Transport and urban growth in the first industrial revolution

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Abstract[6]

During the first industrial revolution the English economy underwent a spatial transformation to go along with its structural transformation in employment. It became highly urbanized and, apart from London, its urban center shifted to the northwest. This paper examines the role of transport in causing this spatial transformation. Transport changed greatly with infrastructure improvements and technological and organizational innovations. We focus on those occurring before the era of railways and steam ships, when wagons, canals, and sail ships were dominant. We construct a measure of market access for 458 towns in 1680 and 1830 using a new multi-modal transport model and then estimate the effects of lower trade costs through changes in market access. Our regression model controls for various town characteristics, including coal endowments. The results show that changes in market access had a large positive effect on changes in urban population. Through counterfactuals we estimate that England's urban population would have been 11% lower if trade costs remained constant from 1680 to 1830. The results contribute to a new understanding of the industrial revolution and spatial economic growth more generally.

Keywords: Urbanization, transport, market access, industrial revolution

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Cities generally grow with the process of economic development. Sometimes change is so radical that a new urban-industrial cluster emerges. Britain experienced such a fundamental change in economic geography during the industrial revolution. Around 1680 most of the urban population was in or near London and most other towns were very small in comparison. By 1841 a large urban cluster emerged in the northwest near towns like Manchester, Liverpool, and Birmingham. At the same time, London continued to grow but its share of the urban population fell between 1680 and 1841. This new urbanization occurred in a context where the share of the labor force in agriculture fell dramatically and the share in manufacturing and services increased. As laborers sought new employment, they turned to cities and towns where manufacturing and services were located. Also, newly established firms set up in towns with an available labor force. These new urban clusters became the factories of the world.

What factors encouraged the labor force and firms to choose certain locations, like the cities and towns in the northwest or London? The traditional view is that endowments, most importantly coal, was the major factor determining the location of urban growth. Most of the rapidly growing industrial cities, like Manchester and Birmingham, had coal nearby. While coal was always present, large-scale extraction required new technologies invented in the eighteenth century like the steam engine. Therefore, the importance of being near coal and related endowments increased in eighteenth century. A different explanation is that some towns grew more because they had greater access to markets, giving them advantages in attracting workers and firms. Market access was a function of geographical location, transport infrastructure, and technology. The latter two were transformed by an early revolution in transport in England and Wales. New canals, bridges, and ports were built, while existing roads and rivers were improved by trusts and joint stock companies. Technology changed through innovation in vehicles, like wagons, coaches, and vessels. For example, the switch from square sails to fore-and-aft rigging meant vessels could maneuver better (Armstrong 1991). The sum effects of infrastructure and technology were large in changing transport costs. What is not clear is whether they can explain urban population change between 1680 and 1841, beyond the effects of endowments like coal.

Previous studies on the role of transportation and urban or regional development often emphasize the effects of individual infrastructures or technologies. For example, maritime historians emphasize the development of new shipping technologies and their impact on freight costs across coastal and international markets.[7] Other studies on inland transport focus on where canals and roads were built and if growing towns were nearby or not.[8] While valuable, these studies do not incorporate inter-modality and network structure. Transport historians have shown that some shippers reached distant markets using a combination of roads, canals, and ports.[9] Therefore, if inter-modality was common, a town's growth prospects would depend not just on whether it was near a better road, canal, or port, but also whether that proximity increased access to larger markets.

New empirical methods allow for a multi-modal modeling and to estimate the effects of changing transport costs through market access. In the literature, market access is defined in various ways.[10] One school builds on theoretical models of trade to define market access using population-weighted inverse trade cost and parameters capturing the dispersion of productivity across locations. In this approach trade costs are the ratio of producer prices plus transport costs divided by producer prices. Thus, they measure changes in transport costs relative to change in the prices of goods being shipped to consumers and downstream firms. This approach has been used in several empirical papers to study a wide variety of topics like the effects of railroads, highways, and shipping mainly in the 19th and 20th centuries.[11] We adopt a similar approach, but we extend this literature significantly by bringing geography and infrastructure quality into estimates of market access. We also analyze pre-railway and pre-modern highway infrastructures in a market access framework for the first time. Finally, we are the first to examine how market access affected population change during the industrial revolution, which involved the formation of a new industrial cluster: the northwest of England.

[7] See Armstrong (1991) and Solar (2013) for two examples.
[8] See Gerhold (1996, 2014), Bogart (2005), Turnbull (1987), Harley (1988), Armstrong (1991), Maw (2011), and Solar (2013), Leunig (2006).
[9] Turnbull (1979) shows how the famous shipper Pickfords relied on inter-modality. See also Bogart, Lefors, and Satchell (2019) for more cases of inter-modality. Others are described in the general histories of transport Bagwell (2002) and Aldcroft and Freeman (1983).
[10] See Gibbons et. Al. (2019) for an example.
[11] See Donaldson (2018), Donaldson and Hornbeck (2016), Jaworski and Kitchens (2019), Alder (2014) and Faber (2014), Jacks and Novy (2018).

In our approach, market access is calculated using transport costs derived from a multi-modal freight model. It incorporates networks through new GIS data on roads, inland waterways, ports, and coastal shipping routes. These networks are further differentiated by infrastructural quality measures based in historical sources. Geography is incorporated through the slope of the terrain, which affects infrastructure networks differently. Technology is incorporated through transport cost parameters, like coastal freight rates per mile, also estimated from historical sources. Our model identifies the least cost route across all available networks, allowing for inter-modality. The output is a matrix of freight transport costs by origin and destination between 458 towns at two benchmark dates, 1680 and 1830. Our baseline market access measure is the inverse trade cost weighted sum of town populations following the literature. We also use formulas derived from trade models.

Our analysis of market access is restricted to 1680 and 1830 for several reasons. First, there is little available spatial economic data for England and Wales prior to the 1801 census. Town populations are probably the most accurate and informative, but they must be estimated. To our knowledge, Langton (2000) is the only source with comprehensive town population estimates at an earlier date, namely around 1680. Moreover, Langton links the town unit with the census to provide further population estimates in 1801 and 1841. Building on Langton's data we create a multi-modal transport model for 1680 and 1830. The latter date is meant to capture the full development of transport prior to the steam era. Several canals were completed in the early 1800s and 1810s. Also, once railways and steamships arrived around 1830 transport changed fundamentally once again and they require a separate analysis. The last reason is practicality. As will become clear later, the multi-modal model requires a lot information, and we go to some lengths to ensure its accuracy.

Our reconstruction of inter-urban transportation infrastructure and technology shows that market access increased substantially across most of England and Wales in the pre-steam era. However, the degree of change was very different across space. Originally market access was high only near London and some coastal areas. By 1830 market access increased substantially in the midlands and northwest industrial clusters, approximately equaling market access near London. Next, we estimate the effects of changes in market access on town population growth from 1680 to 1841. The specification is a ‘change on change,’ meaning the log difference in population is regressed on the log difference in market access. The specification also includes control variables for endowments, like coal and being located on the coast, and for unobserved factors at the regional level. The results show that changes in market access are robustly associated with higher population growth. Moreover, a similar estimate is found when focusing on transport changes by fixing 1680 population in calculating market access. The same applies when we exclude market access associated with towns within a 50 km buffer.

Naturally our estimates do not imply that all town population growth is explained by market access. Consistent with our expectations and those of the literature, we find that being located on the exposed coalfields had a large and positive effect on town population growth. Thus our estimates confirm the importance of first-nature variables, while also pointing to a new determinant: the expansion of market access through transport improvement.

The importance of transport is further illustrated using a counterfactual, where transport networks and technology are assumed to not change between 1680 and 1830. We find that the total urban population in England and Wales would have been 6.24 million in 1841 instead of 7.02 million, or a 11% decline. Interestingly, some cities and towns would retain much of their population even with higher transport costs. London for example, retains 91% of its 1841 population under the counterfactual. However, the largest inland manufacturing towns, like Manchester, Birmingham, Leeds, and Sheffield are estimated to be much smaller in the counterfactual. In summary, our findings imply that changes in transport infrastructure and technology had a large impact on the size of many important towns during the industrial revolution.

Our paper is related to the emerging literature which uses GIS tools to study transport and economic development. Our study is unique in that we analyze the period before 1830. They suggest the relationship between market access and growth is quite robust and consistent.

Our paper also contributes to the literature on the drivers of growth during the industrial revolution. Transport improvements are thought to be a key engine of economic growth in the English economy. The economic gains from steamships and railways are often discussed but far less is known about the extent of change in the pre-steam era and its effects.[12] In this paper, we show that pre-steam transport innovations were a significant driver of economic growth.

The paper is organized as follows. Section I gives background on urbanization and transportation. Section II presents data. Section III discusses the methodology for estimating market access and IV the empirical specification. Section V presents the econometric results and VI counterfactuals. Section VII concludes.

I. Background

A. Urbanization in England and Wales

Urbanization increased substantially in England between 1650 and 1801. Wrigley (1985) estimates that 13.5% of the population lived in cities and towns of 5,000 or more in 1670. This figure rose to 17% in 1700, 21% in 1750, 27.5% in 1801, and 43.5% in 1851. While the urban population increased overall, there was significant variation in population growth across towns. Cities are considered to have been large urban settlements, but towns are not as precisely defined in the literature. Historians generally refer to towns as urban settlements recognized by contemporaries as being different from rural areas. For simplicity, we refer to all urban settlements as towns, no matter how large. London was the largest. Its population is estimated to have increased from 575,000 to 2.3 million between 1700 and 1851. The rate of increase was much larger in Manchester and Liverpool. Both had no more than 2500 inhabitants in 1700, but by 1851 they had more than 300,000 inhabitants. Other large towns grew less than Manchester and Liverpool. For example, York was the third largest town around 1680 but its population only doubled between 1700 and 1851. Overall, there were towns which grew marginally and others which experienced large increases.

Town populations increased through a combination of migration and natural increase. The relative contribution of each to town population growth is not known with precision, but it is accepted that migration was probably the more important factor than lower mortality in creating urban divergence up to 1850 (Pooley and Turnbull 2005, Davenport 2020). Much

[12] See Crafts and Harley 1985, Crafts (2001), and Broadberry et. al. 2019 for drivers of growth.

migration went from rural to urban areas. Fertility rates were high in rural areas, which created a surplus of labor, even with agricultural demand increasing. Structural changes in agriculture, such as enclosures, also played a role in encouraging rural out-migration. Some rural migrants went to nearby towns, while others travelled further to London. Urban to urban migration also occurred. These would generally be young apprentices, who might start in one town and migrate to another when completing their training.

B. Town employment and industrialization

Towns naturally had more employment in manufacturing and services than rural areas. Manufacturing was very diverse and included textiles, food, household goods, and metal working (Shaw-Taylor and Wrigley 2014). Some of these manufacturing activities used little capital, while others were more capital intensive. The skill level was also higher in urban areas, which is one reason that urban wages were generally higher. A higher share of service employment was perhaps the most distinctive aspect of town versus rural employment. These could include transport, retail, and professional activities. Wages and skill levels in services could vary dramatically across these types.

Town employment underwent substantial changes with industrialization. The earliest factories were normally set up in or near towns (Berg 2005). They offered a supply of labor and complementary services like finance. Factories increased the level of technology and made labor more productive. For example, the spinning jenny dramatically increased the productivity of textile workers. While many technological changes were labor saving, they generally lowered prices sufficiently to raise the overall demand for manufacturing labor. Industrialization also fostered greater employment in services. Factories required transport and retail workers to serve the new urban factory workers in towns. The share of service employment increased substantially, perhaps more than manufacturing and agricultural employment during the process of industrialization (Wrigley and Shaw-Taylor 2014).

While towns were generally more productive than rural areas, there were several constraints on their growth. Food and fuel were the two main necessities. Therefore, low agricultural productivity in a town's hinterland and limited supplies of wood and coal could inhibit their growth (Wrigley 2014). Good transport infrastructure allowed towns to overcome local limitations in food and fuel by bringing in imports. The problem was that transport needed to be developed through investment and/or technological change. Moreover, local endowments meant the opportunity to develop transport was not the same across all towns. We now turn to this issue.

C. Transport infrastructure and technology

Like most economies, transportation in England and Wales was poor and often precarious around 1680. The poor state of road maintenance made it extremely difficult to reach large distances at a reasonable cost. Main rivers allowed the navigation of boats, but only in specific segments. Meteorological conditions also affected communications both in roads and rivers, adding to even more uncertainty. Coastal routes allowed the transport of heavy goods between ports and harbors at reasonable cost. However, sailing vessels showed high unpredictability in terms of travel time which meant higher costs. To summarize, the 17th century economy lacked reliable transport infrastructure, which kept transport costs high, and maintained distance as the main barrier for trade between towns.

Transport infrastructure in England and Wales had evolved dramatically by 1830, especially the inland networks. Old roads started to be modernized using new paving materials. Turnpike trusts emerged to keep roads in good condition and to finance new investments. Acts of parliament gave powers to bodies of trustees to improve and expand the road network. They allowed trustees to levy tolls on users with the aim of better maintaining roads. Turnpike trusts were remarkably successful in improving roads up to the 1830s (Bogart 2005). Innovations in vehicles and firms were significant too (Gerhold 1996). Waterways were the network in which changes were perhaps most crucial. From navigable rivers in the previous period, the construction of canals gave transport accessibility to remote and isolated locations. Coals mines could be exploited wherever the minerals emerged, and the new infrastructure allowed its transport to the cities or factories (Turnbull 1987). Changes were also noteworthy in coastal trade. Port infrastructure developed considerably, as well as the design of ships and vessels.

Navigation techniques also evolved with the introduction of lighthouses and charts (Armstrong 1991).

Foreign shipping also underwent significant change in the eighteenth and early nineteenth centuries. Innovations like copper sheathing dramatically increased the speed of slave ships (Solar and Ronnback 2015). Ships also sailed significantly faster indicating broad technological change (Kelly and O'Grada 2019, Bogart et. al., 2020). Overall, the changes in overland, inland waterway, coastal, and foreign shipping produced a transport revolution. We now examine their implications, especially internal transport improvements.

II. Data

A. Town populations and location

Several sources are used to measure town populations across time. The first is Langton (2000), who estimates 1005 town populations in the late 17th century.[13] Langton also matches these towns to the census, providing further population figures in 1801 and 1841. The second and third sources are Law (1967) and Robson (2006) who provide a consistent time series of population for urban centers in England and Wales in every decade between 1801 and 1911. An urban center is defined as a census place that had a population above 2500 at some point between 1801 and 1911. All three sources are digitized and available through the 'Urban Population Database, 1801-1911' (Bennet).[14]

We take these sources and identify 590 Langton towns that are also listed in Law and Robson. Among these, 458 towns have population figures in the late 17th century, 1801, and 1841, which represents our main sample for our analysis of population change between the late 17th century and 1841. We also study a sample of 449 towns in Langton's list that have population data from Law and Robson starting in 1831.

[13] Langton's population figures are widely used in the urban history literature (e.g. Ellis 2001) and present a reasonably accurate picture.
[14] http://doc.ukdataservice.ac.uk/doc/7154/mrdoc/pdf/guide.pdf

Langton's late 17th century population estimates are not without controversy, mainly because assumptions are needed to work with the sources. The vast majority are based on counts of enumerated households in the contemporary hearth taxes dated around 1660.[15] Langton expressed particular doubts about his estimates for the largest towns, which were calculated from counts of hearths, rather than counts of households and noted that his estimates based on such counts could be 30 per cent below the true value.[16] Since we know Langton's population estimates contain error, the question is how much. As one check, we find that the sum of Langton town populations in a county divided by total land area is highly correlated with county population density measured from different sources. County population density c.1660 is estimated by taking the weighted average of Wrigley (2009)'s English county population figures in 1600 and 1700 and then dividing by land area in the county. The correlation between total Langton town population density and county population density c.1660 is 0.98. This high correlation shows that Langton town population estimates c.1660 are very accurate in comparing town populations across counties. Nevertheless, measurement error at the town-level is a concern and our estimation of population change starting in the late 17th century is subject to that caveat. To address robustness, we will also study town population change from 1801 to 1841 and from 1831 to 1911. These figures are more reliable as they come from census data.

We link our Langton-Law-Robson towns to a georeferenced candidate town database provided by the Cambridge Group for the History of Population and Social Structure (CAMPOP).[17] In the CAMPOP data, towns are treated as points in GIS and their coordinates are identified based on a hierarchy of characteristics for trade. To decide towns' location, the first step was to identify the coordinates of its market place. In the absence of an urban market, parish church coordinates

[15] Langton 'Urban growth' pp. 460, 462 463, 486, 489. Fifty-six population estimates derive from the Compton Census. Fourteen towns, for which data were not available, are reasoned guesswork based on nearby towns. Ibid, p.460 and fn. 39.

[16] Langton, 'Urban growth, p. 461, especially footnote 46. London's population was 66 per cent of Wrigley's estimate for 1670 and 65 per cent of that by Gregory King (much the best informed and statistically literate contemporary for 1695. Norwich's estimate, then the second city, is only 70% of the most widely cited estimate, Ibid, p 461 and fn. 48.

[17] See Satchell, Potter, Shaw-Taylor, and Bogart (2017) for GIS data on towns.

were assigned. If no parish church, then inns, post offices, public houses, and high streets are used in that order.

B. Transport networks

Roads, waterways and coastal routes have been digitized from historical sources for 1680 and 1830[18]. These GIS databases are the core of our analysis. Maps of each transport network are provided in appendix 2. The road network in 1680 is constructed in two steps.[19] The first step digitizes the strip maps of John Ogilby's Atlas published in 1675. It includes the principal roads in England and Wales. Specifically, 85 routes were plotted, covering over 7,500 miles in total. Ogilby's maps only represented the main roads of the network though. A second type of road was created to fill this gap based on a military survey in 1686. The survey identified sites with spare stables for horses. We chose sites with more than 15 stables and connected them to our Ogilby network using a database of old tracks.[20] The main differentiation in 1680 roads concerns vehicle accessibility. De Laune's London directory identifies whether packhorse or wagon services were offered between London and numerous towns across England and Wales. It is clear from De Laune that vast areas of the north and west were only accessible by packhorse, which was higher cost. We use this information to classify roads as packhorse or wagon in 1680.[21]

For road transport in 1830, we use the turnpike network as it represents the main roads. The turnpike network was digitized based on John Cary's *New map of England of Wales and a part of Scotland*, OS 1st ed.[22] Turnpike roads were known to vary in quality. A parliamentary survey of all turnpike roads in 1838 asked trustees to rate the quality of the roads under their authority. These ratings can be associated with all roads under the authority of each trust, which on average represented 20 miles. We classify 1830 roads as either high or low quality.[23]

[18] Our GIS transport networks were digitised, georeferenced, and vectorized from historical sources. For easier comprehension we just use the term digitization.
[19] See Satchell, Rosevear, Dickinson, Bogart, Alvarez, and Shaw-Taylor (2017) for GIS data on 1680 roads.
[20] The routes for 1680 secondary roads are explained in the documentation with Satchell, Rosevear, Dickinson, Bogart, Alvarez, and Shaw-Taylor (2017).
[21] A map of De Laune wagon and packhorse services in the appendix.
[22] See Rosevear, Satchell, Bogart, Shaw Taylor, Aidt, and Leon (2017) for GIS data on 1830 roads
[23] High quality corresponds to trustees rating their roads as good, very good, and excellent. Trustee ratings of middling and below are coded as bad quality.

Bridges and ferries are added as singular segments of roads. 1680 ferries and bridges were digitized from Ogilby and De Laune. For 1830 most ferries are replaced by toll bridges. They were digitized from Cary's *New map.*

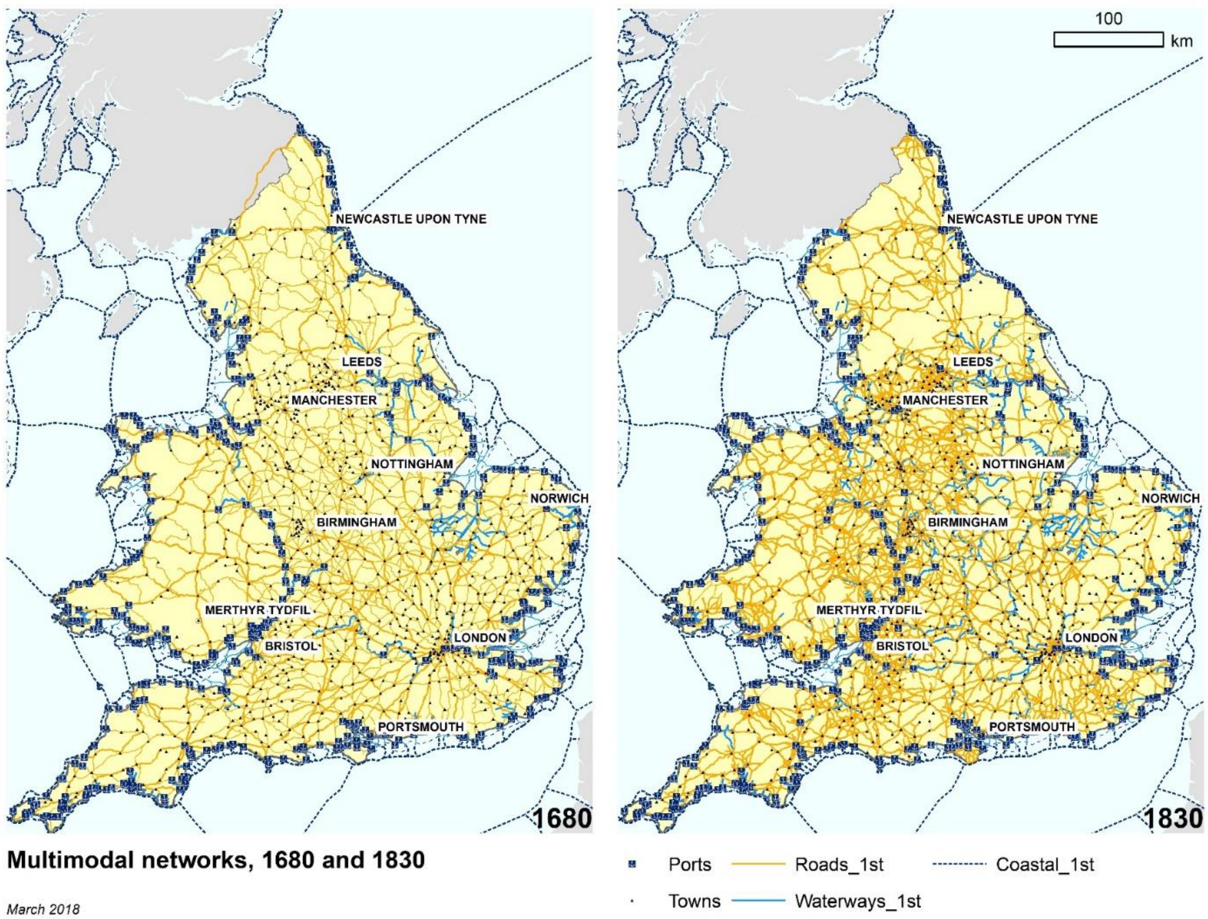
For inland navigation, we use a digitization of 1680 and 1830 waterways which is derived from a dynamic GIS dataset of rivers and canals from 1600 to 1948.[24] The dataset uses several sources like Dean's *Inland Navigation. A Historical Waterways Map of England and Wales*. In 1680 the inland waterway network mostly includes tidal rivers, like the Thames, but there were some improved rivers in the mid-17th century. In 1830 the inland waterway network includes tidal rivers, improved navigable rivers, and canals. Improved rivers and canals were generally more expensive for users because they paid tolls. The primary determinant of the toll appears to have been the number of locks along the waterway since these needed to be built and maintained. Most locks survive to this data and have been digitized by the canal and river trust. We add their GIS data on locks to our 1830 inland waterways.[25]

In the case of maritime and costal transport, we use a historical database of ports and coastal routes.[26] The list of ports in 1680 and 1830 are taken from historical sources like Daniel (1842). Ports were then georeferenced using the location of the most historic infrastructure, like a harbor or dock works. Coastal routes between ports were digitized according to the navigation knowledge of the era and the physical geography of the coast. The main primary sources used to determine coastal routes were navigation charts included in Collins (1693), *Great Britain's Coasting Pilot*.[27] We have some information on the amount of shipping that was devoted to foreign trade by port. We have linked the registered tonnage of ships involved in foreign trade in 1791 to the ports database using figures from the Atlas of Industrializing Britain (Langton and Morris 2002). There was huge skew in the distribution with London having by far the most registered ships involved in foreign trade.

[24] See Satchell, Shaw-Taylor, and Wrigley (2017) for GIS data on 1680 waterways
[25] See the River and Canal Trust, Locks, http://data-canalrivertrust.opendata.arcgis.com/datasets/locks-public. Accessed on 1 Aug. 2018.
[26] See Alvarez, Dunn, Bogart, Satchell, Shaw-Taylor (2017) for GIS of port lists and see Alvarez and Dunn (2019) for GIS of ports and coastal routes.
[27] For details on coastal routes, see Alvarez and Dunn (2019) for GIS of ports and coastal routes.

Figure 1 shows a full picture of the different transport networks in 1680 and 1830. Of note there were few inland waterways in 1680, especially compared to 1830. In the case of roads, turnpikes increased the total length and density of the network by 1830. Ports were common along the coast in both periods. Transport networks were clearly large and complex before the steam era.

Figure 1. Transport networks in 1680 and 1830.



Source: created by authors using source in text.

C. Freight cost data

Estimates of average freight costs per mile are needed for our network analysis. They come from several sources. Nef (1979, pp. 404-412) gives figures for coastal freight and port loading costs in the important northeast coal trade between London and Newcastle around 1690. We convert Nef's freight costs into a per ton mile rate using coastal distance between Newcastle and London and the Nef loading cost into a per ton flat figure.[28] In the 1830s, we use a series of parliamentary reports on the coastal coal trade. One of the most often-cited witnesses in the reports, Bentley, gives figures for loading costs and coastal freights (see Ville 1986). The data imply that the coastal freight rate fell from 0.21 to 0.17 pence per ton mile between around 1690 and 1830. The per ton loading coast fell from 27.1 to 22.9.

Willan (1936) summarizes inland waterway freight rates around 1700 as being 1 pence per ton mile. This figure applies to tidal rivers, like the Thames, which were then the main waterway. For 1830 a contemporary, Allnut, summarized freight rates on the river Thames as being 2.25 pence per ton mile.[29] Allnut also gives figures for several canals. They were more expensive than tidal rivers but with much variation. One factor was the number of locks, which we have included in our network data. Priestley (2014) gives a case where the cost of passing an individual lock was 1 pence per ton. We use this figure.

Road freight rates in the late seventeenth century are summarized in Gerhold (2005) separately for wagons and packhorses. The average for wagons was 10.6 pence per ton and the average for packhorses was 11.9. For 1830 Gerhold (1996) reports a road freight rate of 7.5 pence per ton mile between London and Leeds. This rate comes from a large overland trade in woolen textiles, and along one of the best roads in England at the time. However, not all road transport was a cheap as between Leeds and London due to varying road quality. Contemporary engineers, like John McNeil, noted that draught animal power changed significantly with road quality and slope. In testimony to parliament, McNeil provided a formula based on several field experiments. The formula computes draught power based on road condition and slope. McNeil's formula is used to estimate the freight rates per ton mile on turnpike roads of different quality and with different slopes. The quality metrics were described above. Slope was obtained by extracting

[28] Note there was a tax on sea coal brought into London which Nef details. We do not include this sea coal tax in our coastal loading or freight costs for two reasons. First, the tax was specific to the northeast coal trade and second we want to model coastal freight costs for all heavy products, including grain which was not subject to this tax.
[29] Bogart, Lefors, and Satchell (2019) discuss Allnut as source in more detail.

elevation values in the vertices of the road segment and dividing by the length between them. Our elevation raster is 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 (Jarvis et. al. 2008).

A trans-shipment cost is need in our model to switch from inland waterways to roads and vice versa. We use the labor component from coastal loading costs as detailed by Nef (1979), which implies inland trans-shipment costs were about half as large as seaport costs. This makes sense as in ports there were additional charges for infrastructure.

D. Price data

The price of goods at production sites are also needed for our analysis. We focus on pit-head coal prices because it was the most important traded good in terms of weight (Armstrong 2009). Moreover, with current sources it is not currently possible to measure all producer prices, especially in the late 17th century. Houghton's price lists are regarded as the best source of coal prices across several markets in the 1690s and early 1700s (Hatcher 1993). We digitized coal prices for all markets as reported in Rogers (1987) who summarizes the range of prices reported in Houghton each year. We focus on prices in Newcastle and Carlisle because they were very close to coalfields. In 1701, the one year of peace, the average coal price in Newcastle and Carlisle was 58 pence a ton. Peacetime is significant because it meant lower prices overall and should reflect prices in the 1680s when peace was the norm. In the early 1840s, the Poor Law Reports provide the comprehensive information on prices paid for coal at workhouses (Crafts 1982). The prices paid at workhouses near Newcastle and Carlisle averaged 86 pence a ton in that data. To summarize, our producer prices in 1680 and 1830 are 58 and 86 pence per ton respectively.

E. Town geographic and infrastructural data

For the regression analysis it is useful to incorporate geographic characteristics of towns as they have been identified as an important predictor of population growth. Here we build on a rich database of geographic characteristics for 9700 spatial units in England and Wales.[30] Towns are linked to one of these 9700 units based on their latitude and longitude. The town takes the linked-unit's values for geographic variables. Some towns are linked to the same spatial unit and we address this issue. The list of variables includes nine regional indicators, indicators being on exposed coalfields and being on the coast, average elevation, ruggedness measures, like average slope and the standard deviation of slope. More variables include average rainfall and temperature, wheat suitability, latitude, longitude, and the share of land in 10 different soil types. These variables are available for 9700 spatial units in England and Wales, which are linked to the town points. Coastal is identified using an intersection of the seacoast with spatial unit boundaries. The elevation and slope variables are calculated in GIS. Annual rainfall and temperature (both averaged from 1961 to 1990) and wheat suitability come from FAO. Of special significance to our analysis, 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.

The spatial unit data also includes infrastructural characteristics which are drawn from the network data introduced above. The main variable is distance to inland waterways in 1830 and 1680.

Summary statistics for town-level population change variables are shown in panel A of table 1. Our main outcome variable the difference in log 1841 and 1680 town population fits with overall population trends. The average difference in log pop. is 1.685, which implies an average annual growth rate of 1.05% between 1680 and 1841. The total English population grew by an average of 0.80% per year between 1700 and 1851. London's population grew by 0.94% per year between 1700 and 1851 (Shaw-Taylor and Wrigley 2014).

[30] See Bogart, You, Alvarez, Satchell, and Shaw-Taylor (2019) for details on spatial units and their variables.

Table 2: Summary Statistics

Panel A: Population vars.	(1) N	(2) mean	(3) sd	(4) min	(5) Max
ΔLn Town population 1841-1680	458	1.681401	0.811658	-0.30656	5.467073
ΔLn Town population 1841-1801	458	0.614231	0.345097	-0.10564	2.323528
Panel B: coordinate and regional vars.					
Longitude	458	430311	105112	147275	655050
Latitude	458	265417	131975	27475	652900
Southeast	458	0.198	0.399	0	1
Southwest	458	0.185	0.389	0	1
Eastern	458	0.135	0.342	0	1
West Midlands	458	0.111	0.314	0	1
East Midlands	458	0.096	0.295	0	1
Northwest	458	0.098	0.297	0	1
Yorkshire and Humber	458	0.078	0.269	0	1
Northeast	458	0.037	0.189	0	1
Wales	458	0.058	0.235	0	1
Panel C: first nature control vars.					
Coastal town	458	0.281	0.450	0	1
On exposed coal field	458	0.222	0.416	0	1
Percent soil type 2	458	0.345	4.327	0	64.674
Percent soil type 3	458	5.832	15.348	0	92.567
Percent soil type 4	458	4.401	13.310	0	100
Percent soil type 6	458	42.358	30.846	0	100
Percent soil type 7	458	4.300	12.072	0	97.062
Percent soil type 8	458	28.172	29.516	0	98.963
Percent soil type 9	458	11.890	21.003	0	100
Percent soil type 10	458	0.621	4.347	0	77.655
Percent soil type other	458	1.334	4.777	0	44.757
Elevation, mean	458	0.741	1.499	0	16.097
Elevation, st. dev.	458	83.077	65.157	0.325687	401.489
Slope, mean	458	29.610	27.290	0.5	166.016
Slope, st. dev.	458	4.777	3.040	0.69708	16.654
Panel D: first nature control vars.					
Diff. log 1830 and 1680 dist. to inland waterway	458	-1.37193	1.722314	-6.48062	3.124524

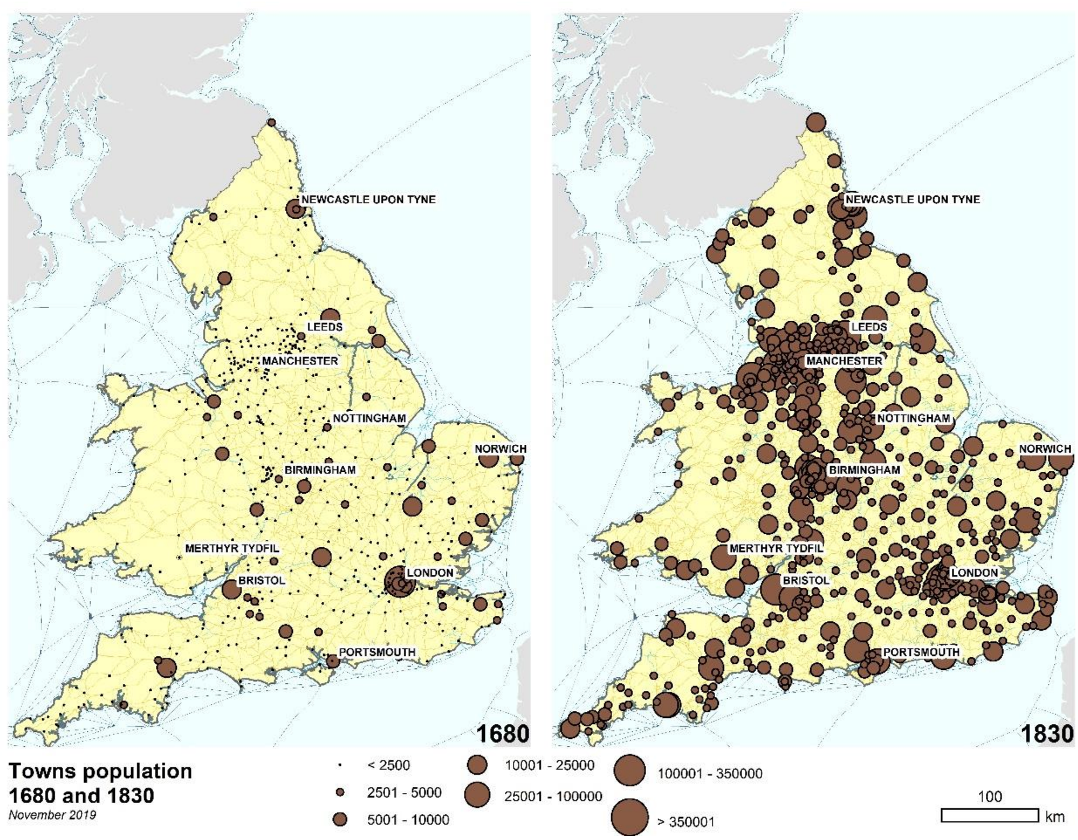
Sources: see text.

Panel B in table 1 gives coordinate and NUTS 1 regional indicator variables. Most towns are from the Southeast which includes London. However, our data includes towns throughout England and Wales. The spatial patterns and change over time for 458 towns are shown in figure

2. The rise in the level of urban populations between 1680 and 1841 fits with prior views. There was remarkable urban population growth in the northwest led by Manchester and Liverpool. Bristol and Birmingham also grew substantially, and of course, so does London. Appendix 1 provides more details and lists the population of the largest 20 towns in 1680 and 1841.

Panel C summarizes the geographic variables, which we collectively call 'first-nature' variables borrowing from the economic geography literature. Towns have a wide variety of first-nature features. Two of the most important on coastal access and being on the exposed coalfield. The latter is an extremely important factor in accounting for population growth. Units with exposed coal had 74 log points higher difference in log 1841 and 1680 population. That means they had 0.4% of additional annual growth. Panel D shows our infrastructural variable, the difference in 1830 and 1680 log distance to inland waterways. The average distance declines as the canal network was built. This too can explain population growth as we will see.

Figure 2: Towns and populations in 1680 and 1841



Source: Population data are from Langton (2001). Geo-coding is from Satchel et. Al. (2017).

Notes: The size of each settlement is proportional to their total population.

III. Methodology for estimating Market Access

Our empirical analysis builds on new estimates of market access for English and Welsh towns. To develop those estimates, we proceed in steps beginning with estimation of transport costs using multi-modal network analysis.

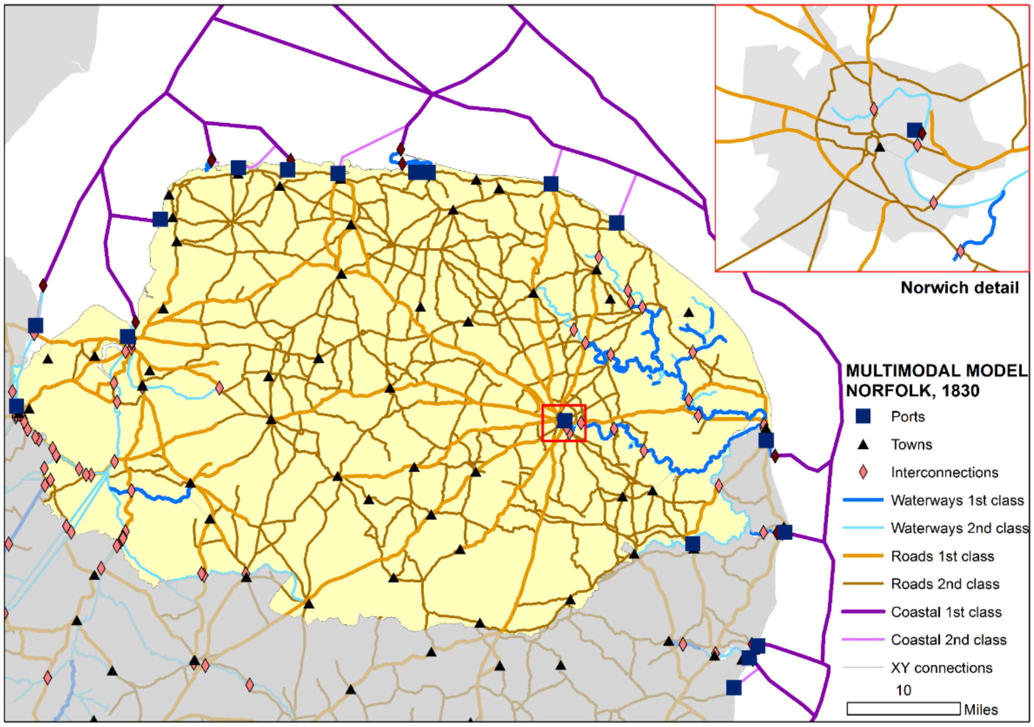
A. Measurement of transport costs

Multi-modal network analysis combines several modes of transport to create an integrated model, which identifies the most appropriate route between each pair of towns through all the available networks. Cost parameters for freight are used as the impedance of the model to solve for the least-cost-route between all towns in two time-slices: 1680 and 1830.

The framework of the multi-modal model can be observed in the figure 3. It integrates geographical information about transport and territory using points and polylines. In our case, we use points to represent towns, ports and the intersections between networks. Polylines are used to represent roads, waterways, coastal routes and the interpolated connections between the previous elements. To ensure the connectivity in the model, interpolated lines between point layers, towns and ports, and the respective networks are created. These “XY” connections in figure 3 are created as straight lines from the points to the nearest network, imposing certain restrictions. Also, interconnections were created when two different modes crossed.

We define connectivity and turns’ policies and the routing parameters for each mode of transport. In terms of turns, we opt for a global turns policy. This means we allow all the movements within each network, but also between them. For example, if a wagon is moving on a road, and this road intersects a river, we allow the trans-shipment to the river paying a fee.

Figure 3. Multi-modal model framework: roads, waterways, coastal routes, towns, ports and their interpolated interconnections.



Sources: Authors' own work from sources in text.

Explain!

We use Dijkstra's algorithm for finding the least cost route. It is worth giving some details as we use multiple networks and have trans-shipment costs. The algorithm minimizes a cost accessibility function composed of several factors. Cost accessibility between points i and j, C_{ij}, is shown in equation (1) as the sum of costs from the origin of the journey to the network (c_i^o), the cost in the n transport modes between p and q (c_{pq}^n), the cost of each trans-shipment between modes r (c_r^t), and the cost to reach the final destination (c_j^t).

$$C_{ij} = c_i^o + \sum c_{pq}^n + \sum c_r^t + c_j^d \qquad (1)$$

Each transport mode has been assigned a unique ton per mile cost for each time-slice, or what we call the parameter value. The parameter values are shown in table 2. Dijkstra's algorithm uses the parameter values to estimate the least-cost-route between the origins and destinations over all pairs in equation (1) and gives the transport cost for the least cost route.

Table 2 parameter values for multi modal model in 1680 and 1830.

Year	1680		1830	
	parameter	source basis	parameter	source basis
coastal, pence per ton mile	0.211	Nef (1979), p. 412	0.168	Bentley in BPP
Sea port fee in pence per ton	27.1	Nef (1979), p. 404	22.9	Bentley in BPP
Trans-shipment fee, road to water in pence per ton	17.14	Nef (1979), p. 404	13.9	Bentley in BPP
inland waterways in pence per ton mile	1	Willan (1936)	2.25	Allnut (1810), p. 20
lock fee in pence per ton	n.a.		1	Priestly (1831)
Low quality road, pence per ton mile (function of height/length)	11.2+(h/l)*(298.67)	Gerhold (2005), MacNeil in BPP	9.87+(h/l)*(238.93)	Gerhold (1996), MacNeil in BPP
High quality road pence per ton mile as a function of height/length	9.97+(h/l)*(298.67)	Gerhold (2005), MacNeil in BPP	7.5+(h/l)*(238.93)	Gerhold (1996), MacNeil in BPP
ferry pence pence per ton	1	Willan (1936)	2.25	Allnut (1810), p. 20

Sources: see text.

Our model is novel in that road freight rates are based on infrastructure quality and slopes, specifically the height change divided by length of road segments (see table 2). Incorporation of quality and slope yield reasonable variation in road freight rates based on other sources. At zero slope, the differences in quality can change road transport costs by approximately 30% in 1830. Estimates for getting a turnpike road reduced road freight rates by approximately 30% and therefore our 1830 quality range is reasonable (Bogart 2005). Our formula also implies that slopes of 2% can raise road freight rates by 40 to 60%. While slope makes a large difference, contemporaries, like McNeil, often stressed the importance of avoiding hills when designing roads.

In bringing the network and cost parameters together, we estimate transport costs between 458 towns in England and Wales in 1680 and 1830. As a reminder we incorporate technology differences across networks, infrastructure quality differences within networks, differential transshipment at ports and inland, and the effects of geography through slopes. Even with these details, there are limitations. Our parameters for freight costs are general and could vary locally for reasons we do not capture. The quality of the infrastructures embedded in the networks might be greater than we allow for in our classifications. Geography could have further effects than just slope. Nevertheless, our estimates of transport costs capture several key features, including infrastructure quality and slope.

B. Measurement of market access

Our analysis uses several formulations of market access. As a baseline we focus on inverse trade cost weighted access to 458 English and Welsh towns with weights based on their 1680 and 1841 populations. The baseline market access formula in a single year (say 1680) is

$$MA_i = \sum_j^J \frac{pop_j}{{\tau_{ij}}^{\theta}} \qquad (2)$$

where MA_i is the market access of town i, pop_j is the town population of town j, indexed from $j = 1, .. J, i \neq j$, τ_{ij} are trade costs, and θ is parameter greater than 1. Trade costs are defined

Why coal price to benchmark trade costs?

using the formula $\tau_{ij} = \frac{tc_{ij}}{CoalPrice} + 1$ where tc_{ij} is the transport cost from town i to town j derived from our multi-modal model and $CoalPrice$ is the pit head price of coal. Notice that trade costs are bounded below by 1 which reflects the icberg cost assumption. Also notice that higher transport costs relative to coal prices will increase trade costs. The parameter θ takes several values in the literature. Some studies set θ equal to 1 as the baseline and then use others to test for robustness. In studies building on trade models, θ is chosen to capture variation in productivity across locations.[31] In our baseline we follow the literature and assume $\theta = 8$, but we also calculate market access for different values.[32]

[31] According explained by Donaldson and Hornbeck (2016), the parameter θ captures, inversely, the (log) standard deviation of productivity, which corresponds to the scope for comparative advantage. A low θ means town productivity draws are dispersed, creating large incentives to trade on the basis of productivity differences.

[32] Donaldson and Hornbeck (2016) and Kitchens and Jawarski (2019) use theta equal to 8.22 and 8 respectively.

We use several alternative measures of market access. The first fixes populations at 1680 levels and calculates MA using 1680 trade costs and again using 1830 trade costs. The second restricts the accessed populations (i.e. towns $j = 1, .. J, i \neq j$) to be more than 50 km from town i. The 50-km buffer around i removes changes in MA driven by nearby towns. Third, we use a market access formula taken from the trade model proposed by Donaldson and Hornbeck (2016). Their formula is

$$MA_i = \sum_j^J \frac{pop_j}{\tau_{ij}{}^{\theta}} MA_j^{\frac{-(1+\theta)}{\theta}} \qquad (3)$$

Where the first term is the same as before but now it is multiplied by market access of each town j taken to the exponent $\frac{-(1+\theta)}{\theta}$ which is less than 0. Notice that non-linear MA terms appear on both sides of equation (3) and thus there is no analytical solution. We use a computer to approximate (3).

Finally, we create a variable that measures access to centers of foreign trade. Specifically, we replace town populations with registered tonnage of ships involved in foreign trade in 1791 at ports and uses trade costs between town i and each port. The so-called 'foreign-trade weighted MA' for each year is

$$MA_i = \sum_p^P \frac{tonnage_p}{\tau_{ip}{}^{\theta}} \qquad (4)$$

where $tonnage_p$ is the tonnage of registered ships at ports $p = 1, .. P$ and τ_{ip} is the trade cost between town i and port p. Note here that some towns are ports and in these cases, $tonnage_p$, is omitted from the numerator.

Our empirical specifications, explained in the next section, will use the log difference in 1830 and 1680 market access (MA hereafter). Summary statistics for different MA variables are shown in table 3. Comparing [1] and [2] notice that fixing the 1680 population implies that market access changes by 4.25 instead of 6.2 in the baseline. That means that much of the increase in market access is driven by lower trade costs. In fact, the average trade cost between towns declines from 15.1 in 1680 to 7.0 in 1830. The largest change in market access is found in [3] which has 50 km buffers. That implies that on average trade costs fell more to towns beyond

50 km. The smallest difference is shown by the trade model derived MA variable in [4]. The reason is that this variable takes into account that a decrease in trade costs between i and j lowers access for some other town k all else equal.

In panel B the correlations are reported between the difference in log MA variables. They are generally highly correlated. The least correlated is based on the trade model. For the reasons just explained it offers a different quantitative perspective.

Table 2: Summary Statistics

	(1)	(2)	(3)	(4)	(5)
Panel A: Diff. in log Market access variables	N	mean	sd	min	Max
[1] ΔLn MA 1830-1680, ($\theta = 8$)	444	6.202	3.867	0.034	16.542
[2] ΔLn MA 1830-1680, ($\theta = 8$) fixed 1680 pop.	444	4.251	3.615	-2.12	13.683
[3] ΔLn MA 1830-1680, ($\theta = 8$) 50 km buffer	444	6.621	3.884	0.224	15.458
[4] ΔLn MA 1830-1680, ($\theta = 8$) trade model derived	425	2.86	2.139	-4.493	8.622
[5] ΔLn MA 1830-1680, ($\theta = 8$) ports foreign trade	444	4.651	4.12	-2.763	15.033
Panel B: Correlation between MA diff. variables	[1]	[2]	[3]	[4]	[5]
[1]	1				
[2]	0.9871	1			
[3]	0.9012	0.8957	1		
[4]	0.7539	0.7347	0.64	1	
[5]	0.9046	0.9103	0.9675	0.6518	1

Sources: see text.

IV. Empirical Specification

There are two common econometric models for estimating the effects of infrastructure on population. The first model analyzes the effect of changes in infrastructure on simultaneous changes in population, hereafter changes-on-changes. As explained by Duranton and Puga (2014), the changes-on-changes model is akin to assuming that populations are in equilibrium. It estimates the change in equilibrium population implied by the change in infrastructure. The second model analyzes infrastructure levels and their effects on changes in population going forward, hereafter changes-on-levels. It is akin to assuming an adjustment process where every year the population comes closer to the equilibrium. It estimates population change over a specific time period implied by the base infrastructure level.

As our main goal is to analyze changes between 1680 and 1841, the changes-on-changes specification makes most sense. The baseline specification is

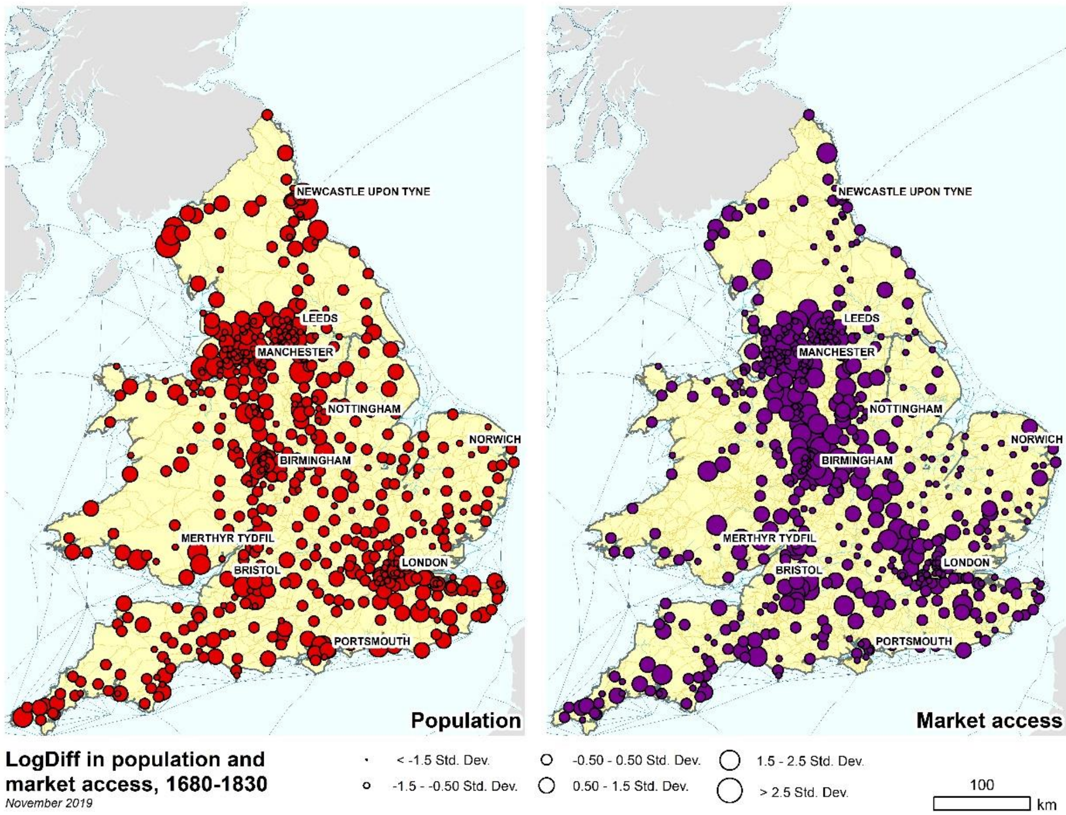
$$\Delta 1841{,}1801 \ln\left(pop_{it}\right) = \Delta 1830{,}1680 \ln\left(MA_{it}\right)\beta + \delta_r + \gamma x_i + \omega_i \qquad (5)$$

where $\Delta 1841{,}1801 \ln\left(pop_{it}\right)$ is the log difference in town i's population from 1841 and 1680, $\Delta 1830{,}1680 \ln\left(MA_{it}\right)$ is the log difference of market access from 1830 to 1680, and δ_r includes the constant and indicators for regions and the vector x_i includes time invariant geographic controls. This specification is common in the literature. For example, Donaldson and Hornbeck (2016) use a similar specification to analyze change in the US from 1870 to 1890.

Reverse causation is one of the main endogoneity concerns in equation (5). Specifically, the growth in a town's population could itself influence the change in market access either through the feedback of effect of neighboring population growth or by creating more local users to pay for infrastructure improvements. One solution is to use our MA variable which fixes population in 1680. This will eliminate the potential endogenous feedback from town i's population growth to its neighbors j which would enter through our baseline formula, $MA_{i1830} = \sum_j^J pop_{j1841} \tau_{ij1830}{}^{-\theta}$. A second approach to address endogeneity uses the MA variable which eliminates access from towns within the 50 km buffer. The application of MA foreign trade variable services a similar role as most towns are not ports and did not affect their development.

Figure 4 provides a preview of our results by illustrating the spatial relationship between the difference in log 1841 and 1680 town population and the difference in log 1830 and 1680 market access. Population change was largest in the northwest, west midlands, and the southeast. MA change was largest in the corridor from Manchester to London. There is a close overlap between the two variables.

Figure 5. Log difference in market access and town population between 1680 and 1830.



Source: authors calculations, see text.

Notes: population data is from Langton and georeferenced by authors. For market access see figure 5.

V. Regression Results

Table 4 reports our coefficient estimates from various versions of equation (5). All specifications include 9 regional fixed effects and cubic polynomials in latitude and longitude as controls. The first three columns use the baseline MA formula: $MA_i = \sum_{j=1, j\neq i}^{J} pop_j \tau_{ij}^{-8}$. Robust standard errors are reported in columns (1) and (2). Conley standard errors are reported in column (3) with a distance cutoff of 50 km. In column (1) which is the most parsimonious, the difference in MA coefficient is positive and implies that a 100% increase in market access increased town population by 1.9%. The beta coefficient in brackets is 0.089, meaning a one standard deviation increase in market access was associated an 0.089 standard deviation increase in town population. Column 2 adds the first nature controls like coal. The coefficient on market access is larger at 0.027 and the beta coefficient is 0.126. In column 3 we see that using Conley standard errors with a distance cutoff of 50 km does not change the precision of the estimates. A similar conclusion is found for other distance ranges.

Table 4: Market access and town population growth, 1680 to 1841

	Baseline MA variable			Alternative MA variables			
	1	2	3	4	5	6	7
				Trade Model derived MA	Fix at 1680 pop. MA	50 km town buffer MA	1791 Port Foreign trade MA
	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)
Diff. Log market access	0.019	0.027	0.027	0.052	0.029	0.033	0.029
	[0.089]	[0.126]	[0.126]	[0.134]	[0.130]	[0.159]	[0.148]
	(0.001)*	(0.011)**	(0.010)**	(0.017)***	(0.011)***	(0.011)***	(0.010)***
N	447	444	444	429	444	448	448
First nature controls	N	Y	Y	Y	Y	Y	Y
Conley SEs, cutoff 50 km	N	N	Y	N	N	N	N
R-squared	0.237	0.345	0.345	0.342	0.345	0.349	0.345

Notes: The dependent var is difference log 1841 and 1680 town population. All specifications included 9 region fixed effects and cubic polynomials in latitude and longitude. For first nature controls see summary statistics in table 2. Robust Standard errors are reported except in column 3. *, **, and *** represents statistical significance at the 10, 5, and 1% levels.

Columns 4 to 7 in table 4 use alternative MA variables. Column 4 uses the MA variable derived from the trade model. The coefficient estimate is larger and more precise. Column 5 uses the MA variable holding 1680 population fixed. The estimate is remarkably like column 2 reducing concerns about feedback processes. Column 6 uses the MA variable with the 50 km buffer. The coefficient is larger than the baseline and remains statistically significant. Column 6 uses the port foreign trade MA variable. The estimate is like the baseline.

The alternative MA variables generally imply a larger effect on population change. In column 6 the beta coefficient is 0.159. How does this compare to other variables? The regression coefficients for other variables are not reported to save space, but the summary is that having coal and being coastal were two of the most significant observable factors causing the difference in log 1841 and 1680 population. Their beta coefficients were 0.236 and 0.188 respectively. This suggests that first-nature factors were highly important in this period and changes in market access come close to matching their significance.

We now turn to other specifications to check robustness. Table 5 reports specifications using different market access parameters for theta in the formula is $MA_i = \sum_{j=1,j\neq i}^{458} pop_j \tau_{ij}^{-\theta}$. All specifications in columns 1 to 5 include first nature control variables, regional fixed effects, and cubic polynomials in latitude and longitude. One can see the coefficients on market access change substantially with the different theta parameters. However, the standardized coefficients are not that different. Generally, the estimate of market access gets more precise with lower values of theta and the beta coefficients get larger. Thus, our use of theta = 8 in the baseline, yields a lower bound effect.

Table 5: Robustness to different values of theta

	1	2	3	4	5
Market access parameter	$\theta = 1$	$\theta = 2$	$\theta = 4$	$\theta = 8$	$\theta = 12$
	Coeff. [beta coeff.] (Stan. err.)	Coeff. [beta coeff.] (Stan. err.)	Coeff. [beta coeff.] (Stan. err.)	Coeff. [beta coeff.] (Stan. err.)	Coeff. [beta coeff.] (Stan. err.)
Log diff. market access	0.345***	0.163***	0.0680***	0.0268**	0.0118*
	[0.170]	[0.177]	[0.163]	[0.126]	[0.085]
	(0.118)	(0.0530)	(0.0229)	(0.0109)	(0.00691)
n	448	448	448	444	446
First nature controls	Y	Y	Y	Y	Y
R-squared	0.349	0.350	0.349	0.345	0.341

Notes: The dependent var is difference log 1841 and 1680 town population. All specifications included 9 region fixed effects and cubic polynomials in latitude and longitude. For first nature controls see summary statistics in table 2. Robust standard errors are reported. *, **, and *** represents statistical significance at the 10, 5, and 1% levels.

In table 6 we report estimates using the difference in log 1841 and 1801 population. The replacement of 1680 population with 1801 population reduces some concerns about measurement error from Langton's 17th century population estimates. However, it should also yield a smaller coefficient estimate since some of the change in market access led to population growth between 1680 and 1801, which is not captured. Indeed, we find the coefficient estimates for the difference in log MA to be smaller. In the baseline reported in column 2, the difference in Log MA remains significant, but only at the 10% level. The largest effect is associated with the trade derived MA variable (see column 4). Its beta coefficient is 0.097. For comparison the beta coefficient for exposed coal variable is 0.089 which is similar. It turns out that in this period, average rainfall is the variable with the largest beta coefficient, 0.639. We think this makes sense because rainfall is related to humidity which has been shown to be important in the growth of the cotton textile industry (Crafts and Wolf 2014). Much of the population growth from 1801 to 1841 was in the cotton producing region.

Table 6: Market access and town population growth, 1801 to 1841

	Baseline MA variable			Alternative MA variables			
	1	2	3	4	5	6	7
				Trade Model derived MA	Fix at 1680 pop. MA	50 km town buffer MA	1791 Port Foreign trade MA
	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)
Diff. Log market access	0.006	0.008	0.008	0.016	0.008	0.007	0.006
	[0.062]	[0.084]	[0.084]	[0.097]	[0.084]	[0.086]	[0.071]
	(0.004)	(0.004)*	(0.004)*	(0.007)**	(0.004)*	(0.005)	(0.004)
N	447	444	444	429	444	448	448
First nature controls	N	Y	Y	Y	Y	Y	Y
Conley SEs, cutoff 50 km	N	N	Y	N	N	N	N
R-squared	0.116	0.273	0.273	0.342	0.273	0.269	0.268

Notes: The dependent var is difference log 1841 and 1801 town population. All specifications included 9 region fixed effects and cubic polynomials in latitude and longitude. For first nature controls see summary statistics in table 2. Robust Standard errors are reported except in column 3. *, **, and *** represents statistical significance at the 10, 5, and 1% levels.

Table 7 reports specifications adding a single infrastructural control variable, the difference in the log 1830 and 1680 distance to an inland waterway. The latter variable is generally imprecisely estimated, but its inclusion reduces the coefficient for the baseline MA variable and also renders it insignificant. This shows that changes in the baseline market access are conflated with changes in proximity to inland waterways. However, in the specifications with alternative MA variables, the conflation is far less. For example, using the trade-model derived MA variable the beta coefficient is 0.123, which is only slightly lower than if the difference in log distance to inland waterways. If one favors specifications building on the trade model, market access is capturing some different than changes in proximity to infrastructure.

Table 7: Market access and town population growth, 1680 to 1841 controlling for change in distance to inland waterway

	Baseline MA variable			Alternative MA variables			
	1	2	3	4	5	6	7
				Trade Model derived MA	Fix at 1680 pop. MA	50 km town buffer MA	1791 Port Foreign trade MA
	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)	Coeff. [beta coeff.] (St. err.)
Diff. Log market access	0.004	0.022	0.022	0.048	0.026	0.031	0.027
	[0.019]	[0.102]	[0.102]	[0.123]	[0.114]	[0.151]	[0.139]
	(0.014)	(0.015)	(0.014)	(0.021)**	(0.015)*	(0.015)**	(0.013)**
Diff. 1830, 1680 Log dist. to Inland waterway	-0.051	-0.016	-0.016	-0.011	-0.012	-0.006	-0.007
	[-0.108]	[-0.034]	[-0.034]	[-0.025]	[-0.024]	[-0.012]	[-0.014]
	(0.084)*	(0.027)	(0.027)	(0.027)	(0.027)	(0.026)	(0.027)
N	447	444	444	429	444	448	448
First nature controls	N	Y	Y	Y	Y	Y	Y
Conley SEs, cutoff 50 km	N	N	Y	N	N	N	N

R-squared	0.239	0.345	0.345	0.342	0.346	0.349	0.349

Notes: The dependent var is difference log 1841 and 1680 town population. All specifications included 9 region fixed effects and cubic polynomials in latitude and longitude. For first nature controls see summary statistics in table 2. Robust Standard errors are reported except in column 3. *, **, and *** represents statistical significance at the 10, 5, and 1% levels.

VI. Counter-factual

In this section, we estimate how urban population would have evolved in England and Wales if trade costs did not change between 1680 and 1841. Counterfactuals have been long studied in economic history, mainly starting with Fogel (1964). But there has not been a counterfactual with the pre-railway data we have developed. We will consider several counterfactual scenarios for different trade costs in 1830 labelled as τ_{ij}^{c}. In each case, this implies a counterfactual market access for every town i in 1830 through the formula $MA_{i1830}^{c} = \sum_{j\neq i}^{n} pop_{j1830}(\tau_{ij}^{c})^{-\theta}$. Notice that other town populations pop_{j1830} enter the market access term for town i. Therefore, if we want to estimate how all town populations changed with new trade costs τ_{ij}^{c}, we need to use the functional form of our model. Our regression model implies the following cross-sectional relationship between town population, market access, and series of town specific factors and common time shocks interacted with those specific factors.

$$\ln(pop_{it}) = \beta \ln(MA_{it}) + \alpha_i + \delta_t + \delta_{rt} + \delta_t x_i + \varepsilon_{it} \qquad (6)$$

Define the variable $fundamentals_{it} = \alpha_i + \delta_t + \delta_{rt} + \delta_t x_i + \varepsilon_{it}$ which is the sum of the last five variables in equation 6 (including the error term). If we use our observed market access in 1830, $MA_{i1830} = \sum_{j\neq i}^{n} pop_{j1830}\tau_{ij}^{-\theta}$, our estimate for beta $\hat{\beta}$, and our observed town population in 1830, then we can solve for the each town population fundamental in 1830.

$$\widehat{fundamentals}_{i1830} = \ln(pop_{i1830}) - \hat{\beta}\ln(MA_{i1830}) \qquad (7)$$

Now we use this town fundamental and a counterfactual market access $MA_{i1830}^{c} = \sum_{j\neq i}^{n} pop_{j1830}(\tau_{ij}^{c})^{-\theta}$ to solve for counterfactual 1830 populations pop_{i1830}^{c} using the following $i = 1, .., n$ equations:

$$\ln(pop_{i1830}) = \hat{\beta}\ln\left[\sum_{j\neq i}^{n} pop_{j1830}(\tau_{ij}^{c})^{-\theta}\right] + \widehat{fundamentals}_{i1830} \qquad (8)$$

The main counterfactual considers a case where trade costs did not change between 1680 and 1830, but towns retained the same fundamentals in 1830. One approximation of this scenario is to use 1680 trade costs rather than 1830 trade costs in equation (8). With this assumption, our model estimates imply that the total urban population would be 6.24 million in 1841 instead of 7.02 million, or a 11% decline. Interestingly the correlation between counterfactual town population and observed population remains quite high (rho=0.99). The reason is that London and the largest towns are still much larger than other towns even with low transport costs. London for example, loses only 9.24% of its 1841 population under the counterfactual and it is more than 5 times as large as Manchester the second largest town. To get a more detailed picture of changes in the top 20 cities see table 8. The major coastal towns like Liverpool and Newcastle lose only 4.4 or 0.1% of their 1841 population levels in the counterfactual. However, the largest inland towns are much smaller in the counterfactual. The population of Manchester, Birmingham, Leeds, and Sheffield are 20.6%, 22.9%, 25%, and 21% of their factual 1841 levels. In other words, the largest towns of inland Britain would have been much smaller in size.

Table 8: Factual and Counter factual 1841 population for top 20 cities if trade costs did not change from 1680 to 1830

City/town	Factual 1841 pop	counterfactual 1841 pop	Percentage population loss
LONDON	1948417	1768391	-9.24
MANCHESTER	311269	247037.5	-20.635
LIVERPOOL	286487	273972.3	-4.368
BIRMINGHAM	182922	141730.5	-22.519
LEEDS	152074	114037.8	-25.012
BRISTOL	125146	114973.3	-8.129
SHEFFIELD	111091	87317.99	-21.4
WOLVERHAMPTON	93245	76636.36	-17.812
NEWCASTLE UPON TYNE.	70337	70247.29	-0.128
HULL.	67308	67368.96	0.091
BRADFORD	66715	48772.22	-26.895
NORWICH	61846	62528.26	1.103
NEWINGTON	54606	52305.36	-4.213
SUNDERLAND	53335	50822.09	-4.712

BATH	53196	38141.79	-28.3
PORTSMOUTH	53032	52802.27	-0.433
NOTTINGHAM	52360	48521.41	-7.331
BOLTON	51029	40092.87	-21.431
PRESTON	50887	48163.12	-5.353
LEICESTER	50806	38715.74	-23.797

VII. Conclusion

This paper studies the role of transport improvements in determining urban population change in England and Wales between 1680 and 1830. It presents new estimates of market access in 1680 and 1830 for 458 towns. Market access is calculated using measures of trade costs derived from a new multi-modal transport model. The changes in log market access between 1680 and 1830 are then related to changes in log urban population between 1680 and 1830 using a regression framework. The results show that market access robustly affected town population. In the baseline model, a one standard deviation increase in market access was associated an 0.126 standard deviation increase in town population.

Counter-factual calculations further illustrates the effects of market access. Our estimates suggest the urban population would have been 11% lower if transport costs remain unchanged between 1680 and 1830. We take this as strong evidence that pre-steam transport improvements were a major engine of economic growth during the Industrial Revolution.

Our paper is related to the emerging literature which uses GIS tools to study transport and economic development. Our study is unique in that we analyze the period before 1830. However, our estimated effects are like other studies despite very different contexts, and they suggest the relationship between market access and growth is quite robust and consistent.

Finally, our paper contributes to the literature on the drivers of growth during the industrial revolution. Transport improvements are thought to be a key engine of economic growth in the English economy. The economic gains from steamships and railways are often discussed but far less is known about the extent of change in the pre-steam era and its effects. In this paper, we show that pre-steam transport innovations were a significant driver of economic growth.

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Appendix 1: Urban population data

Appendix table 1 shows the population of the largest 20 towns in 1680 along with their population estimates at two dates. London is at the top of the list, naturally. London grows from 1680 to 1841, but many others do not. Salisbury and Deptford are two towns that fall out of the top 100 in 1841. Several other large towns in 1680 are not as exceptional in population by 1841. York, Oxford, and Cambridge are three examples.

Appendix Table 1: Population of the largest 20 towns 1680 in comparison with situation in 1841

Town Name.County	Pop 1680	Pop 1841	Rank 1841
LONDON.MIDDLESEX	500000	2051380	1
NORWICH.NORFOLK	14216	62116	14
YORK.YORKSHIRE NORTH RIDING	14201	28842	38
BRISTOL.GLOUCESTERSHIRE	13482	136276	6
NEWCASTLE UPON TYNE.NORTHUMBERLAND	11617	99870	8
OXFORD.OXFORDSHIRE	11065	23834	48
CAMBRIDGE.CAMBRIDGESHIRE	10574	24453	46
EXETER.DEVONSHIRE	10307	38425	28
IPSWICH.SUFFOLK	9774	25264	45
GREAT YARMOUTH.NORFOLK	9248	27863	40
CANTERBURY.KENT	7671	15435	70
WORCESTER.WORCESTERSHIRE	7046	25401	43
DEPTFORD.KENT	6919	27676	101
SHREWSBURY.SHROPSHIRE	6867	18285	63
SALISBURY.WILTSHIRE	6811	10086	102
COLCHESTER.ESSEX	6647	17790	65
HULL.YORKSHIRE EAST RIDING	6600	67606	12
COVENTRY.WARWICKSHIRE	6427	37806	29
CHESTER.CHESHIRE	5849	23112	49
KENDAL.WESTMORELAND	5730	11770	91

Source: Langton (2000).

Appendix table 2 shows the population of the largest 20 towns in 1841 and their population estimates at the two dates. London is again at the top. But interestingly the next two, Manchester and Liverpool, are not large towns in 1680. Liverpool is not even in the top 100. Bradford is another example of a town that grows significantly by 1841.

Appendix table 2: Population of the largest 20 towns in 1841 in comparison with situation in 1680

Town Name.County	Pop 1680	Pop 1841	Rank C17th
LONDON.MIDDLESEX	500000	2051380	1
MANCHESTER.LANCASHIRE	2356	340708	64
LIVERPOOL.LANCASHIRE	1210	318852	123
BIRMINGHAM.WARWICKSHIRE	2745	197680	49
LEEDS.YORKSHIRE WEST RIDING	3501	146523	37
BRISTOL.GLOUCESTERSHIRE	13482	136276	4
SHEFFIELD.YORKSHIRE WEST RIDING	2050	109690	87
NEWCASTLE UPON TYNE.NORTHUMBERLAND	11617	99870	5
NOTTINGHAM.NOTTINGHAMSHIRE	4264	83102	28
PLYMOUTH.DEVONSHIRE	4000	82946	32
BRADFORD.YORKSHIRE WEST RIDING	940	82732	128
HULL.YORKSHIRE EAST RIDING	6600	67606	17
PORTSMOUTH.HAMPSHIRE	5007	66542	22
NORWICH.NORFOLK	14216	62116	2
BATH.SOMERSETSHIRE	2652	59497	56
BOLTON.LANCASHIRE	1830	58856	106
SUNDERLAND.DURHAM	1147	54740	125
HUDDERSFIELD.YORKSHIRE WEST RIDING	610	53504	138
STOCKPORT.CHESHIRE	1303	52831	121
PRESTON.LANCASHIRE	1700	50887	110

Source: Langton (2000).

Appendix 2 transport networks

Ports and coastal network

In this section, we describe the database of historical ports and the database of historical coastal routes. For more details see the following two papers:

Alvarez-Palau, E. J., O. Dunn, D. Bogart, M. Satchell, L. Shaw-Taylor, 'Historical ports and coastal sailing routes in England and Wales 1540-1914', UK Data Service – Reshare, 2019, https://doi.org/10.5255/UKDA-SN-853711

Alvarez-Palau, E. J., and Dunn, O., 'Database of historic ports and coastal sailing routes in England and Wales', Data in brief, 25 (2019), 104188.

1.1 Ports

Eleven different sources were used to create a list of ports and other smaller places where coasting vessels regularly landed to load and discharge goods. The existing literature provides convenient lists of the most important ports. However, coasting vessels called at a much larger range of landing locations than these suggest –including beaches, natural bays, piers, etc. To locate and record more places we drew on new sources that provided us with an array of landing locations at different benchmark dates[33].

Digitizing port information from secondary sources was relatively easy. What was more difficult was to gather port data from 'port book' and 'crew list' coastal shipping data (see Bogart et. Al. 2020). Both sources give the movements of coasting ships, and as a result, also recorded myriad landing locations and ports that often do not appear in the secondary sources. These were included in the port data presented here.

In the nineteenth century, the number of reported ports of all kinds increased compared with the sixteenth century due to better information about ports in general, but also because of the expansion of the network. According to earlier sources, ports included harbours, piers, small creeks and even beaches.

[33] We understand landing locations, creeks, harbours, ports, etc. are different, for example in terms of their facilities and scale. However, we do not distinguish them within the paper. Our sources do not provide enough information to deal with this categorisation. For simplicity, we call them all ports.

Another ambiguity arises from the term "port" in itself. Some historical sources used the term to refer to customs port, which is the entire stretch of coastline under the jurisdiction of regional customs subsystems. In our case, we linked them to the physical port of the same name.

These were overseen by larger ports with customs houses. Figure A.2.1 shows the geographical distribution of all 479 ports with one or more appearance in our sources[34].

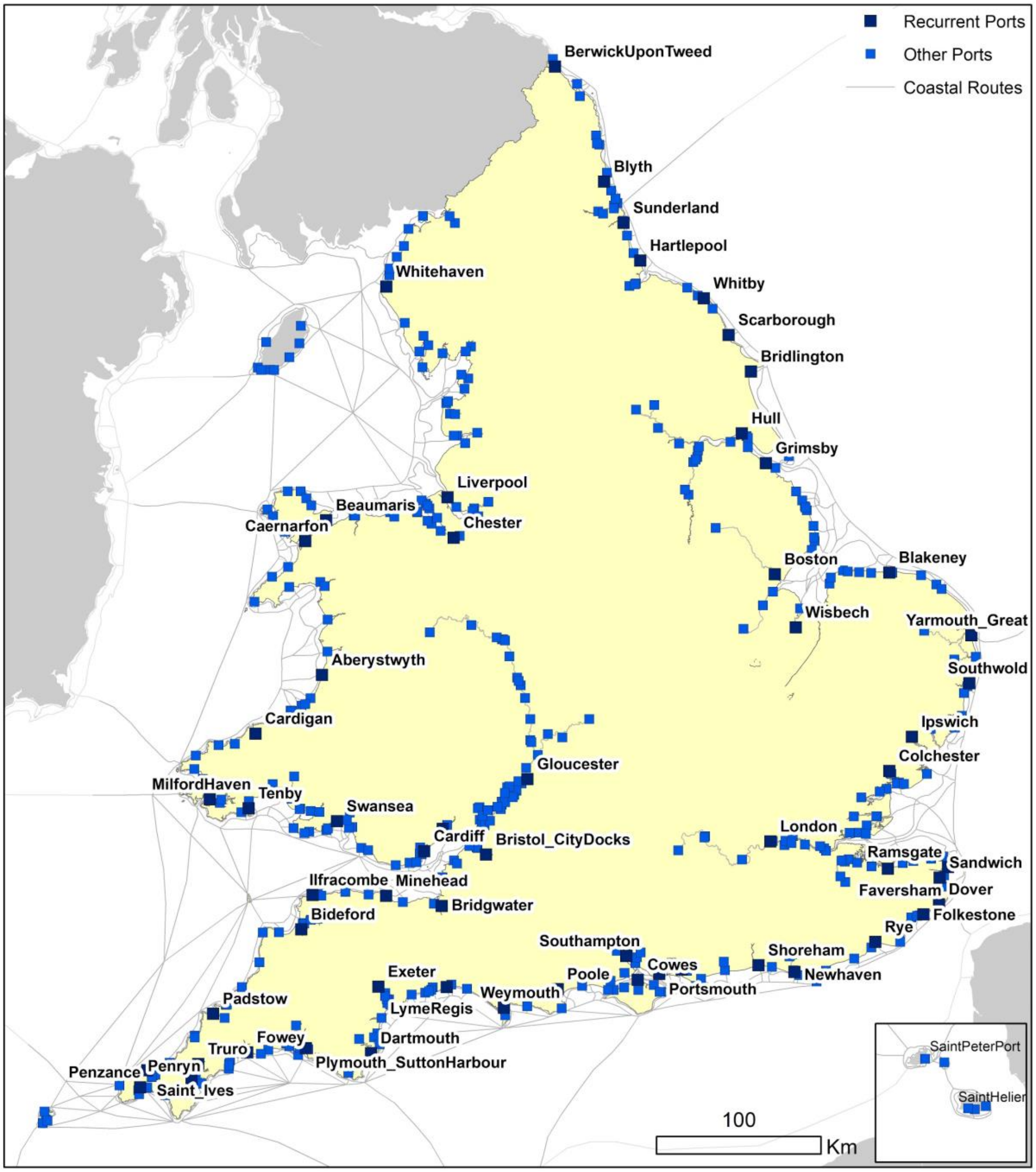


Figure A.2.1: Ports with one or more mentions within the sources used. Those places marked as dark blue (recurrent ports) are mentioned in at least nine out of eleven sources.

[34] Ports were removed from the database if they were located at more than two kilometres from a navigable way.

1.2 Data on coastal routes

In the sailing era, natural conditions constrained operations, especially storms, tides and waves, but also low light, which clearly all had adverse effects. In terms of navigation, instruments used at the time allowed travel only under certain circumstances, and good visibility was necessary for safe passage. Knowledge of bathymetry was key to avoiding damage by grounding on sandbanks or rocks. Navigational charts reported the depth of water at certain locations, but for these to be of any use it was crucial to know the exact position of the ship. Mariners used landmarks to track their position, often using triangulation, and it was thus normal to sail in sight of the coast. During the night or in poor visibility navigation became difficult. Beacons, lighthouses and light-vessels etc. served as an alternative to landmarks where available, but their presence on the coast was very limited at the beginning of our period of study.

We used an amalgamation of different sources to identify coastal routes mariners most likely followed. Specifically, we relied on historical coastal charts, bathymetric depth rasters, topographic elevation rasters, and parliamentary reports to create our database. The main primary sources used to determine coastal routes were navigation charts included in Captain Collin's publication, Great Britain's Coastal Pilot, first published in 1693. For later years, we also looked at coastal charts published by the admiralty in 1830 at the UK Hydrographic Office, Taunton. These documents were digitised and geolocated to gain a workable understanding of the contemporary navigation techniques of each period. Charts always contain landmarks and bathymetry information so mariners could determine their position and avoid danger. Collins also gave specific directions for some routes with their distance in miles given, and this information revealed the routes the author directed ships to take when sailing round the coast.

Bathymetry data was used to distinguish those areas with sand banks and submerged rocks. Although we understand the position of sands changed over time, we assume there was stability in other parts of the coast that were less affected by tides and oceanic currents. We relied on the EMODnet Bathymetry data for the Atlantic Ocean, published by the European Marine Observation and Data Network in 2016. Specifically, we obtained a Digital Terrain Model (DTM) raster with bathymetric depth data with an approximate resolution of 200-metre cell.

Topographical data was gathered from the NASA Shuttle Radar Topography Mission (SRTM). Our raster, though, was a processed version offered by the International Centre for Tropical Agriculture (CIAT); in particular, we worked with its version 4.1. In this case, the different rasters were provided in TIFF format with a resolution of 90-metre cell.

Finally, we also used five sources to obtain the location and visibility range of lighthouses, beacons[35] and light-vessels. Collins' Coastal Pilot Chart was used for the first period because it shows their location and detailed visibility ranges for night-time navigation. It was reviewed and complemented secondary sources. For the second period we used The *Light-Houses of the British Islands* in two editions, one published in 1832 and the other in 1851. Figure A.2.1 shows the coastal routes and ports.

Inland waterway network

In this section, we describe the GIS data on inland waterways. For more details see the following papers:

Satchell, M., Newton, G, and Shaw-Taylor, L., 'Navigable waterways of England and Wales Time Dynamic GIS 1600-1948' (2017).

Satchell M., 'Navigable Waterways of England and Wales 1600-1948 time dynamic GIS shapefile documentation' available at

http://www.campop.geog.cam.ac.uk/research/projects/occupations/datasets/documentation/navigabl e

waterwaysofenglandandwales1600to1948dynamicgisdraftdatasetdocumentation.pdf

Satchell, A.E.M., Navigable waterways and the economy of England and Wales 1600-1835

Previously the extent and expansion of navigable waterways in England and Wales could only be established in a very laborious way. Estimates of national mileage at various dates had to be used, salient information had to be extracted from the regional studies of Hadfield et al and a variety of paper maps of varying accuracy and utility had to be consulted. The creation of the first dynamic Geographical Information System (GIS) model of the English and Welsh waterway network has fundamentally altered our capacity to study this important transportation system. This works was largely carried by Max Satchell with the assistance of Owen Tucker, Zoe Crisp, Ellen Potter, and Gill Newton.

We started by digitising the major navigable rivers of England from geo-rectified scans of the Ordnance Survey 1:10560 first edition. Next we digitized 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,

[35] Beacons were open fires used for navigation and communication.

it was not sufficiently detailed to produce a high standard GIS. As a consequence, the Dean digitisation as 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. For the modest number of waterways which had disappeared before being surveyed by the Ordnance Survey 1:10560 series earlier mapping principally sheets 1-90 of the Ordnance Survey 1:63,360 Old Series (surveyed 1789-c.1840). This work was done using each of Hadfield regional volumes in succession. In every instance emphasis was on establishing as far as possible when each section of the waterway was in commercial use. In addition to the sources already mentioned, usage dates were derived from T.S. Willan, River Navigation in England 1600-1750 (1936), the Royal Commission on Canals and Waterways, BPP, 11 vols, (1906-1911) and H. de Salis, Bradshaw's Canals and Navigable Rivers of England and Wales (1904). Where available secondary studies of particular regions and individual waterways were also consulted. Opening, closing and commercial disuse dates for each section of waterway linked to the GIS polyline were entered in an excel table. We used this to create an Access database which enabled the network of navigable waterways for any given year from 1600 to 1948 to be generated.

The following maps show the (1) coastal network, (2) inland waterway network by river and canal, (3) interpolations that were made to connect the inland waterway and coastal networks, and (4) locks. The distinction between canals and rivers is important. One must recognise that canals are different from rivers because their routes are deliberately chosen. While a canal route does not require the pre-existence of a potentially navigable river, it is constrained by modest changes in elevation. Locks are also a crucial future. In the eighteenth century, one pound lock was considered necessary for every 7ft (2.13 metres) of elevation and locks constitute a major capital expense. For example, in the late seventeenth century, two new pound locks were built on the River Weaver at an approximate cost of £7000 each - or about £800,000 each in today's money. Consequently, canals routes only tackled significant changes in elevation when the economic case was compelling or investors were unwise. In summary, geographical and associated cost factors determined that most canals followed river valleys, only crossed watersheds when necessary and made minimal elevation changes. Indeed, for much of the eighteenth century, canals tried to follow a specific contour to minimize changes in elevation and keep costs down. These constructions are termed 'contour canals' by historians and they are characterised by gentle curves and meandering routes.

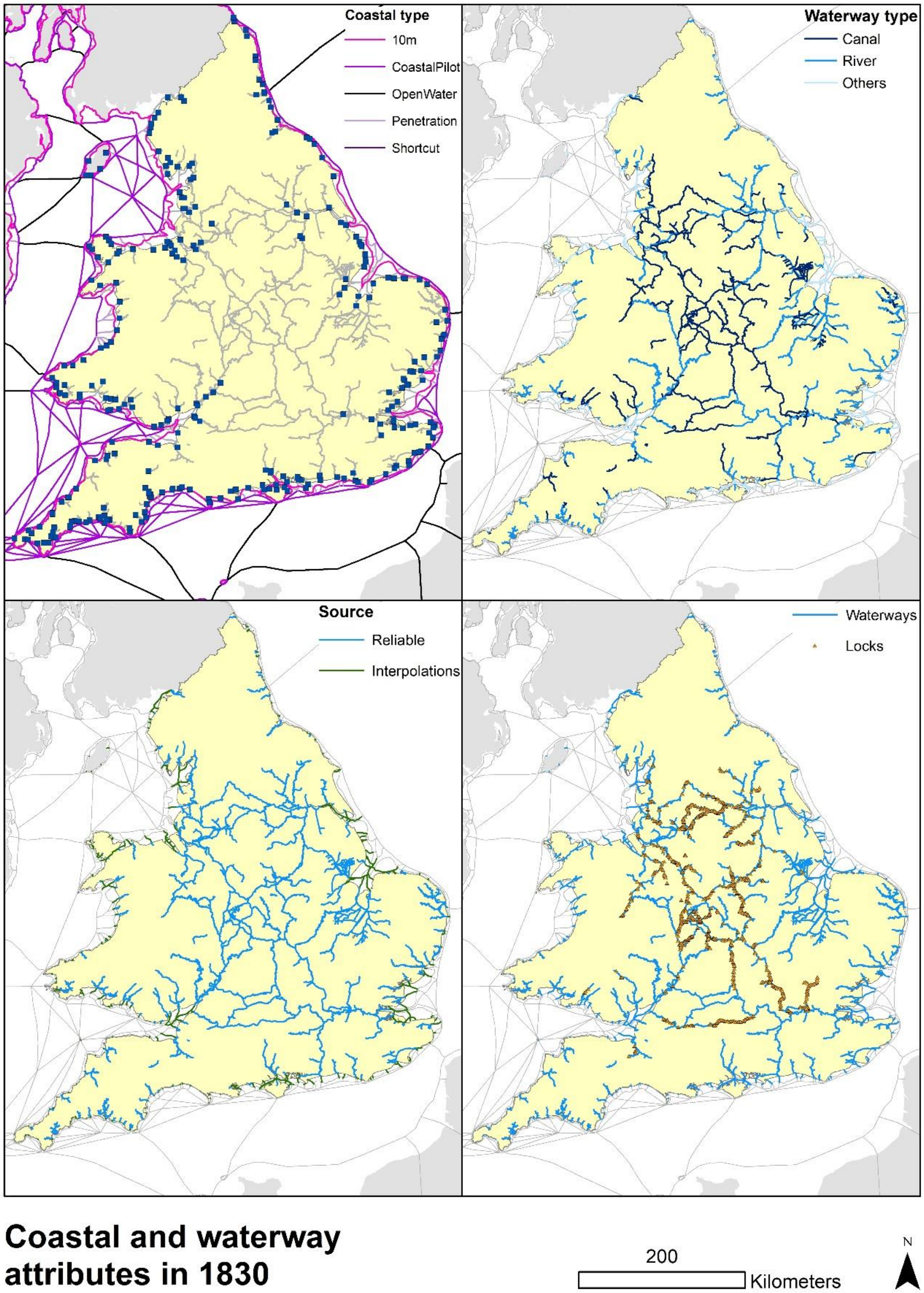


Figure A.2.2: Coastal and waterway attributes in 1830

Road network in 1680

In this section, we describe the GIS data on 1680 roads. This work was largely carried out by Alan Rosevear and Max Satchell with assistance from Spike Gibbs and Jacob Field. A description of the dataset can be found in

Satchell, M., and Rosevear, A., 'Candidate main roads of England and Wales, c. 1680 GIS shapefile documentation' available at:

https://www.campop.geog.cam.ac.uk/research/occupations/datasets/catalogues/documentation/candidatemainroadsofenglandandwalesc_1680.pdf

The 1680 roads data is official cited as

Satchell, M. Rosevear, A., Dickinson, G., Bogart, D., Alvarez, E., Shaw-Taylor, L.,' Candidate main roads of England and Wales, c. 1680' (2017).

The 1680 roads GIS contains two distinct elements: a digitisation of some 7,493 miles of road which derive from the strip maps of Ogilby's atlas and 13439.8 miles of other roads which derive from a variety of other sources. Identifying and mapping the main roads of England and Wales c.1680 is no easy task. In terms of cartographic sources, the national road network is hardly depicted at all, and certainly not with any accuracy, until John Ogilby published Britannia, his atlas of "principal roads" of England and Wales in 1675. Work by Satchell using a wide range of evidence for road transport has shown that most roads Ogilby mapped were important. Ogilby's Atlas consisted of strip maps at 1:63360 scale of 85 routes on 100 copper plates which surveyed and mapped over 7500 miles of road.

The Ogilby digitisation was created as follows. We identified as a digitisation source O.G.S. Crawford's mapping of Ogilby roads in his A Map of XVII Century England. This was then digitised and a handful of omissions added. However, the 1:1,000,000 scale of Crawford's map meant that the polylines digitised might be up to 1km out of alignment. This degree of inaccuracy is too great for some sorts of spatial analysis, so a more accurate version of Ogilby was begun using the Crawford derived GIS as a guide. This was made practicable by access to the unpublished work of others scholars who had invested thousands of hours in working on particular sections of Ogilby. The GIS that resulted would not have been possible without permission to use the unpublished marked up paper maps of the late Gordon Dickinson (4700 miles), and Derek Bissell (331 miles – Wales and the borders). Use was also made of the maps in the doctoral thesis of Andrew Jones (Yorkshire) and data from online resources created by Jean and Martin Norgate (Hampshire). To ensure congruency with other datasets the digitization was done using a pre-existing GIS of turnpike roads - where the Ogilby roads and the turnpikes coincided the turnpike polylines were recycled to form part of the Ogilby GIS. Ferry crossings were also added. Turnpike roads are described in detail in the following section on 1830 roads.

It was clear from the outset that the network of main roads was larger than what was represented by Ogilby's roads alone. A second class of roads were created to fill this gap. They were not added randomly but were used to link settlements with significant evidence of road travel/ connectivity apparent from their provision of spare stabling given in a military survey of 1686. This comprehensive survey gives counts of spare beds and stables for some 11,000 separate locations in England and Wales. A threshold of 15 or more stables was set, and a network constructed programmatically that connected stable points with 15+ stables by polylines to the nearest section of Ogilby road. 15 spare stables was chosen as this number reasonably well represented the number of horses in a single packhorse gang engaged in long-distance travel in this period. This increased the number of places that needed to be connected by the network to c. 1,350. We used actual roads to connect stables to Ogibly.

Alan Rosevear took on the formidable task of systematically integrating these disparate materials to build the rest of the network. To assist in selecting routes and interconnections from the Ogilby Roads, he displayed following additional GIS data was over the 1st edition OS 1:10,560 base map;

1. All sections of turnpike road included in Acts that did not mention “Making new” or “Diversion” in the preamble (referred to as “ancient turnpikes”)

2. Destinations in the De Laune 1681 and Carriers 1637 Directories.

3. The routes and traffic nodes listed in the Itinerary section of the 1727 Directory

4. The ARC GIS layer of Roman Roads and Old Tracks

5. The full turnpike network

6. Carrier routes listed in the 1791 Universal Directory

7. Recorded ferries (estimated to be operating ca 1700)

The additional roads were added in a hierarchy based on relevance to 1680 and an “uncertainty” value given to this road as a 1680 road. Roads were added until a minimum level of inter-connection was achieved with the “15 or more” stabling points. The following criteria were adopted in drawing lines connecting points;

- The road goes through the point, connecting it with two Ogilby roads (i.e. it is on a route not normally a terminus except at coasts, major river crossings or moorland where no obvious trace remains on the OS map)
- Features are relevant if they are within 10 miles of each other in lowland areas and 15 miles in (sparsely populated) upland areas.
- Two stabling points on Ogilby roads may be joined if secondary evidence for a route
- Roads may be added if two secondary features occur (secondary features include smaller stabling (between 12 and 14), a de Laune destination, a 1727 transport node, a 1727 route, a 1791 Traffic route)
- Sections of Roman Roads may be added, even when not turnpiked, when the road has survived in use to be mapped by the OS. Where stabling is listed next to an old ferry it is assumed the route used the ferry
- Since the stabling is a parish based survey, it is sufficient for the road to pass through any part of the parish (including acting as a boundary line).
- Routes were chosen which were consistent with those in the 1727 Directory Itinerary
- If an Ogilby road exists between two points no other parallel route is drawn (i.e. ancient turnpike option not added)
- Where a ferry occurs between two points, this route is favoured.

A map of the main Ogilby roads and non-Ogilby roads is shown in the upper left box of figure A.2.3.

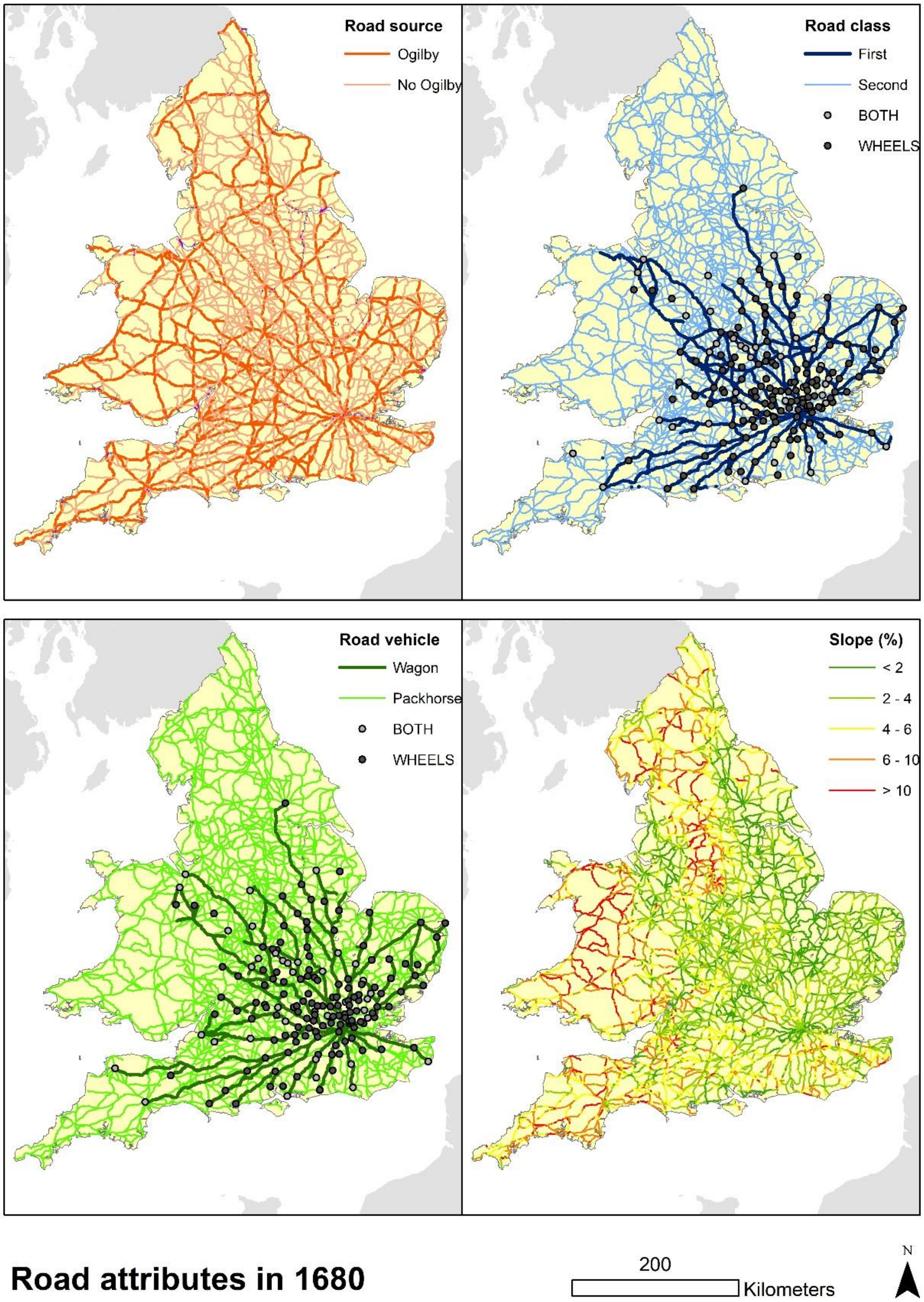


Figure A.2.3: Roads and attributes in 1680

We further enhance the 1680 roads by adding an attribute to determine whether wheeled transport or packhorses were used on the road. Our classification is derived from DeLaune's 1637 publication, The Carriers Cosmographie, which details whether packhorse or wagon/car services were available from London to several towns. We have mapped packhorse versus wagon using Delaune's data. It is shown in figure A.2.4 along with Ogilby's main roads in 1680. It is clear wheeled transport was not available everywhere. We use this information to identify a 'first class' road network where only wheeled transport was used and a second class network where packhorses or both where used. This is shown in the upper right hand box of figure A.2.3. Wheeled transport and packhorse transport were both used in transport to some towns (both) so we assume the 1680 road network where wheeled transport was available was larger than first class roads. The full network available for wheeled transport in 1680 is shown in the lower left hand box of figure A.2.3.

Finally, slope is a crucial factor in road transport. We overlay a raister file of elevation on the map of 1680 roads to calculate segments where the average slope was fit into different categories. These segments are shown in the lower right hand box of figure A.2.3

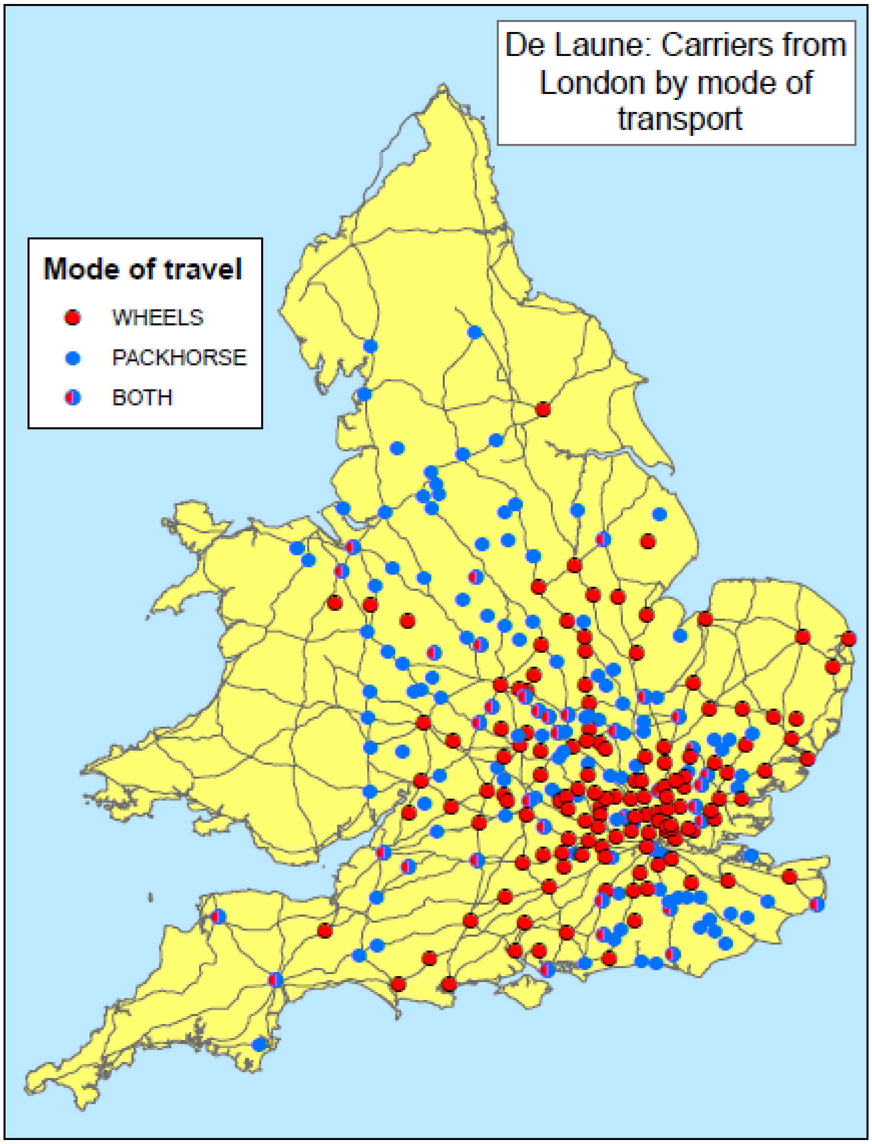


Figure A.2.4: Delaune's map of wheeled and packhorse services from London to various towns in 1637.

Road network in 1830

In this section, we describe the GIS data on 1830 roads. The 1830 roads are derived from a GIS of the turnpike road network as of 1830. The work in creating turnpike roads was largely carried out by Alan Rosevear, Max Satchell, and Dan Bogart with assistance from Rachel Taylor. A description of the dataset can be found in

Bogart, Dan, Rosevear A., and Satchell, A.E.M. 'Turnpike roads of England and Wales 1667-1892 GIS shapefile documentation' available at:

https://www.campop.geog.cam.ac.uk/research/occupations/datasets/catalogues/documentation/turnpikeroads16671892.pdf

The turnpike roads data is official cited as

Rosevear, A., Satchell, M., Bogart, D., Shaw Taylor, L., Aidt, T. and Leon, G., 'Turnpike roads of England and Wales, 1667-1892', 2017.

A turnpike road was a road managed by a turnpike trust. They were organizations authorized by acts of parliament to build, maintain and operate toll roads. Trusts were most prominent in the 18th and early 19th century prior to railways. They maintained individual roads previously maintained by local governments, specifically parishes. The finances of turnpike trusts were distinctive because they levied tolls on road users and issued bonds mortgaged on the tolls. Also, they were locally managed and financed.

Turnpike roads were digitized using the following method. We identified Cary's New Map of England and Wales and part of Scotland as the primary source for an initial digitisation of the network was done by Satchell. Carey's sheets were published between 1820 and 1828. Cary's road line work distinguishes turnpikes and post roads. It also maps "other main roads" but these were not digitised. However, Cary's map does not identify the individual trusts and the road segments they managed. Scans of the Cary mapping were geo-rectified by Ziyue Chen. The turnpike network was then digitised using the scans laid over Ordnance Survey 1:10560 first edition mapping (25 inches to the mile).

For England the next step used two resources that identify the territories of turnpikes trusts from surviving wayside features, parliamentary records, acts of parliament and historic county maps. The first of these was a dataset of known milestones and tollhouses created by the Milestone Society.[36] Alan Rosevear digitised these records and added the turnpike trust authority name. The second was a series of marked up county maps (generally Thomas Moule's County series ca 1830) with the roads under the jurisdiction of each trust and its opening date clearly identified. Satchell took the milestones digital data and used GIS to link these to the turnpike polylines digitised from Cary. From that we acquired the provisional road

[36] The database manager is Alan Rosevear.

segments of each trust. 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 was a provisional dynamic turnpike network for England. In the final step, we checked the trust name and dating was correct and the inter-trust boundaries were clear for each road segment and added the date of closure using parliamentary records and acts of parliament. The acts of parliament are drawn from the Portcullis database of all acts at the Parliamentary Archives in London.[37] The main parliamentary record used in this exercise is the 'Appendix to the report of the commissioners for inquiring into the state of the roads in England and Wales,' British Parliamentary Papers (BPP 1840 XXVII). The appendix records the mileage of individual trusts in each parish in 1838. Tollhouse locations found during mapping were used to confirm the allocation of sections to trusts and better specify trust boundaries. Local history studies of individual trusts were used to date and plot diversions made by the trusts where possible and the recorded trust mileage in 1820, 1838 and 1847 used to interpolate a date for improvements seen on maps where no records found. Unless specified in the Act, it was assumed that the older section of road lapsed at the date the improvement was made.

The acts of parliament also provide an indication of whether the road was old or new. Wording mentioned repairing of roads implied the road was old. Wording mentioning the diversion of the road suggested there was some improvement. Wording mention the making of the road suggested that it was new.

For Wales there was no comprehensive milestone record or marked up county maps with which to work. Rosevear took the raw Cary turnpike data and added the trust name and date of opening and closure using parliamentary records and acts of parliament described above. The network for South Wales was refined using the maps and commentary in The Report of the Parliamentary Commission (1843) made after the Rebecca Riots.

The GIS map of all turnpike trusts was used as the starting point for selection in 1830 roads. Polylines were selected first on the basis of the start date of the Turnpike trust and all those with a date after 1830 excluded. A map of turnpike roads in 1830 is shown in the upper left box of Figure A.2.5. Other main roads were added to link a small number of towns to the turnpike network, ensuring complete connection. The parliamentary report 'Appendix to the report of the commissioners for inquiring into the state of the roads in England and Wales,' British Parliamentary Papers (BPP 1840 XXVII)' includes an assessment of the road

[37] http://www.portcullis.parliament.uk/calmview/

quality. Several classifications are given from poor, average, above average, Good, and excellent were given. We creat a simple quality classification ‘Good’ if the road was described as good, very good, and excellent. Otherwise it is classified as ‘Bad’. The mapping of road quality is shown in the upper right box of figure A.2.5.

There were some 1680 roads that were not included in the 1830 turnpike network. However, we are almost certain those roads were used. Therefore we include 1680 roads to the 1830 turnpike network. 1680 roads added to 1830 turnpike roads are shown in the lower left hand box of Figure A.2.5. Note they are classified as ‘bad’ on the quality metric. This assumption is reasonable as parish roads were generally of lower quality. Finally, as with 1680 roads we add slopes to each road segment. The slopes are shown in the bottom right box of figure A.2.5.

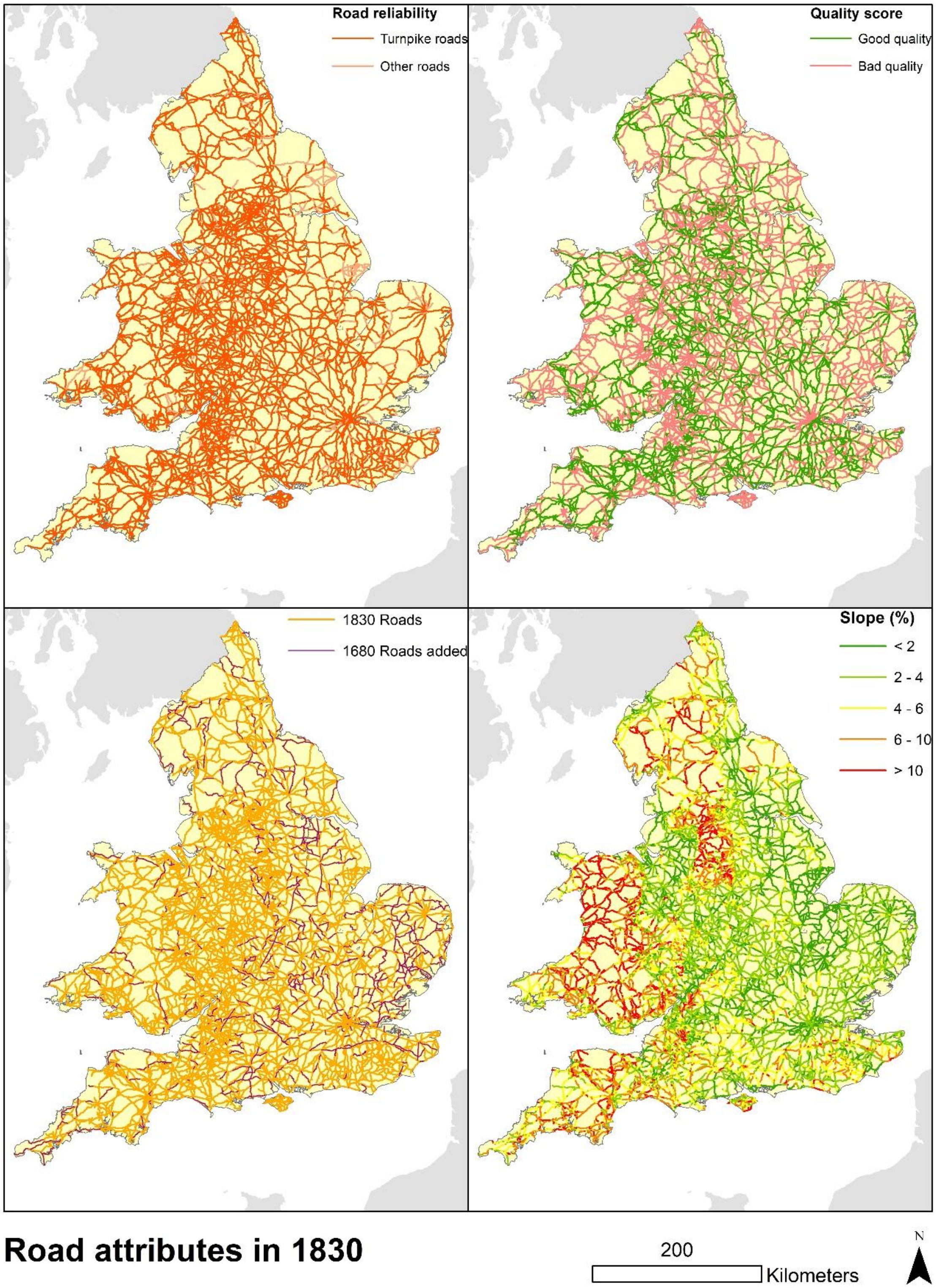


Figure A.2.5: Roads and attribute data in 1830

Bridges and Ferries were also plotted into the 1830 roads GIS files. We now explain the sources and strategy for plotting data on river crossings in the shape files used in the Cambridge Historic roads GIS.

Bridges

Only major river crossings are considered here – loosely defined as a structure requiring large capital cost for construction and likely to have significant maintenance costs. Roads crossed streams and small rivers on structures ranging from simple culverts to small single arched bridges – these are not considered significant in the context of costing travel or determining travel speed on the GIS road network and are not plotted individually.

There are four major categories of bridge to consider in building the roads GIS file.

- Toll Bridges are generally new structures built during the period when roads were being turnpiked. They may have been built by local trusts, Improvement Commissions or by a private company but were for public use. Each required an Act of Parliament to define powers of the Commissioners, Trustees or Proprietors and which limited lending for construction of the bridge and approach roads. Many of these were totally new bridge crossings; a few replaced older bridges, generally a little to the side of the earlier bridge. In many cases the new bridge replaced an ancient ferry and the "rights" of the ferry owner had to be purchased in order to close this down or compensate for the inevitable loss of business. A number of medieval bridges that had been administered by a charitable foundation (Bridgemasters or trustees) had powers to levy tolls for the upkeep of the bridge. Many of these were rebuilt in the 18th and early 19th century and were covered by Acts of Parliament as with new toll bridges. These bridges may abut turnpiked roads but are separately administered; some have approach roads that were not turnpikes. (these toll bridges are designated TB in the database file field "was turnpike" and are given a Trust or Company name)

- County Bridges were old bridges that by 1700, were already the responsibility of the county or counties on the river bank (rivers often form civil administration boundaries). Finance for repairs and any rebuilding fell on the counties, raised through local taxation and administered through the Magistrates. This category included medieval bridges that had originally been the responsibility of Charities or Foundations but had subsequently fallen on the county as well as important crossings that had been built by the civil administration prior to the 18th century. These bridges were toll free, and may be replaced by a new toll bridge during the turnpike period. (these County Bridges are designated CB in the database file field "was turnpike")

• Free Bridges is a category covering bridges which were built by a trust or a Commission that did not levy a toll on users. Some were ancient charities which had been bequeathed property or given the revenues from a source of taxation (e.g. coal) to cover maintenance costs or were under an Improvement Commission for town or river. Later this category included bridges which had been freed from toll when the civil administration took over the bridge or bought out the original proprietors (e.g. all London bridges by the late 19th century) (these Free Bridges are designated B in the database file field "was turnpike").

• Turnpike Road Bridges were new bridges built under the Act authorising a new turnpike trust. In some instances they were fully incorporated into the road administration and there was no specific toll related to the crossing. In others (e.g. Shillingford) the Act included a specific toll for the bridge crossing. The subsequent administration of these bridges generally followed that of the associated turnpike road. (these are designated T in the database file field "was turnpike" and are assigned to the relevant turnpike Trust)

Most new bridges required a new approach road on either bank. Generally these were the responsibility of the bridge administrators; some approach roads could be long, stretching for a mile or more. The bridge toll usually covered travel on the approach road. Where it was clear that the road was administered with the bridge it is given the trust name, otherwise it is designated as an Urban Link Road.

Recording and plotting the bridges

The Chadwick archive of Parliamentary Acts (covers 1799 to ca 1833) was searched through the Welcome Library web site for Acts that concerned the building of bridges. The Acts identified when a bridge would be a toll bridge (coded TB in the "was turnpike" field of the Arc GIS File) or when bridges were toll-free (coded B). Some bridges required several Acts of Parliament to increase the approval limit of building costs, and a number of bridges required new Acts for rebuilding soon after construction of a first bridge, due to collapse of the initial structure. Wikipedia entries were checked to confirm the most likely date of the first successful bridge being built – the default date used was the latest Act for building a first bridge at the site.

A google search was made for bridges on the major rivers and estuaries of England and Wales – all entries that identified a toll bridge built before 1900 were recorded and the date at which tolls were lifted was noted.

Finally a visual inspection was made of all points where a turnpike road crossed a major river and any instances of a toll bridge recorded. Not all County Bridges have been separately identified in the present version of the Roads GIS.

In the Roads GIS, bridges were plotted as polylines joining roads on the adjoining banks. The OS 6inch first edition was used to locate the bridge alinement where possible. All bridges that were not part of a turnpike trust were plotted as discrete items and associated data was that of the Bridge Trust or administrative unit. Bridges that were part of a turnpike trust were drawn as discrete polylines but the associated data was that of the turnpike trust.

Where several bridges or ferries were recorded at a particular location, the bridge in use in 1830 was given priority as the straight line joining the abutting roads.

Ferries

Ferries using boats were often the first major investment made at a river crossing (sometimes replacing fords which were dangerous and seasonal). Charges were made to use the ferry (fords were free) and it was one of the more lucrative Manorial rights that could be leased out. Ferries varied in size from a simple punt carrying a few passengers to sizable boats capable of carrying a coach or a wagons as well as passengers, livestock and horses. Ferries were able to offer crossings at deeper and wider sections of river than was the case with fords but they were still vulnerable to extremes of weather and so may be unreliable and often fatally dangerous. As traffic along the roads increased, ferries became significant bottlenecks in the flow of traffic and were progressively replaced by bridges. As bridge building technology improved, the sequential replacement of ferries along the major rivers moved downstream to span wider and wider sections of river.

Recording and plotting the ferries

All instances where a bridge building Act mentions an earlier ferry were recorded and the date at which the ferry was replaced by the bridge noted.

A sketch map of major Medieval Ferries was taken from Campbell and georeferenced by Max Satchell – these points were matched with potential ferry sites on Roads GIS.

The OS6 inch First series was inspected for all major rivers starting from the estuary and moving up stream along all significant tributaries. All ferries marked on this map were recorded.

A google search for ferries on major rivers was used to confirm information on the possible earliest date and where applicable date of closure of ferries.

An Excel sheet (ferries v10.xls) containing basic information was set up the record the common name of the ferry, the stretch of water crossed, the most probable date of its first use and the date the ferry was closed (if not still operating). Ferries were designated F in the database file field "was turnpike" but larger ferries that were known to carry horses were designated HF and the largest ferries thought to have carried vehicles were designated FXL)

In the Roads GIS, ferries were plotted as polylines joining roads on the adjoining banks. The OS 6inch first edition was used to locate the ferry alinement where possible. Where the ferry was replaced by a bridge, the most direct line was used for the bridge and the ferry was drawn displaced slightly from the bridge but with lines joining to the bank where bridge, road and ferry meet.

Many ferries (particularly those surviving into the 19th century) were not connected to the turnpike network. In order to incorporate these into the 1680 network, link roads to the nearest main road were drawn using the OS 6 inch First Series maps and these link roads to a ferry crossing designated {XLR)

Appendix 4 Road freight transport costs

John MacNeil was a civil engineer who was an expert in road building. MacNeil testified before parliament on the value of building better roads, in particular reducing draught animal power. The testimony was given on 20 May 1833 (BPP, find)

MacNeil proposed empirical formula for draught. The formula was the following:

$$P = \frac{W'+w}{93} + \frac{w}{40} + c * v + \frac{h}{l}(W' + w)$$

Where P is draught, W' is the weight of the wagon, w is the load, c is a parameter for the quality of the road, v is the velocity in feet per second, $\frac{h}{l}$ is the slope where h is height and l is length. MaCNeil gives 6 values for c. $c = 2$ on a paved road, $c = 5$ on a well made broken stone road in a dry state, $c = 8$ on a well made broken stone road with dust, $c = 10$ on a well made broke stone road covered with mud, $c = 13$ on a gravel or flint road when wet, and $c = 32$ on a gravel or flint road when covered with mud. From this formula we can calculate draught P given a wagon load, a weight, a road type, a speed, and slope and calculate draught.

We want to estimate road transport costs under different conditions. This requires a calibration. First, we assume P is energy required in road transport. The cost of energy in monetary terms is some constant β times P. Gerhold (1996) has evidence that energy costs [feeding horses] were 75% of total freight transport costs TC. The rest were labor and capital costs like paying for the wagon and horse. Gerhold's evidence implies the formula: $0.75 * TC = \beta P$. We need to solve for β in 1680 and 1830 to get TC. We use observed transport costs under known road conditions, loads, and speeds at zero slope. In the 1680 calibration, we consider a wagon of 2240 pounds, a load of 4 times 2240 pounds, a velocity of 3.7 feet per second (which MacNeil used), and a road quality $c = 8$, which is well made broken stone with dust. Our road quality may appear arbitrary however, we can estimate relative c for packhorses roads since we observe a freight cost for packhorse and wagon from Gerhold (11.9 and 10.6). We solve the following equation for β in 1680.

$$\beta\left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 8 * 3.7\right) = 0.75 * 10.6$$

Given this $\beta = 0.02$, we can solve for the packhorse road quality that gives a packhorse freight transport cost of 11.9 using the following equation.

$$0.02 * \left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + c * 3.7\right) = 0.75 * 11.9$$

The final formula for packhorse roads in 1680 as a function of slope is

$$0.02 * \frac{4}{3}\left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 20.4 * 3.7 + \frac{h}{l}(2240 + 4 * 2240)\right) = TC$$

Or

$$11.2 + \frac{h}{l}(298.67) = TC$$

The final formula for wagon roads in 1680 as a function of slope is

$$0.02 * \frac{4}{3}\left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 8 * 3.7 + \frac{h}{l}(2240 + 4 * 2240)\right) = TC$$

Or

$$9.97 + \frac{h}{l}(298.67) = TC$$

A related calibration is done for 1830, but here we have two qualities of road: good and bad. Again we assume energy costs were 75% of total road freight transport costs. In 1830 we only know transport costs for a good quality road, Leeds to London. The cost was 7.5 pptm from Gerhold (1996). We assume that the Leeds to London road quality was $c = 2$, equivalent to a paved a road. Therefore, we can solve for β using the following formula

$$\beta\left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 2 * 3.7\right) = 0.75 * 7.5$$

The solution is β=0.016. With this β we can calculate a transport cost on bad roads if we assume a quality coefficient $c = 32$, which in MacNeil's framework is a gravel or flint road with mud.

The final formula for good roads in 1830 as a function of slope is

$$0.016 * \frac{4}{3}\left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 2 * 3.7 + \frac{h}{l}(2240 + 4 * 2240)\right) = TC$$

Or

$$7.5 + \frac{h}{l}(238.93) = TC$$

The final formula for bad roads in 1830 as a function of slope is

$$0.016 * \frac{4}{3}\left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 32 * 3.7 + \frac{h}{l}(2240 + 4 * 2240)\right) = TC$$

Or

$$9.87 + \frac{h}{l}(238.93) = TC$$

Appendix 5: multi modal model

The creation of the historical GIS transport networks presented in section III required a topological cleaning to ensure there are no drawing errors, such use overlaps, unwanted intersections or gaps. It ensured all networks are routable, and therefore suitable for network analysis.

The next step was the amalgamation of all the different networks in just one multimodal model including all contemporary transport modes. It included transport infrastructure, such as roads, waterways and coastal routes, plus all those punctual items needed in the model, like towns and ports.

We assembled the multimodal model by coding a python script specifically designed to implement the following steps in ArcGIS:

1. Determine the XY coordinates of all towns and ports.

2. Create straight line connections between towns and the nearest road.

3. Create straight line connections between towns and the nearest waterway, with a 2km threshold.

4. Create straight line connections between towns and the nearest port, with a 2km threshold.

5. Create straight line connections between ports and the nearest road.

6. Create straight line connections between ports and the nearest waterway.

7. Integrate all the previous features: roads, coastal routes, waterways, ferries, ports, towns and XY connections (calculated in steps 2 to 6).

8. Create points at the intersection between roads and waterways.

9. Create points at the intersection between roads and coastal routes (if any).

10. Create points at the intersection between waterways and coastal routes.

11. Create points at the intersection between roads and ferries.

12. Compile all intersection points in one layer, keeping the attributes.

13. Determine XY coordinates of all intersection points.

14. Create small by-passes to circumscribe intersection points when needed.

15. Integrate roads and ferries.

16. Integrate roads, road by-passes and ferries.

17. Integrate waterways and waterway by-passes.

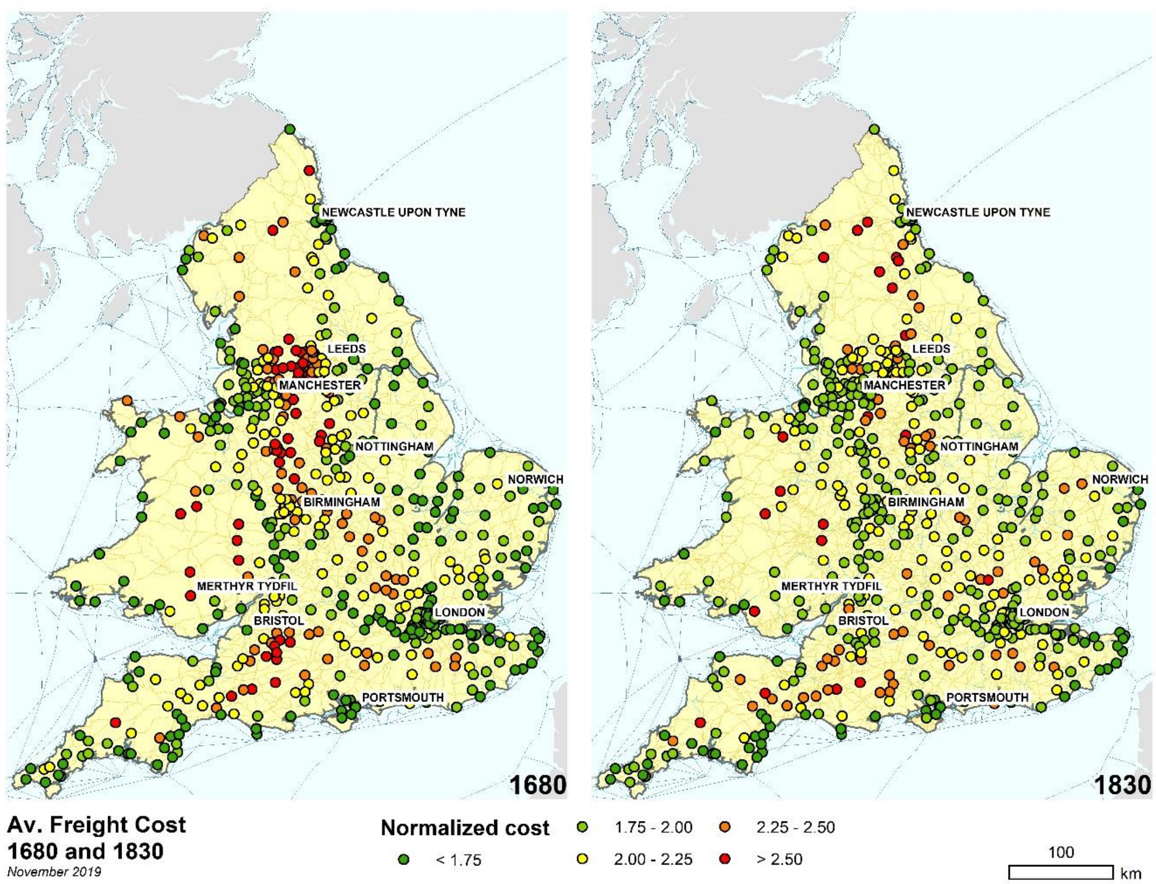
Once the multi-modal networks were ensembled, we proceed to create a GIS feature dataset containing a copy of all the previous features. Then we proceeded to create a network dataset including all features, allowing global turns, applying the appropriate connectivity policies (one independent group for each mode of transport), avoid elevation data (already included in the features) and defining the appropriate freight cost parameters.

Appendix 6: Estimates of multi-modal transport costs

Appendix figure 6.1 shows the spatial distribution of average normalized transport costs in 1680 and 1830. A red color indicates that transport costs to all other towns were larger than average, while green indicates smaller than average. Several facts are worth pointing out. In 1680 transport costs were largely determined by location and physical geography. Coastal towns and those near navigable rivers like the Thames and Severn had the lowest average transport costs. Inland towns and far from rivers had higher transport costs.

In 1830 coastal towns and those near navigable rivers still had low transport costs, but now they were joined by towns in the west midlands and north. The change was largely due to the extension of canals.

Figure A.6.1: Average normalized transport costs across towns



Source: authors calculations, see text.

Notes: Normalized transport costs between towns i and j, τ_{ij}, are the ratio of the transport cost from i to j, tc_{ij}, divided by the average estimated transport cost between all towns i and j, $\overline{tc}$ plus one, or $\frac{tc_{ij}}{\overline{tc}} + 1$. The average normalized costs is $\sum_i^N \tau_{ij}$.