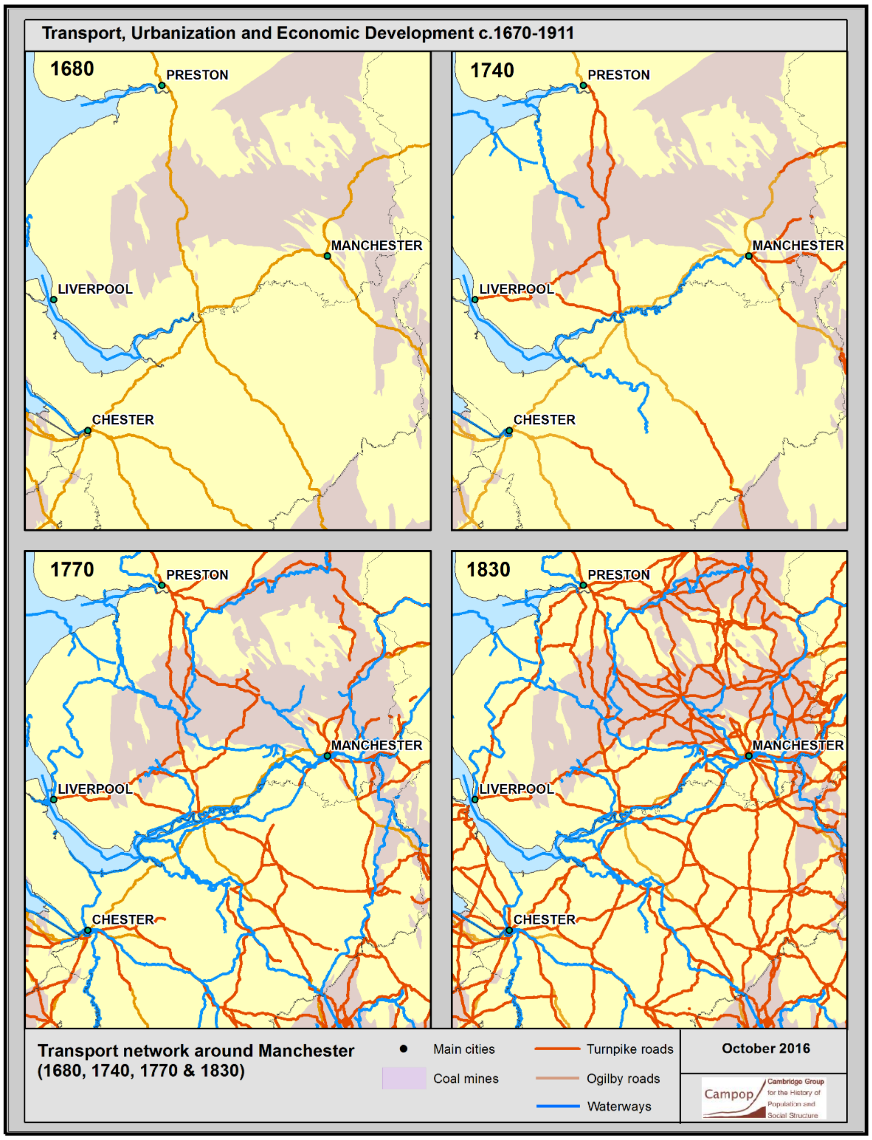
It is useful to briefly focus on transport development in the region around Manchester and Liverpool because of their importance in the industrial revolution (see figure 3). Maps of Ogilby roads (brown), turnpike roads (red), and waterways (blue) are shown at 4 dates: 1680, 1740, 1770, and 1830. In 1680, Manchester had no direct water transport to the coast or inland cities, but it did have direct road connections to the coast near Liverpool, to Leeds through the east-west trunk road across the Pennines, and to London on the southern road through Derby. Most road transport was by packhorse because road quality was low. By 1740 Manchester had water access to the western coast following the improvement of navigation on the Irwell. At that point its shipping costs to Liverpool and international markets declined significantly. Also several roads near Manchester were improved, including its connections to London and nearby coalfields.

By 1770 more turnpike trusts were established on roads near Manchester improving its connections to several cities to the east and south. At this point road carriers began to adopt faster coaches and larger wagons, and Manchester's travel times and freight rates started to decline. The travel time between London and Manchester was around 90 hours in 1700. By 1787 it fell to 24 hours (Jackman 1916). More turnpike roads were established between 1770 and 1830, including better connections to coalfields in the north. A local canal network began to form with connections to the national network of canals. Goods to and from Manchester could now reach a number of large cities throughout England and Wales by water or by road.

IV. Population and employment change in England and Wales, 1801-1851

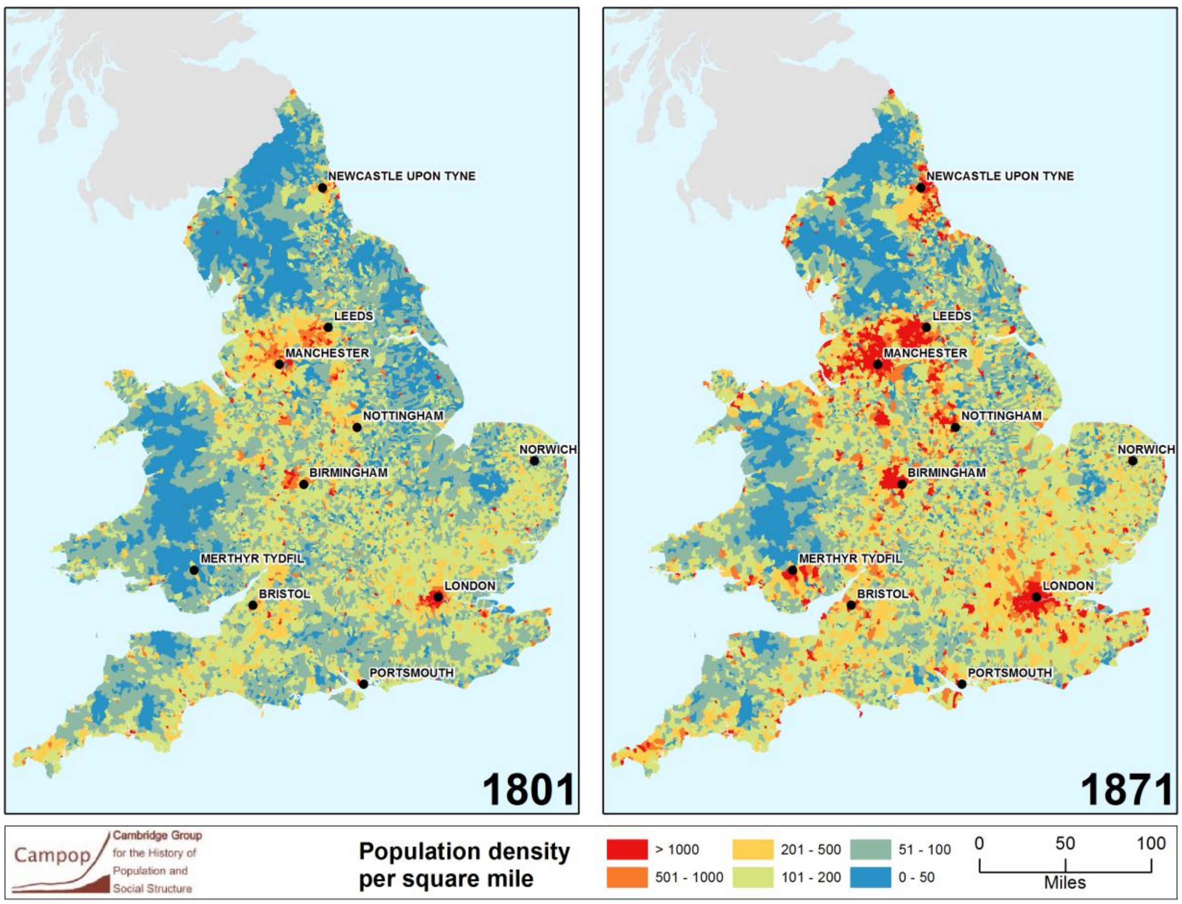
It is well known that England and Wales experienced substantial growth from 1801 to 1851. According to Broadberry et. al. (2015) the average annual growth rate of real GDP was 1.86% from 1800 to 1850. Real industrial production grew more, at an average rate of 2.49%. The early nineteenth century marked an acceleration over the 1750 to 1800 period where real GDP grew at an average rate of 1.2% and industry at 1.48%. The rate of growth could be quite different at the local level. Some locations grew significantly while others stagnated or even declined. Some also experienced dramatic growth in secondary and tertiary employment, while others did not.

Figure 2: The evolution of the transport network near Manchester from 1680 to 1830



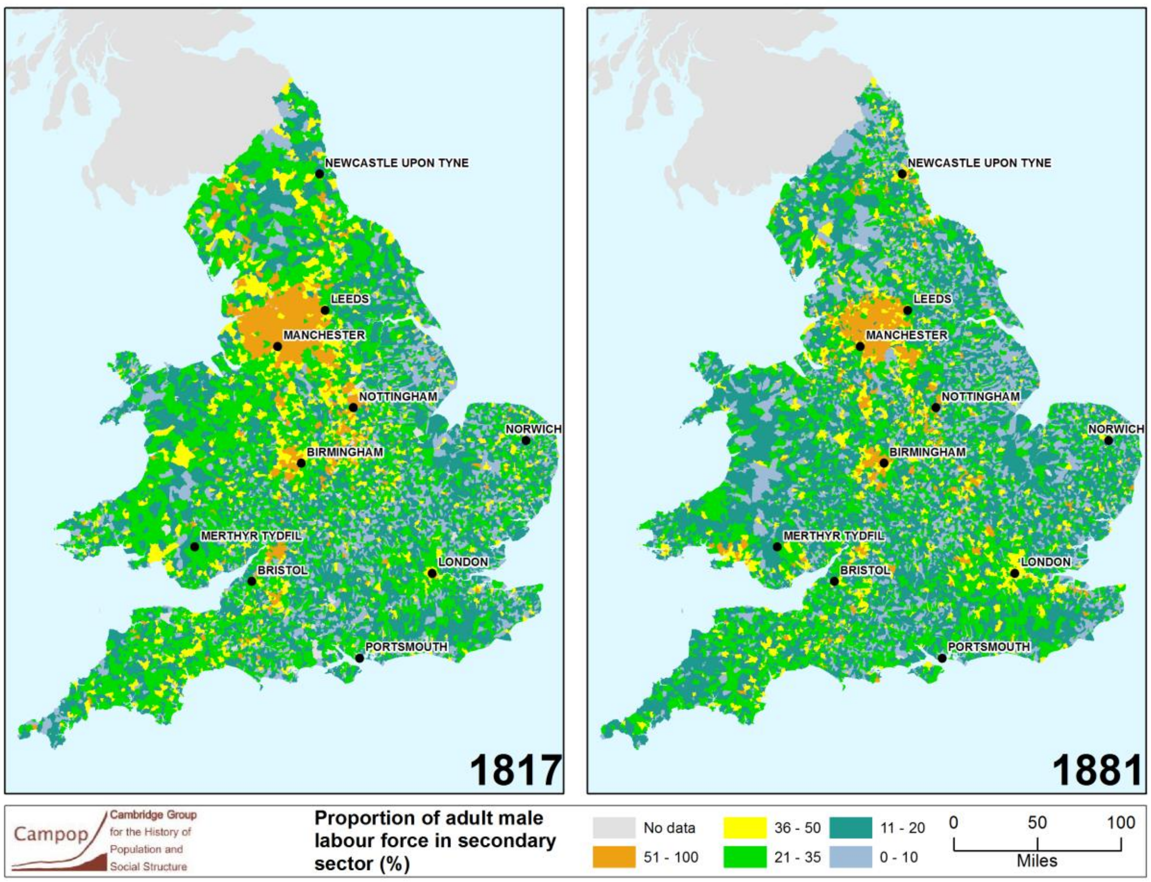
Thanks to new data collected by the Cambridge Group for the History of Population and Social Structure (CAMPOP) it is now possible to map the patterns of growth at a very granular level. The data sources and methods are discussed below in the data section. Here we emphasize the main patterns. Population densities per square mile are displayed geographically in figure 4 for 1801 and 1871. The largest cities of 1801 are also shown. Population density was higher around the major cities in both periods as one would expect. What is most remarkable is that the geographic distribution of population density was fairly similar in 1801 and 1871. The population centers were in the northwest around Manchester and in the southeast around London. There were changes of note in the nineteenth century. Population density increased more near major cities between 1801 and 1871. The growth was especially higher in the hinterland of the major towns.

Figure 4: Population Density in England and Wales, 1801 and 1871



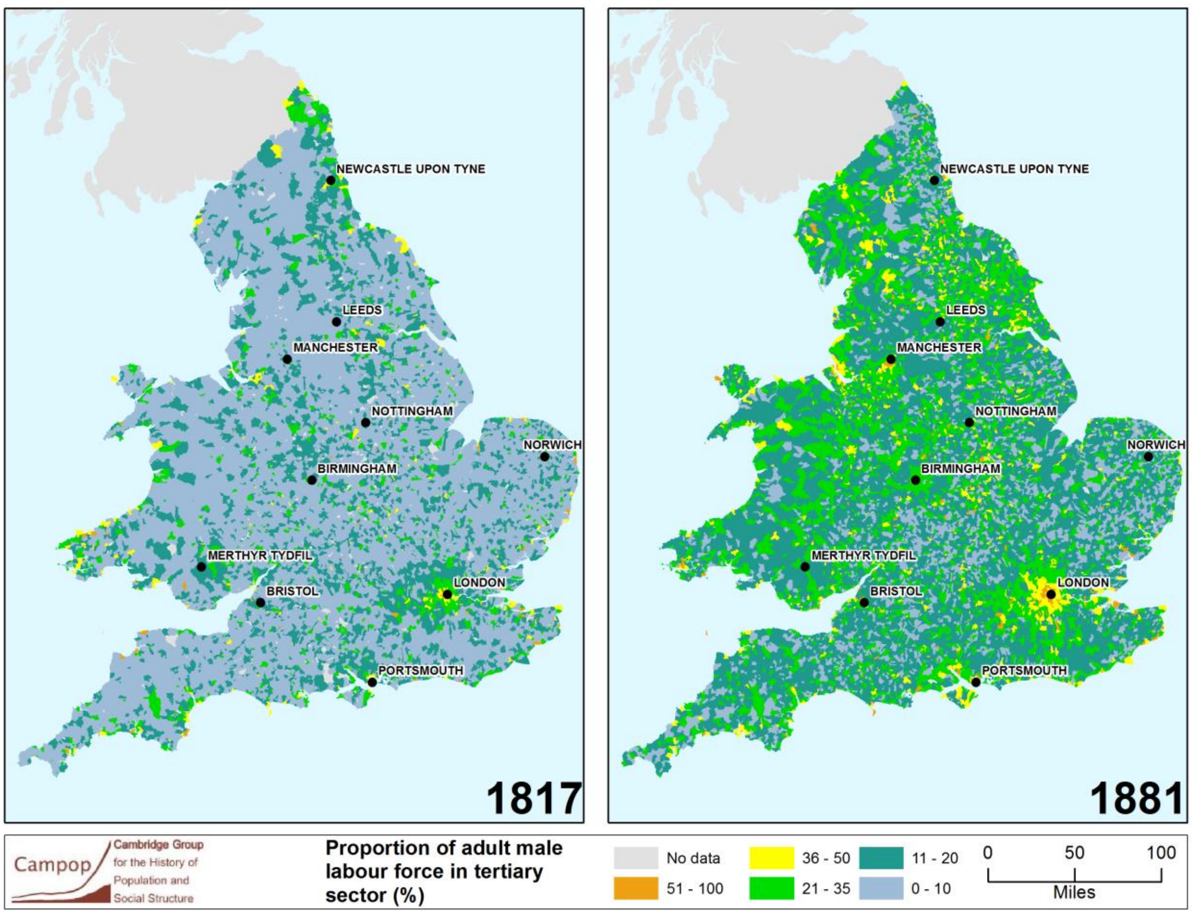
The spatial patterns of employment growth are very similar to population growth. However, there were important differences across male occupational categories for which there is now long-run data. The sources are described in Shaw-Taylor, L. and Wrigley (2014). The main patterns are described here. Secondary (manufacturing) employment shares are shown geographically in figure 5. There was a high degree of specialization between Manchester and Leeds in the northwest and around Birmingham in 1817. The same was still true in 1881, although secondary employment became even more spatially concentrated around these cities. This map highlights a key finding noted by Shaw-Taylor and Wrigley (2014). The spatial concentration of secondary employment was high already in 1801, and during the 19th century secondary concentration accelerated.

Figure 5: Shares of males in secondary in England and Wales



There is a different trend for the tertiary (services) sector. The geographic distribution is shown in figure 6. Tertiary shares were generally low throughout England and Wales in 1817 and concentrated near London. By 1881 tertiary is more common everywhere, but especially in the north, and near the large manufacturing towns of Leeds, Manchester, and Birmingham. It is also remarkable is that by 1881 tertiary employment became concentrated in similar areas as the secondary sector. Thus services and manufacturing employment tended to co-locate.

Figure 6: Shares of males in tertiary in England and Wales



V. Access to transport networks and growth: methodology

In this section, we propose an empirical model to study the effects of turnpike road and inland waterway networks on population and employment growth in the early to mid-19th century. The aim is to estimate the elasticity of population or employment growth with respect to infrastructure access measured by distance. The elasticity is grounded in a theory that transport infrastructure contributed to better consumer and producer access, which made individuals and firms want to locate near these infrastructures (Redding and Turner 2014). The limited supply of land would act as a break on the relocation process. Thus, there should be a population gradient emanating from the turnpike road, port, or waterway. The areas closest to infrastructures should see the biggest growth and the areas furthest should see the least.

Our specifications draw on Duranton and Turner (2012), who estimate the effects of highway density on urban growth in the US since 1980. The main variable of interest here is distance to infrastructures, like turnpike roads and inland waterways. We also include distance to customs ports, a list of official ports which did not change much over time. The estimating equation for population growth is based on a 'long-differences' specification. Our unit of observation is a mappable parish unit, which is explained below. The log difference in parish population from year t to t-j, $\Delta\ln(pop_{it})$, is regressed on the log level of population in year t-j, plus variables for distance to infrastructures at date t-j, and controls for initial conditions or time invariant factors x_{it-j}. The specification is the following:

$$\Delta\ln(pop_{it}) = \alpha + \beta_1\ln(pop_{it-j}) + \beta_2 f\left(distanceinfrastructure_{it-j}\right) + \beta_3 x_{it-j} + \varepsilon_i$$

where the distance function $f(\cdot)$ can take various forms. The baseline is the natural log. It can also be vector of dummy representing distance bins, say from 0-1 km, 1-2 km, etc. Our population data is restricted to census years, 1801, 1811, and so on. One specification examines growth over the time interval 1801 to 1851 (t=1851, j=50). It captures the long-run effect of turnpikes and inland waterways prior to the widespread adoption of railways around the late 1840s. A second specification estimates the medium-run effect using the interval 1831 to 1851 (t=1851, j=20).

Another hypothesis is that distance to turnpikes and canals will affect employment growth differently in the secondary, tertiary, and agricultural sectors. There are several theories motivating the analysis of occupations. One focuses on the intensity land use. All else equal, individuals or firms who use land more intensively will choose to locate further from the turnpike and waterway than individuals or firms using land less intensively because land rents are higher near infrastructure. This implies that agricultural employment should locate away from turnpike roads and waterways, while secondary and tertiary employment should locate closer because these last two use land less intensively than agriculture.

The specification for employment is the following:

$$\Delta \ln(empl_{it}) = \alpha + \beta_1 \ln(empl_{it-j}) + \beta_2 f\left(distanceinfrastructure_{it-j}\right) + \beta_3 x_{it-j} + \varepsilon_i$$

where $\ln(empl_{it})$ is the natural log of employment density in parish i in year t and all the variables are the same as in the population growth models. Due to data limitations described below there is only one time interval for growth c.1817 to 1851 (or t=1851, j=34).

A third hypothesis is that the effects of infrastructure depend on initial conditions. Parishes that had greater population or employment density starting in 1801 likely had some productivity advantage over more dense areas. The productivity is usually associated with knowledge spillovers or the skills of workers (see Desme and Rossi-Hansberg 2014). In many trade models, lowering trade costs when there is an asymmetry in productivity can result in a divergence in growth (Faber 2016). More dense areas may grow more with greater access to infrastructure than less dense areas. However, because of congestion effects, there could be a limit to growth in the most dense areas, so the effects may be strongest for the medium density areas. In the case of the population growth model, the specification using initial population density is the following:

$$\Delta \ln(pop_{it}) = \alpha + \sum_{j=2}^{5} \mu_j \, popquintiles_{t-j} + \beta_2 f\big(distanceinfrastructure_{it-j}\big)$$
$$+ \sum_{j=2}^{5} \gamma_j f\big(distanceinfrastructure_{it-j}\big) \cdot popquintiles_{t-j} + \beta_4 x_{it-j} + \varepsilon_i$$

where $popquintiles_{t-j}$ is vector of dummy variables for the quartiles of population density in t-j which will be 1801. The lowest quintile is omitted. Interactions with the distance to turnpikes and waterways are included to test if the effects are different for parishes with higher density than the lowest quartile. A similar model is run for initial employment density in secondary, tertiary, and agricultural sectors.

Endogeneity is a concern in any model analyzing transport infrastructure. A particular concern is that turnpike roads and canals were placed in locations that were more or less likely to growth in the future. The endogeneity issue is addressed in several ways. First, fixed effects for jurisdictional units larger than parishes are added to the model. The units are explained below, but suffice to say they address some of the unobserved heterogeneity, including differences in skills across regions. A second approach includes pre-period population growth. Specifically, in the following model for population growth from 1801 to 1851 we add the log difference in population growth from 1761 to 1801 :

$$\ln(pop_{i1851}) - \ln(pop_{i1801})$$
$$= \alpha + \beta_1 \ln(pop_{i1801}) + \beta_2 f(distanceinfrastructure_{i1800}) + \beta_3 x_{i1800}$$
$$+ \beta_4 [\ln(pop_{i1801}) - \ln(pop_{i1761})] + \varepsilon_i$$

It addresses the possibility that population growth was occurring before or simultaneous to the establishment of turnpikes and inland waterways in the second half of the 18th century.

Our third strategy is to use instrumental variable (IV) for distance to turnpike roads. One instrument is the distance to England's earlier road network, identified by John Ogilby around 1675.[8] The roads shown on Ogilby's maps were placed onto a modern projection by the Ordnance Survey. It depicts the roads mapped by Ogilby with each road being referenced by its plate number. The map was produced by the cartographer and archaeologist, O.G.S. Crawford. It has been digitized by Satchell (2017) from geo-rectified scans of map. The key assumption is that Ogliby roads were built in locations that were geographically suitable but were not favorable for population growth in the early 19th century. With this assumption, distance to Ogilby roads is a valid instrument for distance to turnpike roads. For waterways, we can isolate the effects of navigable rivers which were not improved. Essentially, natural rivers like the Thames and Severn. We have a GIS of inland waterways of 1670, which we use for this purpose. We now turn to the details of the data.

IV. Data

There is rich data to study the effects of turnpikes and inland waterways at very local level. First, there is a continuous series of total population data for England and Wales from 1801 to 1891 produced by CamPop.[9] The data are given in 1851-based registration districts for each decadal Census year. The database also contains the 1851 Census-based registration parish

[8] For more details on 1680 roads see http://www.geog.cam.ac.uk/research/projects/occupations/onlineatlas/principalroads1675.html

[9] See http://www.campop.geog.cam.ac.uk/research/projects/occupations/datasets/documentation.html for more details.

identifier(s) that have been matched to each place. The place level population data has been rearranged into 12,641 parish-level mappable units for each decadal census year using a shapefile of the boundaries and attributes of the parishes and places in the 1851 census for England and Wales.

There is an additional population data source used in this paper. Wrigley (2007) estimates hundred-level populations for England starting in 1761 and up to 1801. The hundred is an ancient jurisdictional unit that encompasses the parish but is below the county. The parish units are assigned to hundreds, which gives estimates of their larger units in 1761 and 1801. We use this data to create a pre-trend variable for parish population growth before 1801.

The censuses provide data on a wide range of male occupations available at the parish-level. This paper makes use of the 1851 census in which occupational data has been digitized for every parish through Integrated Census Microdata project (Schürer and Higgs 2014). Earlier census records have occupational data at the parish-level, but their accuracy and detail is lower. Fortunately, there is alternative parish-level data created by CamPop for male occupations around 1817. As of 1813 it was a legal requirement that fathers' occupations be recorded in all Anglican parish registers when their children were baptized. Current demographic evidence suggests that at this date fertility differences between major occupational groups were limited. This suggests that counts of occupations derived from baptism registers should provide a good picture of the counts of adult male occupations in a parish. Accordingly, data from virtually every parish register in England and Wales for an eight-year period (1813-1820) was collected to create a quasi-census of male occupations (see Kitson et. al. 2010). This exercise made use of 11,364 baptism registers and resulted in a data set with c.2.65 million observations. For convenience, the data set is described as referring to c.1817, the mid-point of the period.

Occupations are coded using the PST (primary, secondary, tertiary) methodology in 1817 and 1851.[10] Occupations are assigned to agriculture, mining, secondary, tertiary, and labourer groupings. Secondary refers to the transformation of the raw materials produced by the primary sector into other commodities, whether in a craft or a manufacturing setting. Tertiary encompasses all services including transport, shop-keeping, domestic service, and professional activities. Mining refers to a variety of mining occupations, mainly coal. Agriculture includes farmers.

There is another classification which causes some measurement problems. It was common for males to be called labourers in the 1817 baptismal records. Rather than treat them as a different employment group, labourers have been assigned to agriculture, mining, secondary, and tertiary sectors using the parish-level labourer share allocation devised by Keibek (2016). Labourers are not common in 1851 and so the problem is smaller. They have been assigned to agriculture, mining, secondary, and tertiary sectors using the same labourer share allocation as 1817.

We need a further estimate of the working age male population in 1821 order to convert the occupational shares in 1817 into total males employed in each group. Here we use the 1821 population census figure for number of males in a parish and the share of the working age male population in 1851 to get an estimate of the working age male population in 1821.

To summarize, we observe the number of males employed in secondary, tertiary, agriculture, and mining occupations in a parish in 1851. We also observe the best available estimate of the number of males employed in secondary, tertiary, agriculture, and mining occupations in a parish around 1817. To work with the occupational and population data for 1817 and 1851 in GIS, it is

[10] The PST system is described in detail in Shaw Taylor et. al. (2010) and Wrigley (2015).

necessary created a mappable unit, whose boundaries are consistent in both population and employment data sources over the nineteenth century. Our procedure is outline in Appendix A. The number of consistent mappable units is 9479. Most of these units correspond to individual parishes and townships, but others are aggregations. For simplicity, we refer to them as parish units. The parishes are also assigned to hundred, county, and registration districts. There are 59 counties and 616 registration districts in England and Wales. Below we use registration district fixed effects to capture unobserved heterogeneity. Results are similar with county fixed effects.

IV.1 *Transport Infrastructure Data*

The data on transport networks were previewed earlier. The turnpike network was created by Rosevear et. al. (2017).[11] The primary sources for the initial digitization of the turnpike network is Cary's New Map of England and Wales and part of Scotland. Cary's road lines distinguish turnpikes and post roads. Scans of the Cary mapping were geo-rectified and then digitized using the scans laid over Ordnance Survey 1:10560 first edition mapping.

The turnpike road network further distinguishes the individual trusts and the road segments they managed. For England, two resources identify the territories of turnpikes trusts from parliamentary records, acts of parliament and historic county maps. The first of these was a dataset of known milestones created by the Milestone Society. The milestones were digitized, mapped, and then added the turnpike trust authority name. The second was a series of marked up county maps mainly from Humphery-Smith (1984) with the roads under the jurisdiction of each trust and its opening date clearly identified. The milestones digital data were linked these to the turnpike polylines digitized from Cary. The marked-up county maps were then geo-rectified and used to correct and upgrade the trust data acquired from the milestones. The output of this step

[11] For a full discussion of the data source see http://www.socsci.uci.edu/~dbogart/research_page_nsf.htm.

was a provisional dynamic turnpike network for England. Additional steps were taken to check the trust name and dating was correct.

The inland waterway network was created by Satchell (2017).[12] The first step was a digitisation of all waterways shown on Richard Dean's Inland Navigation. A Historical Waterways Map of England and Wales. The c.1:536,448 scale of this map meant that in itself, it was not sufficiently detailed to produce a high standard GIS. As a consequence, the Dean digitisation was a guide to locate the historical waterways on geo-rectified scans of the Ordnance Survey first edition 1:105606 inch map series (surveyed 1840-1890), and the waterways were digitised directly from this map series. Satchell consulted several sources to date the opening and closing of inland waterways. In every instance emphasis was on establishing as far as possible when each section of the waterway was in commercial use.

Accessibility to road transport is measured through the distance between the center of each parish and the nearest turnpike road. Likewise, accessibility to inland waterways is measured by the distance to the nearest inland waterway. The center of a parish is defined as the market location if there was ever a market town in the unit. Otherwise the centroid is used. Distance to the network will be measured at various dates including 1670, 1750, 1770, 1800, and 1830 for waterways and 1750, 1775, 1800, and 1830 for turnpike roads.

The control variables are either time invariant or specific to the initial year 1801. One variable is the shortest distance to one of the largest ten towns in 1801 (Birmingham, Bristol, Leeds, Liverpool, London, Manchester, Newcastle, Plymouth, Portsmouth, Sheffield). It captures the effects of economic geography in the initial year 1801. The other main controls are measures

[12] For more details see http://www.campop.geog.cam.ac.uk/research/projects/occupations/datasets/documentation/navigablewaterwaysofenglandandwales1600to1948dynamicgisdraftdatasetdocumentation.pdf

of endowments including exposure to coal, coastal location, and ruggedness measures. Exposed coalfields are those where coal bearing strata are not concealed by rocks laid down during the Carboniferous Period. The GIS does not capture a handful of tiny post carboniferous coal deposits, such as that at Cleveland (Yorkshire) which was worked in the 19th century.[13] Coastal units are identified using shapefiles for parish boundaries in England and Wales. The ruggedness measures are the average elevation, the average elevation slope in the parish, and the standard deviation in the elevation slope in the parish. Appendix B details how these variables were created. A final important set of controls capture soil types. We use the highly detailed National Soils Map data from the Land Information System (LANDIS).[14] Soils are classified into 10 broad categories following Clayden and Hollis (1984).[15] 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, and (10) other including water features. We use GIS to calculate the percent of parish land area with these 10 soil categories.

The summary statistics of all the variables are shown in the following table. Population growth, measured by the log difference, was large from 1801 to 1851 and 1831 to 1851 increasing on average by 0.36 log points and 0.096 log points respectively. In employment, the highest growth category was tertiary, followed by secondary and then agriculture. The distance to the nearest turnpike road in 1830 was quite small on average. The distance to inland

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[13] The exposed coal data was created by Satchell and Shaw Taylor (2013). See http://www.campop.geog.cam.ac.uk/research/projects/transport/data/coal.html for more details.

[14] See Landis for more details, http://www.landis.org.uk/index.cfm

[15] See http://www.landis.org.uk/downloads/classification.cfm#Clayden_and_Hollis for more details.

waterways was greater on average. The endowment characteristics are also of interest. 15% of parish units were on the coast and 8% had exposed coal.

Table 1: Summary Statistics	mean	Std. Dev.	Min	Max	N
Log difference in population 1851 to 1831	0.0966	0.2121	-1.1418	2.9146	9,489
Log difference in population 1851 to 1801	0.3652	0.3636	-1.2103	5.3682	9,485
Log population density 1831	4.1459	1.3349	0.7344	11.6223	9,485
Log population density 1801	3.8776	1.3105	0.4833	11.4381	9,482
Log difference secondary employment 1851 to 1817	0.1512	0.6361	-3.9262	5.2942	9,486
Log difference tertiary employment 1851 to 1817	0.7252	0.7964	-2.687	4.9591	9,489
Log difference agriculture employment 1851 to 1817	0.0498	0.2905	-1.5319	4.282	9,489
Log secondary employment 1817	1.2211	1.734	-4.2884	9.7531	9,489
Log tertiary employment 1817	0.3804	1.9194	-5.9371	9.9525	9,489
Log agriculture employment 1817	2.4213	0.8636	-2.612	8.6066	9,489
Log distance nearest turnpike road in 1830 in km	-0.7734	1.8979	-19.337	2.731	9,491
Log distance nearest inland waterway in 1830 in km	1.4552	1.2177	-5.0611	3.8792	9,488
Log distance nearest customs port in 1830 in km	3.1856	0.9469	-2.8267	4.6022	9,488
Log distance nearest Ogilby road in 1680 in km	0.8532	1.6218	-8.9321	3.6375	9,496
Log distance nearest inland waterway in1680 in km	2.2023	1.2139	-5.1512	4.1176	9,489
Distance to nearest large town in 1801 in km	136.3901	67.9921	0	418.740	9,497
Dummy for exposed coal	0.0802	0.2716	0	1	9,498
Dummy for being on coast	0.1479	0.355	0	1	9,499
Slope elevation average	4.7675	3.6157	0.4849	37.4272	9,500
Slope elevation standard dev.	3.4324	2.7174	0	23.1755	9,501
Elevation average	89.7215	74.0256	-1.243	524.384	9,502
Percent land with raw gley soils	0.0847	1.3279	0	76.496	9,489
Percent land with lithomorphic soils	8.6151	19.8301	0	100	9,489
Percent land with Pelosols soils	8.2038	20.6374	0	100	9,489
Percent land with Brown soils	41.5641	33.1188	0	100	9,489
Percent land with Podzolic soils	4.6249	14.3262	0	99.565	9,489
Percent land with Surface-water gley soils	24.6329	29.4604	0	100	9,489
Percent land with Ground-water gley soils	10.1871	20.1177	0	100	9,489
Percent land with Man made soils	0.3638	3.2621	0	94.9904	9,489
Percent land with Peat soils	1.1875	5.2798	0	91.4403	9,489
Percent land with Other soils	0.5354	1.9668	0	65.1538	9,489

Sources: see text.

V. Results

The results analyzing population growth from 1801 to 1851 are shown in table 2. The specification in column 1 does not include controls for endowments or distance to the nearest large town in 1801. Greater distance to turnpike roads, inland waterways, and customs ports are all negatively and significantly related to population growth. The log level of population density in 1801 is also negatively and significantly related to population growth suggesting there is some convergence with low population parishes growing more than high population parishes. Column 2 adds the controls for endowments and distance to large towns in 1801. The coefficient on inland waterways and ports decrease in magnitude. The effect of ports becomes especially small. The reason is the addition of the control indicating whether parishes were coastal. Its coefficient is positive and significant, indicating that being coastal was the more important characteristic than being near a customs port. Column (3) adds the registration district fixed effects. This specification is important because it controls for unobserved heterogeneity at a very local level. The coefficients for distance to waterways and turnpikes are largely unchanged, indicating that unobserved heterogeneity is not likely to be a problem. Notice also that population density in 1801 is no longer significant, indicating that convergence does not hold across all registration districts.

Column (4) adds the hundred level population pre-trends. Notice the sample size becomes smaller because Welsh parishes does not have population estimates before 1801. Not surprisingly, population growth for the hundred from 1761 to 1801 is positively associated with parish level population growth from 1801 to 1851. Most importantly, the effects of distance to turnpike roads is largely unchanged. The coefficient for distance to inland waterways is smaller but still significant.

The magnitudes of the coefficients can be interpreted considering a 50% increase in the distance to either turnpike roads or inland waterways. The coefficients in model (3) imply that a 50% increase in distance to turnpike roads is estimated to reduce population growth from 1801 to 1851 by 1.00 percentage point. A 50% increase in distance to inland waterways is estimated to reduce population growth from 1801 to 1851 by 1.15% percentage points. Put differently if distance from a turnpike increased by 50%, the parishes annual growth rate is estimated to decline by 0.02%. If a parish's distance from an inland waterway increased by 50%, its annual growth rate would decline by 0.023%. The hypothetical 50% increase in distance is somewhat arbitrary. Below we also consider a counter-factual where distance to turnpike roads and inland waterways were the same as the distance to main roads and natural rivers in 1680.

Table 2: Infrastructure and population growth over the longer term
Dep. Var.: Δln pop. density parish, 1851 and 1801

variable	(1) Coeff. (Stan. Err.)	(2) Coeff. (Stan. Err.)	(3) Coeff. (Stan. Err.)	(4) Coeff. (Stan. Err.)
ln distance to nearest turnpike road 1801	-0.0207***	-0.0196***	-0.0207***	-0.0204***
	(0.00213)	(0.00213)	(0.00248)	(0.00252)
ln distance to nearest inland waterway 1801	-0.0471***	-0.0308***	-0.0308***	-0.0229***
	(0.00365)	(0.00407)	(0.00613)	(0.00595)
ln distance to nearest customs port	-0.0401***	-0.0129**	-0.0236	-0.0153
	(0.00511)	(0.00629)	(0.0159)	(0.0166)
ln pop. density parish 1801	-0.0305***	-0.0201***	-0.00753	-0.0119
	(0.00467)	(0.00437)	(0.00785)	(0.00819)
Δln pop. density parish hundred 1801 and 1761				0.110**
				(0.0440)
controls for endowments	N	Y	Y	Y
registration dist. FE	N	N	Y	Y
R-square	9,479	9,479	9,479	8,621
N	0.041	0.095	0.351	0.359

Notes: Robust standard errors in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

The turnpike road and inland waterway networks were still expanding between 1800 and 1830 and so it is useful to check whether their effects are different from 1831 to 1851. Table 3 reports the estimates. The specifications are similar, except column (3) uses the pre-trend in parish population density from 1801 to 1831 and (4) uses the hundred-level population pre-trend from 1761 to 1801 for English parishes only. The conclusions are similar in (3) and (4) which are the preferred specifications because they have registration district fixed effects. The estimates in (3) imply that a 50% increase in distance to turnpike roads (inland waterways) would reduce population growth between 1831 and 1851 by 0.42 percentage points (0.525 pps.), or in annual terms by 0.021% (0.026%). From this model, we learn that the annualized effects of turnpikes and canals are relatively similar in the 1831 to 1851 period and the 1801 to 1851 period.

Table 3: Infrastructure and population growth over medium term
Dep. Var.: Δln pop. density parish, 1851 and 1831

variable	(1) Coeff. (Stan. Err.)	(2) Coeff. (Stan. Err.)	(3) Coeff. (Stan. Err.)	(4) Coeff. (Stan. Err.)
ln distance to nearest turnpike road 1830	-0.00863***	-0.00866***	-0.00841***	-0.00761***
	(0.00122)	(0.00121)	(0.00140)	(0.00141)
ln distance to nearest inland waterway 1830	-0.0184***	-0.0108***	-0.0105***	-0.00947***
	(0.00207)	(0.00225)	(0.00308)	(0.00317)
ln distance to nearest customs port	-0.0128***	0.00163	-0.0115	-0.00887
	(0.00261)	(0.00333)	(0.00904)	(0.00926)
ln pop. density parish 1831	-0.00228	-0.000458	-0.00288	-0.00346
	(0.00258)	(0.00261)	(0.00481)	(0.00512)
Δln pop. density parish 1801 and 1831			0.0998***	0.0845***
			(0.0230)	(0.0249)
Δln pop. density parish hundred 1801 and 1761				0.0456*
				(0.0238)
controls for initial cond. & endowments	N	Y	Y	Y
registration dist. FE	N	N	Y	Y
R-square	9,481	9,481	9,477	8,619

N	0.023	0.069	0.292	0.282

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

The Ordinary Least Squares (OLS) models include a wide variety of controls, but there could still be a bias in the estimated effects. This issue is investigated further using our two instruments, distance to the main roads of 1680 mapped by John Ogilby in 1675 and distance to natural rivers in 1680. Note with the second instrument we are not capturing the effects of canals, rather the effects of waterways that were naturally given to a parish. Thus we are more cautious about this instrument because it does not capture the main infrastructure of interest.

The instrumental variables (IV) regressions are reported in table 4 for the 1831 to 1851 period. Column (1) reports the OLS results for comparison. Column (2) shows that when distance to turnpike roads in 1830 is instrumented with distance to Ogilby roads in 1680 the effects of turnpikes are very similar. Moreover, the first stage F-statistic is large as we might expect. We take this as more evidence that the estimated effects turnpikes are not strongly biased.   Column (3) shows that when distance to inland waterways in 1830 is instrumented with distance to natural rivers in 1670 the estimated effects are much smaller. Again we are cautious about giving this result a lot of interpretation because it captures the effects of natural rivers only and cannot identify the effects of canals. Column (4) shows the results are similar when distance to turnpikes and inland waterways are both treated as endogenous in the same equation. Note that here there are two first stage regressions, one for turnpikes and one for inland waterways.

Table 4: Instrumental Variable estimates for population growth
Dep. Var.: Δln pop. density parish, 1851 and 1831

variable	OLS (1) Coeff. (Stan. Err.)	IV (2) Coeff. (Stan. Err.)	IV (3) Coeff. (Stan. Err.)	IV (4) Coeff. (Stan. Err.)
ln distance to nearest turnpike road 1831	-0.00841***	-0.00924**		-0.00864**
	(0.00140)	(0.00393)		(0.00391)
ln distance to nearest inland waterway 1831	-0.0105***		-0.00574	-0.00427
	(0.00308)		(0.00543)	(0.00541)
ln distance to nearest customs port	-0.0115	-0.0128	-0.0117	-0.0123
	(0.00904)	(0.00866)	(0.00878)	(0.00875)
ln pop. density parish 1831	-0.00288	-0.00109	0.00401	-0.00164
	(0.00481)	(0.00525)	(0.00452)	(0.00544)
Δln pop. density parish 1801 and 1831	0.0998***	0.100***	0.101***	0.100***
	(0.0230)	(0.0222)	(0.0223)	(0.0222)
controls for initial cond. & endowments	N	Y	Y	Y
registration dist. FE	N	N	Y	Y
R-square	9,477	9,475	9,484	9,474
N	0.292	0.291	0.288	0.292
Instrument: ln distance 1680 road	N	Y	N	Y
Instrument: ln distance 1680 inland waterway	N	N	Y	Y
Kleibergen-Paap rk Wald F statistic		452.135	851.701	209.933

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

IV.1 Results for employment growth

This section turns to the analysis of employment growth. Our theory suggests that agricultural employment should locate away from turnpike roads and waterways, while secondary and tertiary employment should locate closer because they use land less intensively than agriculture. The OLS results in table 5 largely confirm this prediction. Columns (1) and (2) show that secondary and tertiary employment growth is lower with greater distance to turnpike roads and inland waterways. For secondary, the estimates imply that a 50% increase in the distance to turnpike roads would reduce employment growth by 1.65 percentage points, or by -0.081% in annual growth. A 50% increase in the distance to inland waterways would reduce secondary employment growth by 2.71 percentage points, or by -0.134% in annual growth. Column (3) shows that agricultural employment growth is higher with greater distance to turnpike roads and inland waterways. The effect is only significant with turnpikes though. The estimates imply that a 50% increase in the distance to turnpike roads would raise agricultural employment growth by 0.365 percentage points, or by 0.018% in annual growth.

Table 5: Infrastructure and employment growth OLS estimates
Dep. Var.: Δln employment density parish, 1851 and 1817

variable	OLS Secondary (1) Coeff. (Stan. Err.)	OLS Tertiary (2) Coeff. (Stan. Err.)	OLS Agriculture (3) Coeff. (Stan. Err.)
ln distance to nearest turnpike road 1801	-0.0330***	-0.0467***	0.00723***
	(0.00373)	(0.00419)	(0.00224)
ln distance to nearest inland waterway 1801	-0.0543***	-0.0516***	0.00647
	(0.00955)	(0.00905)	(0.00642)
ln distance to nearest customs port	-0.00172	-0.0465**	0.00659
	(0.0214)	(0.0227)	(0.0126)
ln pop. density parish 1801	0.663***	0.824***	0.289***
	(0.0305)	(0.0227)	(0.0212)
ln secondary employment density parish 1817	-0.536***		
	(0.0154)		
ln tertiary employment density parish 1817		-0.720***	
		(0.0158)	
ln agricultural employment density parish 1817			-0.557***
			(0.0342)
controls for initial cond. & endowments	Y	Y	Y
registration dist. FE	Y	Y	Y
R-square	8,775	8,311	9,402
N	0.411	0.596	0.404

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

Table 6 reports estimates of the same model using distance to 1680 roads and natural rivers in 1680 as instruments. The estimated effects of distance to turnpike roads are similar, and slightly larger. The effects of inland waterways are greatly reduced, but again they cannot capture the effects of canals.

Table 6: Infrastructure and employment growth IV estimates
Dep. Var.: Δln employment density parish, 1851 and 1817

variable	IV Secondary (1) Coeff. (Stan. Err.)	IV Tertiary (2) Coeff. (Stan. Err.)	IV Agriculture (3) Coeff. (Stan. Err.)
ln distance to nearest turnpike road 1801	-0.0570***	-0.0837***	0.0166**
	(0.00999)	(0.0116)	(0.00692)
ln distance to nearest inland waterway 1801	-0.0110	-0.00828	0.0109
	(0.0152)	(0.0152)	(0.0102)
ln distance to nearest customs port	-0.00633	-0.0526**	0.00678
	(0.0203)	(0.0218)	(0.0122)
ln pop. density parish 1801	0.665***	0.818***	0.298***
	(0.0283)	(0.0209)	(0.0219)
ln secondary employment density parish 1817	-0.543***		
	(0.0153)		
ln tertiary employment density parish 1817		-0.726***	
		(0.0159)	
ln agricultural employment density parish 1817			-0.560***
			(0.0334)
controls for initial cond. & endowments	Y	Y	Y
registration dist. FE	Y	Y	Y
Instrument: ln distance 1680 road	Y	Y	N
Instrument: ln distance 1680 inland waterway	Y	Y	Y
Kleibergen-Paap rk Wald F statistic	210.770	200.384	222.860
R-square	8,772	8,308	9,399
N	0.406	0.591	0.403

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

IV.1 Heterogeneous effects

Access to turnpike roads and inland waterways can depend on initial conditions. One hypothesis is that more dense parishes will grow more with greater access to infrastructure than less dense areas. Because of congestion effects, there could be a limit to growth in the very dense areas, so the effects may be strongest for the medium density areas. We test the preceding hypothesis by including interactions between quartiles of population density in 1801 and distance to turnpike roads and inland waterways. The lowest density quartile 1 is omitted and is the reference group. Table 7 reports the estimates. Column (1) includes the baseline model for comparison and column (2) shows the model with interactions. There is weak evidence that distance to turnpike roads had different effects depending on initial density. For inland waterways there is evidence that the largest effects of distance were in quartiles 4 and 5. For example, in quartile 4 a 50% increase in distance to inland waterways is estimated to reduce population growth by 0.655 percentage points, or -0.032% in annual growth. By comparison there appears to be close to zero effect in the lowest density quartile 1. These results may suggest that canals led to greater population concentration across space.

Table 7: Heterogeneous effects of Infrastructure and population growth
Dep. Var.: Δln pop. density parish, 1851 and 1831

variable	(1) Coeff. (Stan. Err.)	(2) Coeff. (Stan. Err.)
ln distance turnpike road 1831	-0.00592***	-0.00436
	(0.00138)	(0.00393)
ln distance turnpike road 1831 x 1831 pop quartile 2		0.000764
		(0.00496)
ln distance turnpike road 1831 x 1831 pop quartile 3		-0.00325
		(0.00467)
ln distance turnpike road 1831 x 1831 pop quartile 4		-0.00107
		(0.00464)
ln distance turnpike road 1831 x 1831 pop quartile 5		-0.00296
		(0.00459)
ln distance inland waterway 1831	-0.0101***	0.00118
	(0.00283)	(0.00743)
ln distance inland waterway 1831 x 1831 pop quartile 2		-0.00130
		(0.00776)
ln distance inland waterway 1831 x 1831 pop quartile 3		-0.00401
		(0.00813)
ln distance inland waterway 1831 x 1831 pop quartile 4		-0.0143*
		(0.00764)
ln distance inland waterway 1831 x 1831 pop quartile 5		-0.0138*
		(0.00789)
ln distance to nearest customs port	-0.0176**	-0.00851
	(0.00879)	(0.00906)
1831 pop quartile 2	-0.0111	-0.00718
	(0.00712)	(0.0160)
1831 pop quartile 3	-0.0146*	-0.00590
	(0.00812)	(0.0167)
1831 pop quartile 4	-0.00373	0.0189
	(0.00886)	(0.0158)
1831 pop quartile 5	0.0314***	0.0483***
	(0.0105)	(0.0165)
controls for initial cond. & endowments & 1801-31 pre-trend	Y	Y
registration dist. FE	Y	Y
R-square	9,477	9,477
N	0.287	0.296

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

Table 8 repeats the analysis for the growth of secondary sector employment. In this specification, initial density is based on secondary employment density in 1817, not population density. Surprisingly, the results are different from population growth. Distance to turnpike roads had greater effects in quartiles 3 and 4. Inland waterways have similar effects across quartiles for secondary employment density. The results warrant further investigation.

Table 8: Heterogeneous effects of Infrastructure and employment growth
Dep. Var.: Δln secondary emp. density parish, 1851 and 1817

variable	(1) Coeff. (Stan. Err.)	(2) Coeff. (Stan. Err.)
ln distance turnpike road 1801	-0.0247***	-0.00708
	(0.00354)	(0.0154)
ln distance turnpike road 1801 x 1817 sec. emp. quartile 2		-0.0114
		(0.0183)
ln distance turnpike road 1801 x 1817 sec. emp. quartile 3		-0.0305*
		(0.0175)
ln distance turnpike road 1801 x 1817 sec. emp. quartile 4		-0.0286*
		(0.0161)
ln distance turnpike road 1801 x 1817 sec. emp. quartile 5		-0.0104
		(0.0169)
ln distance inland waterway 1801	-0.0565***	-0.0537**
	(0.00963)	(0.0269)
ln distance inland waterway 1801 x 1817 sec. emp. quartile 2		-0.0101
		(0.0276)
ln distance inland waterway 1801 x 1817 sec. emp. quartile 3		-0.0176
		(0.0281)
ln distance inland waterway 1801 x 1817 sec. emp. quartile 4		-0.00384
		(0.0281)
ln distance inland waterway 1801 x 1817 sec. emp. quartile 5		0.00378
		(0.0269)
ln distance to nearest customs port	-0.0108	-0.0104
	(0.0217)	(0.0216)
1817 sec. emp. quartile 2	-0.454***	-0.428***
	(0.0268)	(0.0617)
1817 sec. emp. quartile 3	-0.614***	-0.570***
	(0.0258)	(0.0612)
1817 sec. emp. quartile 4	-0.721***	-0.708***

	(0.0275)	(0.0618)
1817 sec. emp. quartile 5	-0.666***	-0.646***
	(0.0318)	(0.0608)
controls for initial cond. & endowments	Y	Y
registration dist. FE	Y	Y
R-square	8,777	8,777
N	0.270	0.271

Notes: Robust standard errors in parentheses. *** p<0.01, ** p<0.05, * p<0.1

V. The impact of turnpikes and canals: counter-factual

In this final section, we return to the broader question of how turnpikes and canals impacted growth in England and Wales. Earlier the coefficient magnitudes were discussed in the context of a 50% increase in the distance to turnpike roads and inland waterways. We now consider a different counter-factual more rooted in the history. Turnpike roads and canals bundled several legal, technological, innovations. These innovations can be dated to the late 17th century and were largely implemented in the 18th century (Willan 1964, Albert 1972). Viewed in the long-term, these innovations were not guaranteed. In other words, they may not have occurred or might have been delayed for several centuries. In that case England and Wales would have to operate with the roads and inland waterways of 1680. Our estimates can inform how much less growth there would have been in the early 19th century in the absence of innovations in turnpike roads and canals.

We answer this question by comparing our model's predicted level of growth given the turnpike and canal network of 1801 with our model's predicted level of growth assuming England and Wales kept its 1680 network. Specifically, we calculate $\Delta \ln(\widehat{pop_{i1851})}^{network=1680}$

which is the predicted log difference in growth for each unit using the network of 1680. We then take exponential of the predicted growth which gives the predicted ratio for population or employment: $\frac{\widehat{pop_{i1851}}}{pop_{i1801}}^{network=1680}$. We then multiply by the 1801 value pop_{i1801} to get each unit's predicted population or employment level in 1851 ${pop_{i1851}}^{network=1680}$. Finally we sum over all units to the national predicted population or employment in the counter-factual ${POP_{1851}}^{network=1680}$. The same calculation is done using the actual network in 1801. This yields ${POP_{1851}}^{network=1801}$. Our model is based on column (3) in table 2. It is our preferred specification, including registration district fixed effects. We also repeat the calculation for the model in column (3) of table 3 which focuses on growth between 1831 and 1851.

The results of the counter-factual are shown in table 9. Panel A shows the counter-factual for 1801 to 1851 and panel B for 1831 to 1851. In the absence of turnpikes and canals there would have been 3.9 percentage points less population growth from 1801 to 1851 and 1.54 percentage points less growth from 1831 to 1851. This amounts to an annual change in population growth between -0.077% and -0.079%. One interpretation from this is that transport innovations were a contributor to the industrial revolution, but at the same time they were one factor among many. Other innovations like the spinning jenny or improvements in mortality are a key part of the story as well.

Table 9: Counter-factual parish growth estimates

Panel A ITEMS for 1801 to 1851	Outcomes
(1) Aggregate population growth between 1801 and 1851 predicted by the model	47.07%
(2) Counter-factual aggregate population growth between 1801 and 1851 predicted by the model if distance to turnpikes in 1800 equaled distance to 1680 roads and distance to waterways in 1800 equaled distance to 1680 waterways	43.17%
(3) Percentage point change in aggregate population growth between 1801 and 1851, (1)-(2)	-3.90%
(4) Annual percentage point change in aggregate population growth, (3) annualized over 1801 to 1851	-0.079%

Panel B ITEMS for 1831 to 1851	Outcomes
(1) Aggregate urban population growth between 1831 and 1851 predicted by the model	19.74%
(2) Counter-factual aggregate population growth between 1831 and 1851 predicted by the model if distance to turnpikes in 1830 equaled distance to 1680 roads and distance to waterways in 1830 equaled distance to 1680 waterways	18.20%
(3) Percentage point change in aggregate population growth between 1831 and 1851, (1)-(2)	-1.54%
(4) Annual percentage point change in aggregate population growth, (3) annualized over 1831 to 1851	-0.077%

VI. Conclusion

From 1680 to 1830 more than 20,000 miles of road were improved, 500 miles of river were made navigable, and 4000 miles of canal were constructed in England and Wales. Remarkably most of these infrastructure investments were financed by turnpike trusts and joint stock companies. By mobilizing capital, turnpike roads, river navigation, and canal companies created a transport revolution that ran side by side with the industrial revolution.

This paper uses accurate geographic data on the locations of all turnpike roads, rivers, and canals for the first time. It also uses recently available data on parish population and employment levels from the late 1700s and early 1800s. Our baseline model is a regression of population or employment growth from 1801 to 1851 on variables for distance to turnpike roads and distance to canals in 1800 plus controls. The main results show that access to turnpikes and canals affected parish population and employment growth. The estimates are also used to quantify the amount of population growth that would have occurred if turnpike roads and inland waterways were the same as the main road and river network in 1680. We find that population growth from 1801 to 1851 would be 3.9 percentage points lower, or put differently the annual population growth rate would have been -0.079% lower. Based on these estimates, it is clear that turnpike roads and canals were a contributor to growth during the industrial revolution, but they cannot account for much of the growth that occurred.

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Appendix A:

Documentation on the creation of mappable units

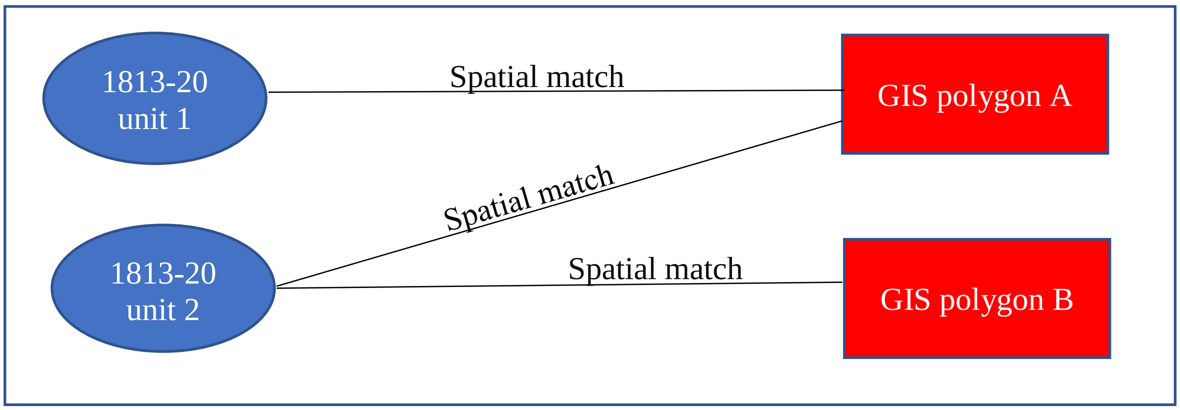
The English administrative units display highly inconsistent features. Several different hierarchal systems can coexist at the same time; different region can use different nomenclature; different systems can exist at different time slices; and boundaries of individual units within each system can change 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 in the context of this paper. This paper draws 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

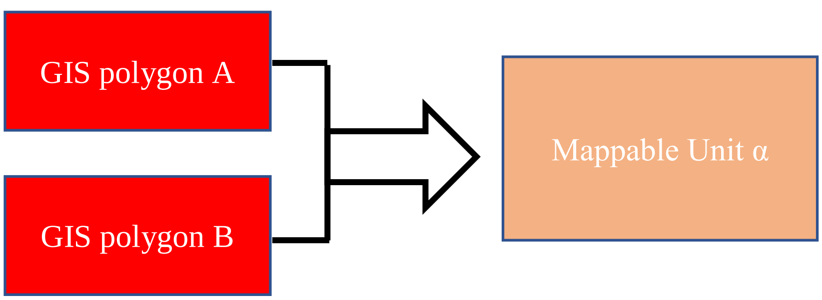
The method of creating a set of consistent geographical units based on the units in each dataset involves two steps. Firstly, we made spatial match between parish level Geographical Information System (GIS) polygons and geographical unit from each dataset. The spatial match essentially made connections 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 in Satchel et. al. (2016). appendix XXX. Part of spatial match process can be carried out automatically, but there are cases where spatial matches can not 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 can not 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:

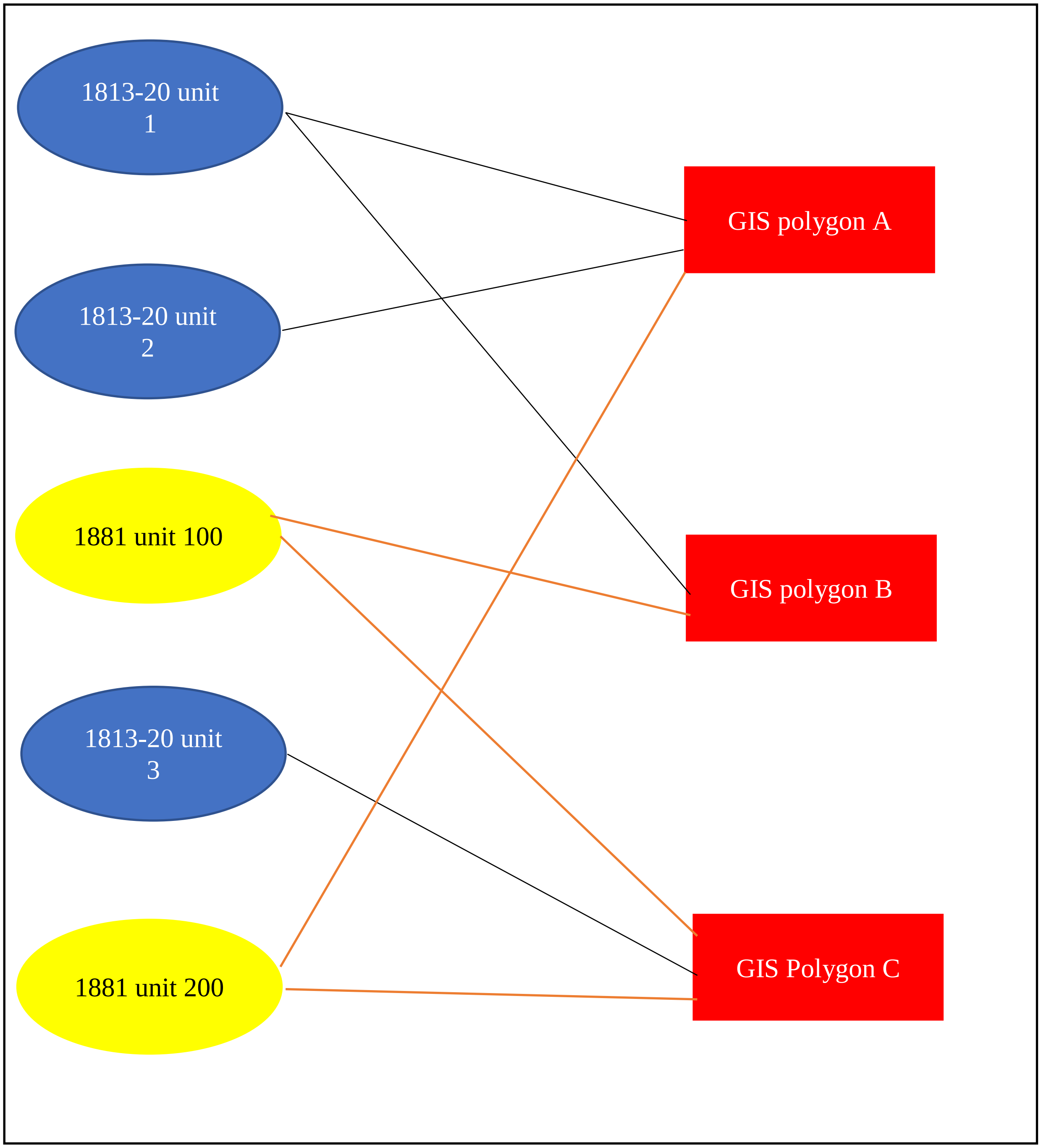


In this case, unit 1 from 1813-20 baptism dataset has a spatial match with the GIS polygon A, and polygon A only. And It does not have direct match with the GIS polygon B. But unit 2 from1813-20 baptism dataset has spatial matches with both GIS polygons A and B. Namely, part of the land enclosed by polygon 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 B: **the creation of elevation variables using DEM rasters.**

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.

Elevation data sources

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.

In order to carry on this work, we have downloaded several elevation DEM[16] rasters, preferably DTM[17], covering the entire England and Wales. In decreasing order in terms of accuracy, the most precise one database was LIDAR (5x5m.), Landmap Dataset 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 Endeavour 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, although the involved contradictions. This simplification may be considered reasonable for rural places but it is more inconsistent in urban surroundings where the urbanisation 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.

Elevation variables and specific methodology

As stated in appendix A, 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

[16] Digital Elevation Model

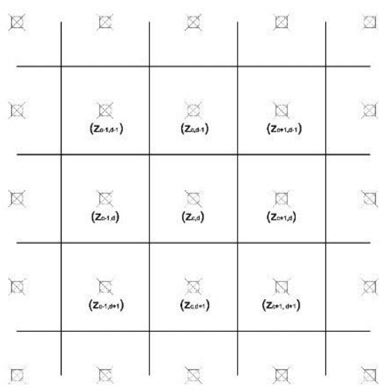
[17] Digital Terrain Model; obtained after removing all the surface features to plot the bare terrain.

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.

The second derivate 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) as follows:



$$I_R = \overline{I_{R_{c,d}}}$$

$$I_{R_{c,d}} = \sqrt[2]{\frac{8 \cdot \sum_{j=d-1}^{d+1} \sum_{i=c-1}^{c+1} (z_{c,d} - z_{i,j})^2}{n}}$$

Where:
$I_{Rc,d}$ is the ruggedness index in the cell (c,d).
$Z_{c,d}$ is the elevation value in the cell (c,d).
8/n is a corrector factor that compensates the boundary effect

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.

Slope was an alternative measure of topographical heterogeneity.

a	b	c
d	e	f
g	h	i

$$Slope_{[rad]} = \tan^{-1}\left(\sqrt{\left(\frac{dz}{dx}\right)^2 + \left(\frac{dz}{dy}\right)^2}\right)$$

Where:
[dz/dx] = ((c + 2f + i) - (a + 2d + g) / (8 * x_cell_size)
[dz/dy] = ((g + 2h + i) - (a + 2b + c)) / (8 * y_cell_size)

Being:
Z = Elevation data
X = coordinate in horizontal axis
Y = coordinate in vertical axis

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.

Sources

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.
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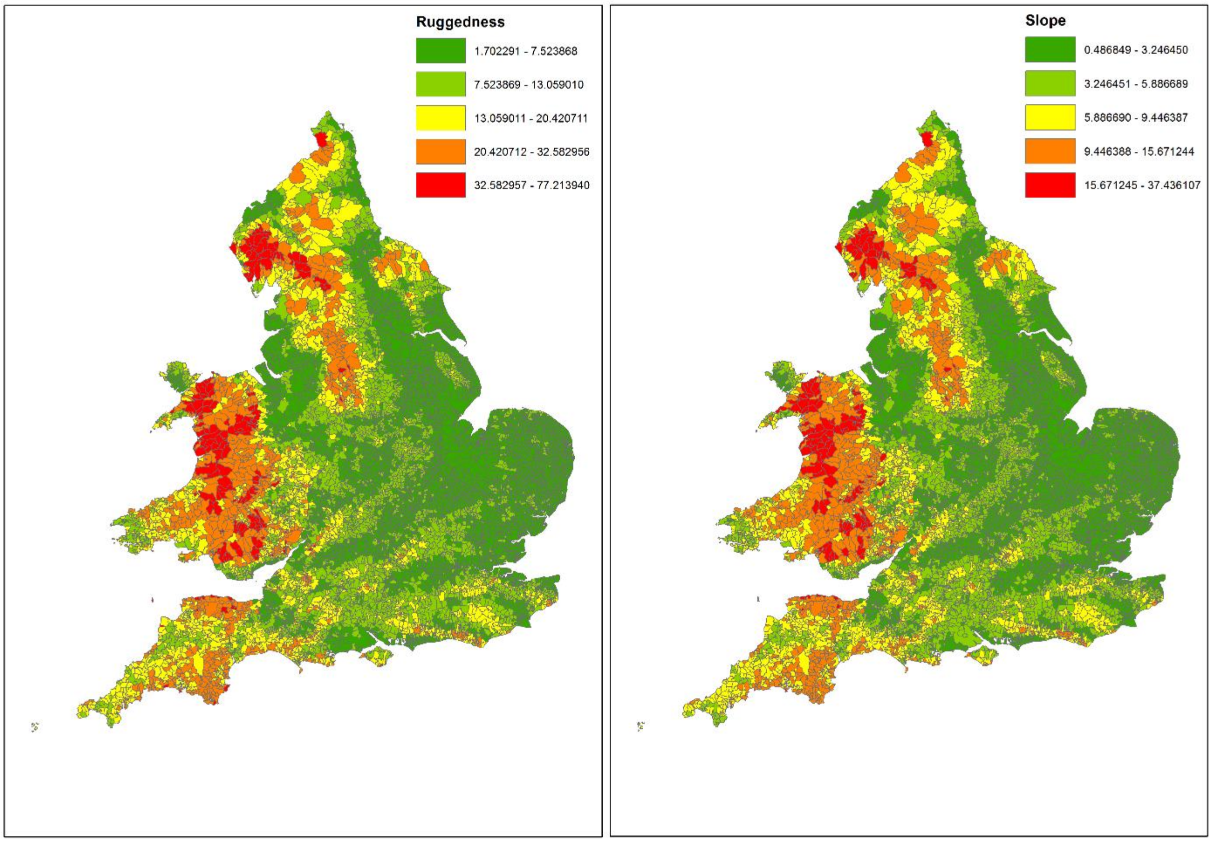

Figure. Ruggedness and Slope indices of topographical heterogeneity. The maps display the average value in each continuous unit.