

Transport and urban growth in the first industrial revolution

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Abstract⁵

During the first industrial revolution the English and Welsh 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 nearly 458 towns in 1680 and 1830 using a new multi-modal transport model and then estimate the effects of market access and on urban populations. Our regression model controls for various town characteristics, including coal endowments. The results show that market access robustly explains urban population. Through counterfactuals we also estimate that England's urban population would be 21% lower if transport costs did not change in real terms from 1680 to 1830. The results have implications for the drivers of the industrial revolution and more generally on economic growth.

Keywords: Urbanization, transport, market access, industrial revolution

JEL Codes: N7, O1, R4

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Urban areas 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 huge new 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 labor sought new employment they turned to 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 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, although related, explanation is that some towns grew more because 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. It is often assumed that transport improved after the industrial revolution with the introduction of steam power. However, in a few economies like England and Wales, new canals, bridges, and ports were built, while existing roads and rivers improved by trusts and joint stock companies. On the user side, 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 the patterns of urban population change between 1680 and 1841, beyond the effects of endowments like coal.

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. Other studies on inland transport focus on where canals and roads were built and if growing towns were nearby or not.⁶ While valuable, these studies do not incorporate inter-modality and network structure. Transport historians have shown that some shippers reached distant markets using roads, canals, and ports.⁷ Therefore, if inter-modality was common, a town's growth prospects would not just depend 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 test the relationship between market access and geographic variables like urban population. In the literature, market access can be defined in many ways, but generally it is a function of transport costs between all locations and their economic mass or income.⁸ One school of thought builds on theoretical models of trade to define market access using trade costs, income, and fundamental parameters. 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.⁹ 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 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 new industrial cluster, the northwest of England.

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,

⁶ See Gerhold (1996, 2014), Bogart (2005), Turnbull (1987), Harley (1988), Armstrong (1991), Maw (2011), and Solar (2013), Leunig (2006).

⁷ 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).

⁸ See Gibbons et. Al. (2019) for an example.

⁹ See Donaldson (2018), Donaldson and Hornbeck (2016), Jaworski and Kitchens (2019), Alder (2014) and Faber (2014), Jacks and Novy (2018).

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 market access measure is a trade cost weighted sum of town populations following the market potential literature. We also market access using formulations from theoretical models used in the trade and development literature.

Our analysis of market access is restricted to two dates for several reasons. First, there is little available spatial economic data for England and Wales prior to the census in 1801. Town populations are probably the most accurate and informative, but they must be estimated too. 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 and in the early 1800s and so 1801 misses some transport development. 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 the inter-urban transportation infrastructure and technology shows that market access increased substantially across most of England and Wales. 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. In northern and midland towns, market access approximately equaled that 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 growth log difference in population is regressed on the long 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 is robustly associated with higher population growth. The elasticity of market access with respect to town population is approximately 0.10 across most specifications. Moreover, when we focus on transport changes, by fixing 1680 population in calculating market access, we find a very similar effect. The same applies when exclude the market access associated with towns within 40 km.

Naturally our estimates do not imply that all town population growth is explained by market access. Consistent with expectations, we find that being located on the exposed coalfields had a large and positive effect on town growth. In an analysis of heterogenous effects, we also show that market access and coal had positive interactive effect. Therefore, our results suggest transport improvements complemented the role of endowments.

The importance of transport is further illustrated using a counterfactual, where transport networks and technology did not change between 1680 and 1830 and the transport sector faced the same input prices of 1830. We find that the total urban population in England and Wales would be 5.58 million in 1841 instead of 7.02 million, or a 21% decline. Interestingly, some cities and towns would retain much of their population even with higher transport costs. London for example, retains 94% of its 1841 population under the counterfactual. However, the largest inland towns are much smaller in the counterfactual. The population of Manchester, Birmingham, Leeds, and Sheffield are 65%, 60%, 56%, and 56% of their 1841 levels. 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.

The paper is organized as follows. Section I gives background on urbanization and transportation. Section II presents data. Section III lays out the conceptual framework. Section IV gives the results. Section V provides discussion.

I. Background

A. Urbanization and towns 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 and 27.5% in 1801. Urbanization rates increased even more by 1841 reaching around 45% (Law 1967). While the urban population increased overall, there was significant variation in population growth across towns. Cities are considered as very 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 50,000 to 2 million between 1680 and 1841, or by 300% (Langton 2000). The rate of increase was much larger in Manchester and Liverpool. Both had less than 2500 inhabitants in 1680, but by 1841 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 increased from 14,000 to 28,000 by 1841. 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 in creating urban divergence (Pooley and Turnbull 2005). There was much migration 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.

Falling mortality was the main factor that led to greater natural increase in towns. There was a substantial urban mortality penalty around 1650, but it lessened slightly by 1800 especially for infants. Falling urban mortality was due to many factors like better sanitation, health knowledge, and food supply (Woods 1997).

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. Relative to rural areas, urban manufacturing generally used more capital. The skill level was also higher, 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). Towns offered a supply of manufacturing employment for factories 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 service sector share of 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. Roads were scarce and their state of maintenance made 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 even more uncertainty. Coastal routes allowed the transport of heavy goods between ports and harbours at a reasonable cost. However, sailing boats showed high unpredictability in terms of travel time which meant higher costs. All in all, this period was characterised by a clear lack of reliable transport infrastructure. This situation kept costs high, maintaining distance as the main barrier for trade between towns.

In 1830, transport infrastructure had evolved dramatically, especially the inland networks. Old roads started to be modernised using new paving materials. Innovations in vehicles and their characteristics were frequent. 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 mainly after 1695. The law allowed trustees to levy tolls on the users with the aim of better maintaining each segment of road. Turnpike trusts were remarkable successful in improving roads up to the 1830s (Bogart 2005). Waterways were a network in which changes were crucial as well. 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). The coastal network was probably the one where changes were less visible. But still, 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). East India Company ships also sailed significantly faster indicating broad technological change (Kelly and O'Grada 2019). 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

The spatial distribution of town population is a key issue for our paper. Our current knowledge is based on Langton (2000), who used various sources to estimate 1005 town populations in the late 17th century. We use c.1680 to describe the date for these population figures.¹⁰ Langton (2000) uses the census to provide town population figures in 1801 and 1841. Due to missing information, only 590 towns have population figures for c.1680, 1801, and 1841. We only include these 590 in our analysis to avoid introducing interpolation errors.

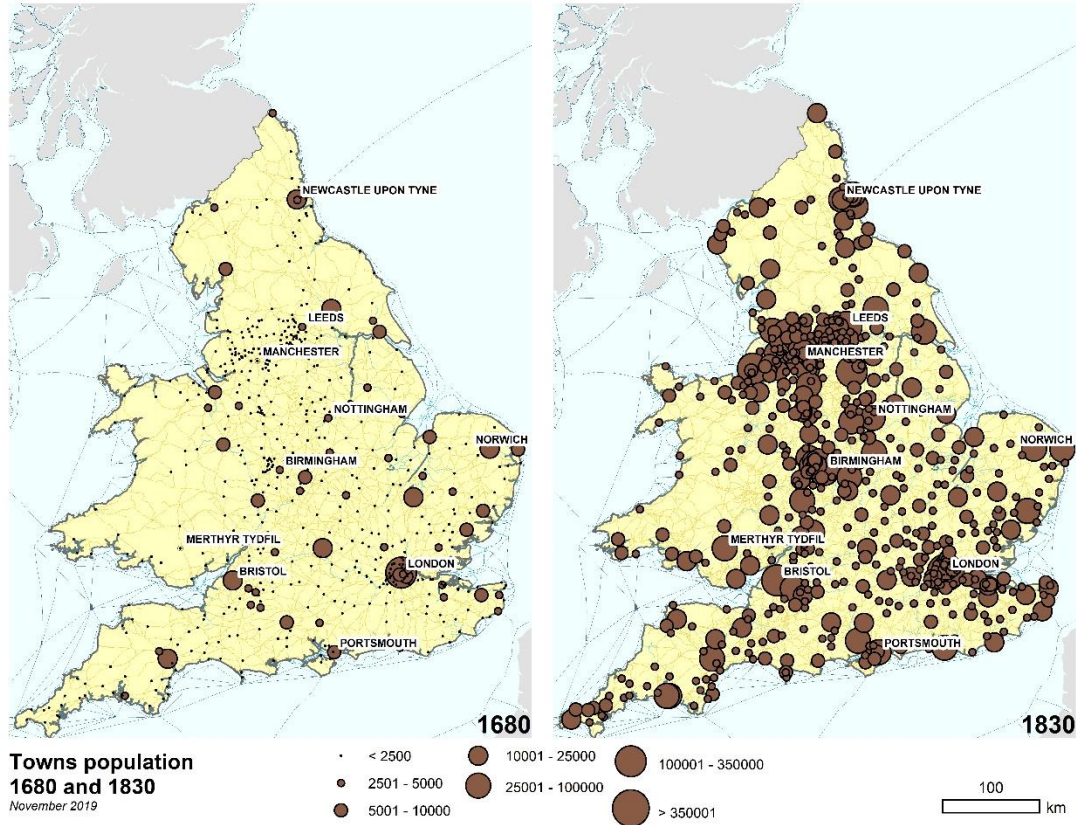
The towns in Langton's data have been georeferenced by the Cambridge Group for the History of Population and Social Structure (CAMPOP).¹¹ Towns are treated as points in GIS and their coordinates are identified based on a hierarchy of characteristics for trade. To decide towns' location, the first step was to identify the coordinates of its market place. In the absence of urban market, parish church coordinates were assigned. If no parish church, then inns, post offices, public houses, and high streets were used.

The locations and population of all towns are shown in figure 1. The rise in the level of urban populations between 1680 and 1841 is clear. There was a remarkable growth of town population in the northwest led by Manchester and Liverpool. Bristol and Birmingham also grew substantially, and of course, so does London. The maps also show that towns with missing population in 1680 are generally very close to London, Leeds, and Manchester. Therefore, we are slightly under-estimating population near the very largest towns by omitting them. Appendix 1 provides more details and lists the population of the largest 20 towns in 1680 and 1841.

¹⁰ Langton's estimates are not without controversy, mainly because the definition of town is not always clear, and assumptions are need to work with the sources. Nevertheless, Langton's population figures are widely used in the urban history literature (e.g. Ellis 2001) and present a reasonably accurate picture.

¹¹ See Satchell, Potter, Shaw-Taylor, and Bogart (2017) for GIS data on towns.

Figure 1: 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.

B. Transport networks

Roads, waterways and coastal routes have been digitised from historical sources for 1680 and 1830¹². 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.¹³ The first 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, though, only represented the main roads of the network. A second type of road

¹² Our GIS transport networks were digitised, georeferenced, and vectorized from historical sources. For easier comprehension we just use the term digitization.

¹³ See Satchell, Rosevear, Dickinson, Bogart, Alvarez, and Shaw-Taylor (2017) for GIS data on 1680 roads.

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.¹⁴ 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 1680.¹⁵

For road transport in 1830, we use the turnpike network as it represents nearly all 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.¹⁶ 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 in high and low quality.¹⁷

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 1948.¹⁸ The dataset uses several sources like Dean's *Inland Navigation. A Historical Waterways Map of England and Wales*. In 1680 the inland waterway network includes navigable rivers. Most were tidal, like the Thames, but there were some improved rivers in the mid-17th century. In 1830 it 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

¹⁴ The routes for 1680 secondary roads are explained in the documentation with Satchell, Rosevear, Dickinson, Bogart, Alvarez, and Shaw-Taylor (2017).

¹⁵ A map of De Laune wagon and packhorse services in the appendix.

¹⁶ See Rosevear, Satchell, Bogart, Shaw Taylor, Aidt, and Leon (2017) for GIS data on 1830 roads

¹⁷ 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.

¹⁸ See Satchell, Shaw-Taylor, and Wrigley (2017) for GIS data on 1680 waterways

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.¹⁹

In the case of maritime and coastal transport, we use a historical database of ports and coastal routes.²⁰ 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 harbour or dock works. Coastal routes between ports were digitised 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.²¹

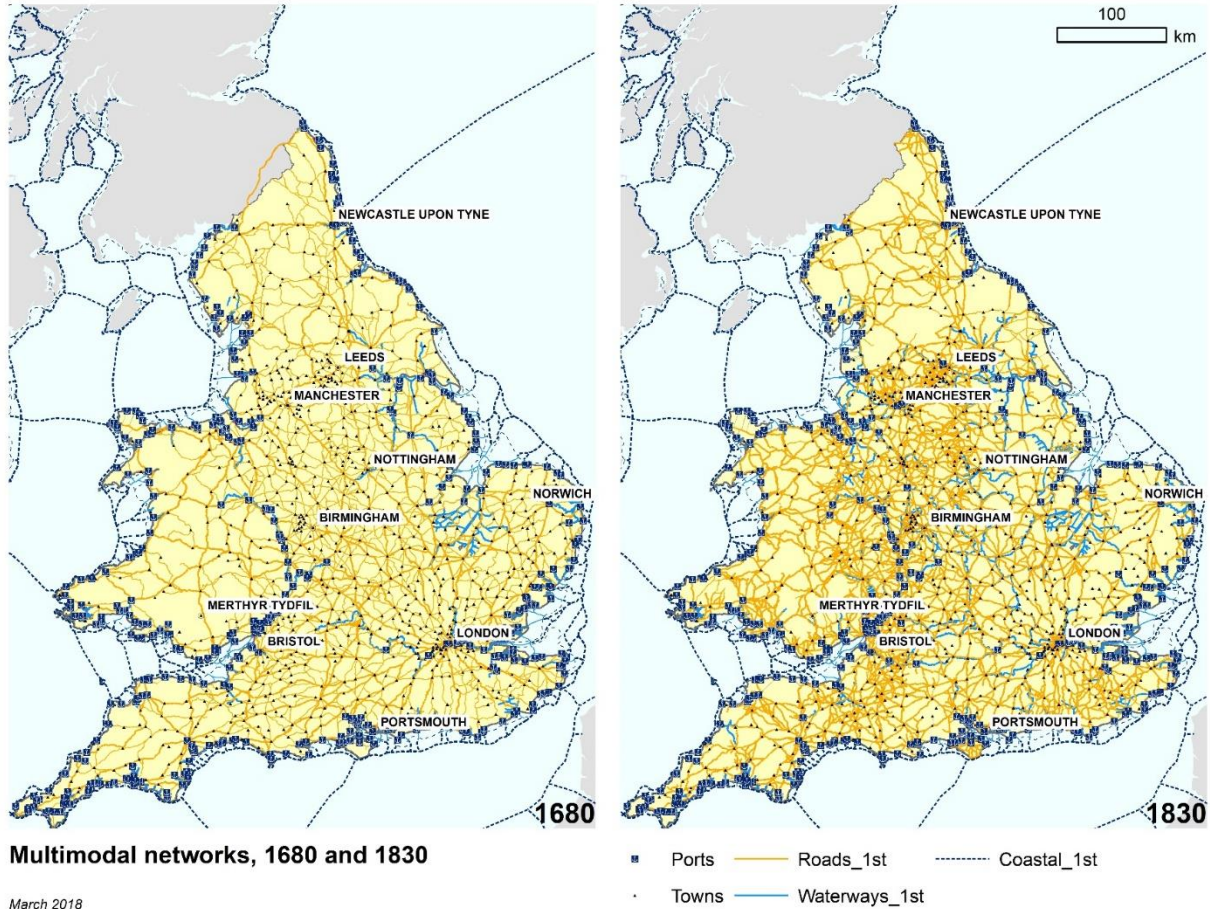
Figure 2 shows a full picture of the different transport networks in 1680 and 1830. Strikingly there were few waterways in 1680. In the case of roads, turnpikes increased the total length and density of the network by 1830. Ports were common along the coast in both periods. Transport networks were clearly large and complex before the steam era.

Figure 2. Transport networks in 1680 and 1830.

¹⁹ See the River and Canal Trust, Locks, <http://data-canalrivertrust.opendata.arcgis.com/datasets/locks-public>. Accessed on 1 Aug. 2018.

²⁰ 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.

²¹ For details on coastal routes, see Alvarez and Dunn (2019) for GIS of ports and coastal routes.



Source: created by authors using source in text.

C. Geographic data

We use elevation data to calculate the slopes along roads. 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).

Our analysis of urbanization also builds on the geographic characteristics of towns. The geographic variables include indicators for being on exposed coalfields and being on the coast, ruggedness measures, average rainfall and temperature, wheat suitability, latitude, longitude,

and the share of land in 10 different soil types. They are calculated aggregating geographic variables at the civil parish level and assigned to towns according to their location.²²

III. Methodology

A. Measurement of transport costs

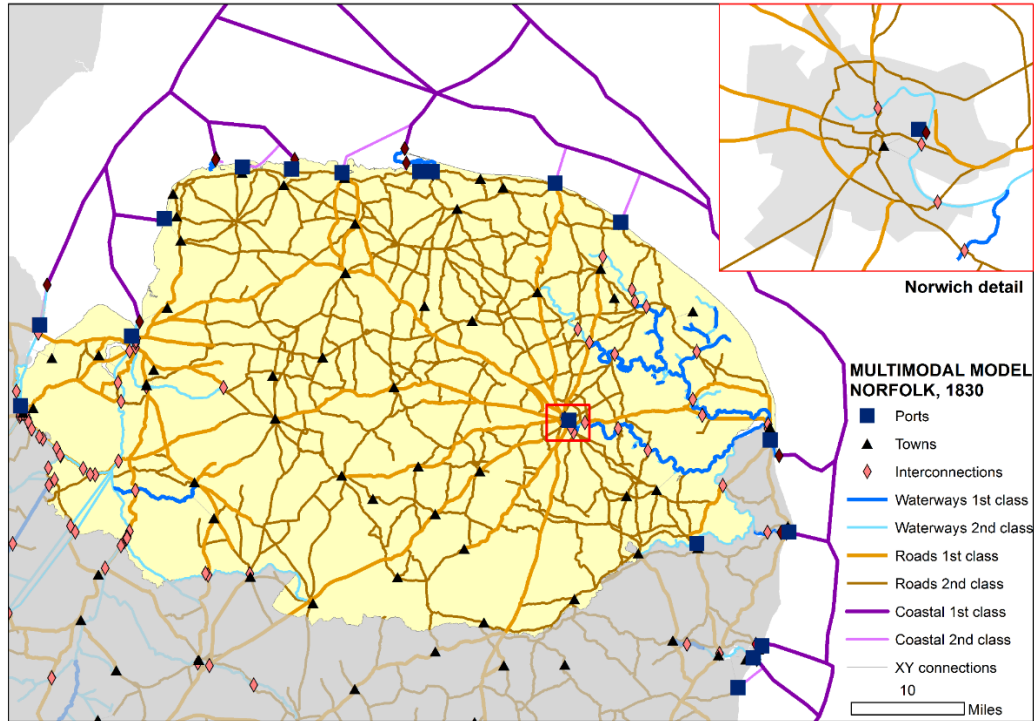
We develop a multi-modal network analysis to quantify changes in transport costs during the early industrial revolution. The proposed method combines several modes of transport to create an integrated model, which allows the identification of the most appropriate route between each pair of towns through 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. The model 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, we create a set of interpolated lines between our point layers, towns and ports, and the respective networks. 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. It means we allow all the movements within each network, but also between them. In our particular case, if a wagon is moving on a road, and this road intersects a river, we allow the transshipment to the river paying a fee.

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

²² See Bogart, You, Alvarez, Satchell, and Shaw-Taylor (2019) for details on parishes and geography.



Sources: Authors' own work from sources in text.

We use Dijkstra's algorithm for finding the least cost route. It is worth giving some details as we use multiple networks and have transshipment costs. The algorithm minimizes a cost accessibility function composed by a sum of several factors. Cost accessibility between points i and j C_{ij} is given by equation (1). It is 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 transshipment between modes r (c_r^t), and the cost to reach the final destination (c_j^d).

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

Each mode of transport has been assigned a unique ton per mile cost for each time-slice, or what we call the parameter value. 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 it gives the transport cost for the least cost route. Let the resulting transport cost from i to j be defined as tc_{ij} .

In choosing parameters, our general approach was to identify transport costs reported in the secondary literature, focusing on heavy commodities like coal and grain. The full set of

parameters is summarized in table 1. Each is measured in pence per ton (ppt) or per ton mile (pptm). The monetary values are nominal. One could convert 1680 or 1830 rates into real terms using a price index, but it is not necessary for our analysis.

Table 1: parameter values for multi modal model

1680				1830			
	Value	Unit	Source		Value	Unit	Source
Coastal freight rate	0.2	pptm	Nef (1979)	Coastal freight rate	0.17	pptm	Bentley testimony (Coal trade report)
Seaport cost	27.1	ppt	Nef (1979)	Seaport cost	22.9	ppt	Bentley testimony (Coal trade report)
Estimated cost freight to at 10m	1.1	pptm	Nef (1979)	Estimated cost freight to at 10m	0.93	pptm	Bentley testimony (Coal trade report)
Transshipment road - water	17.1	ppt	Nef (1979)	Transshipment road - water	13.9	ppt	Bentley testimony (Coal trade report)
River freight rate	1.0	pptm	Willan (1936)	River freight rate	2	pptm	Allnut (useful and correct account)
				Canal freight rate	2	pptm	Lock dues in priesly historical account
Wagon freight rate	10.6	pptm	Gerhold	Freight rate in bad quality road (sl=0)	7.5	pptm	Sample Leeds to London
Packhorse freight rate	11.9	pptm	Gerhold	Freight rate in good quality road (sl=0)	9.9	pptm	Sample Leeds to London
ASSUMPTIONS							
Ferry cost	1.0	pptm		Ferry cost	2.0	pptm	
Ferry transshipments	0.5	ppt		Ferry transshipments	1.0	ppt	
Rhombus roads	11.9			Rhombus roads	9.9		
Rhombus waterways	1.0			Rhombus waterways	2.0		
XY roads	16.8			XY roads	14.0		
XY waterways	1.4			XY waterways	2.8		

Sources: see text.

Nef (1979, pp. 404-412) gives figures for coastal freight and loading cost in the important northeast coal trade between London and Newcastle. 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.²³ 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). We convert these into a per mile freight rate and a per ton port loading cost.

Our coastal freight rate figures imply that coastal shipping became more productive between 1680 and 1830. The freight rate fell from 0.20 to 0.17 pence per ton mile, a 15% decline in nominal terms. Input prices for transport, like wages, capital, and fuel, rose by 75% between

²³ 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.

1680 and 1830 (Bogart 2014). In price dual terms, productivity would have increased by about 90% in coastal shipping. This is in line with recent estimates for the east coast coal trade (Bogart et. Al. 2020).

Inland water freight rates for 1680 are summarized in Willan (1936). Willan's figure captures important tidal rivers like the Thames. For 1830 we use Allnut, a contemporary who detailed freight rates on the river Thames around 1810 (see Bogart, Lefors, and Satchell 2019). We also differentiate 1830 waterways by the number of locks, since it is known to be a major factor on canals and we have most historic locks in our data. We use Priestley (2014) to identify the per ton cost of passing a lock.

Road freight rates in 1680 are summarized in Gerhold (2005) by wagon and by packhorse. We use those rates for two categories of roads in 1680. For 1830 we use Gerhold's (1996) road freight rates per ton mile in the London to Leeds trade. This was a large trade along one of the best roads in England. We think this case represents the lowest per ton mile freight rate achievable in 1830 based on other sources detailing road freight rates (Bogart 2005). We think varying road quality and slopes explains some of the variation in road freight rates. 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. We use McNeil's formula to estimate the freight rates per ton mile on turnpike roads of different quality and with different slopes. In 1830 quality is taken from turnpike trustees' evaluation of their roads, which we have included in our network data at the trust level. In 1680 we use our classification of wagon and packhorse roads to measure quality. Slope was obtained by extracting elevation values in the vertices of the road segment and dividing by the length between them. The details are given in appendix 3.

Our resulting road freight rates yield reasonable variation. At zero slope, the differences in quality can change road transport costs by approximately 10% in 1680 and by 30% in 1830. There are estimates that getting a turnpike road reduced road freight rates by approximately 30% (Bogart 2005). Turnpikes raised road quality and therefore our 1830 quality range is reasonable. Our formula also implies that slopes of 2% can raise road freight rates by 40 and 60%.

While slope makes a large difference, contemporaries, like McNeil, often stressed the importance of avoiding hills when designing roads.

Finally, we assume a trans-shipment cost when switching 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.

In bringing the network and cost parameters together, we estimate transport costs between all 590 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. There are limitations however. 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 market access are a major achievement given the limited sources in the industrial revolution period.

B. Measurement of market access

Our analysis uses several formulations of market access. It should be noted that we focus on ‘domestic’ market access by using only the populations of English and Welsh towns. This defensible if we are mainly interested in transport improvements that integrated the domestic market. The first formula is

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

where MA_i is the market access of town i , pop_j is the population of town j , indexed from $j = 1, \dots, J, i \neq j$, and τ_{ij} are normalized transport costs, which we define as $\frac{tc_{ij}}{\bar{tc}} + 1$ or 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 , \bar{tc} , plus one. τ_{ij} is bounded below by 1 and higher τ_{ij} corresponds to higher

transport costs relative to the average. The average \bar{c} is calculated separately for 1680 and

$$1830, \text{ so } \tau_{ij}^{1680} = \frac{tc_{ij}^{1680}}{\bar{c}^{1680}} + 1 \text{ and } \tau_{ij}^{1830} = \frac{tc_{ij}^{1830}}{\bar{c}^{1830}} + 1$$

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.²⁴ In our baseline we follow the trade literature and assume $\theta = 8$, but we also calculate market access for different values.²⁵

An alternative market access formula comes directly from the trade model proposed by Donaldson and Hornbeck (2016). Their formula is

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

which is the sum over the transport costs to other towns, that other town's population, and that other town's access to other markets. Their model applies to a different context, the US economy in the nineteenth century, but it may capture some features of our setting. We calculate market access as defined in equation (3) by solving numerically.

C. Regression specifications

Our estimating equation tests whether population levels (in logs) were affected by market access (in logs) after controlling for other factors related to geography. The baseline specification is

$$\ln(pop_{it}) = \beta \ln(MA_{it}) + \alpha_i + \delta_t + \delta_{rt} + \delta_t x_i + \varepsilon_{it} \quad (4)$$

where α_i is a town fixed effect, δ_t is a year fixed effect either for 1680 or 1841, δ_{rt} is a region by year fixed effect, and vector x_i includes time invariant controls, which are interacted with the year fixed effect δ_t . The baseline controls include latitude and longitude and in some specifications indicators for towns being on the exposed coalfield, being on the coast, its elevation, variables for ruggedness, soil types, and distance to London and Manchester. These

²⁴ According to 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.

²⁵ Donaldson and Hornbeck (2016) and Kitchens and Jawarski (2019) use theta equal to 8.22 and 8 respectively.

time-invariant control variables for town i capture other initial factors that can influence growth. Having coal, for example, is a classic explanation for town population growth in the industrial revolution.

As we have only two periods, 1680 and 1841, the specification in (4) is equivalent to a first differences specification examining the effects of changes in market access from 1680 to 1830 on population growth from 1680 to 1841. The model is the following:

$$\Delta \ln(pop_{it}) = \beta \Delta \ln(MA_{it}) + \delta_r + \gamma x_i + \omega_i \quad (5)$$

where $\Delta \ln(pop_{it})$ is the log difference in town i 's population from 1680 and 1841, $\Delta \ln(MA_{it})$ is the log difference of market access from 1680 to 1830, and δ_r includes the constant and indicators for regions and the vector x_i includes time invariant controls.

Reverse causation is one of the main endogeneity concerns in equation (5). Specifically, the growth in a town's population could itself influence the change in market access either through more population or through changing trade costs. One approach is to use 1680 town populations to measure market access in 1830. In other words, for one formulation, we use $MA_{i1830} = \sum_j^J pop_{j1680} \tau_{ij1830}^{-\theta}$. This could eliminate the potential endogenous feedback from town i 's population growth to its neighbors j which would enter through our baseline formula, $MA_{i1830} = \sum_j^J pop_{j1841} \tau_{ij1830}^{-\theta}$. Notice also the change in market access is driven entirely by changes in transport costs when using 1680 populations for market access in $t=1680$ and $t=1830$.

A second approach to address endogeneity eliminates all trading connections to towns within a distance of 50 km. Here market access is the transport costs weighted by the population sum for towns more than 50 km away, or $MA_{it} = \sum_{j>50km}^J pop_{jt} \tau_{ij}^{-\theta}$.

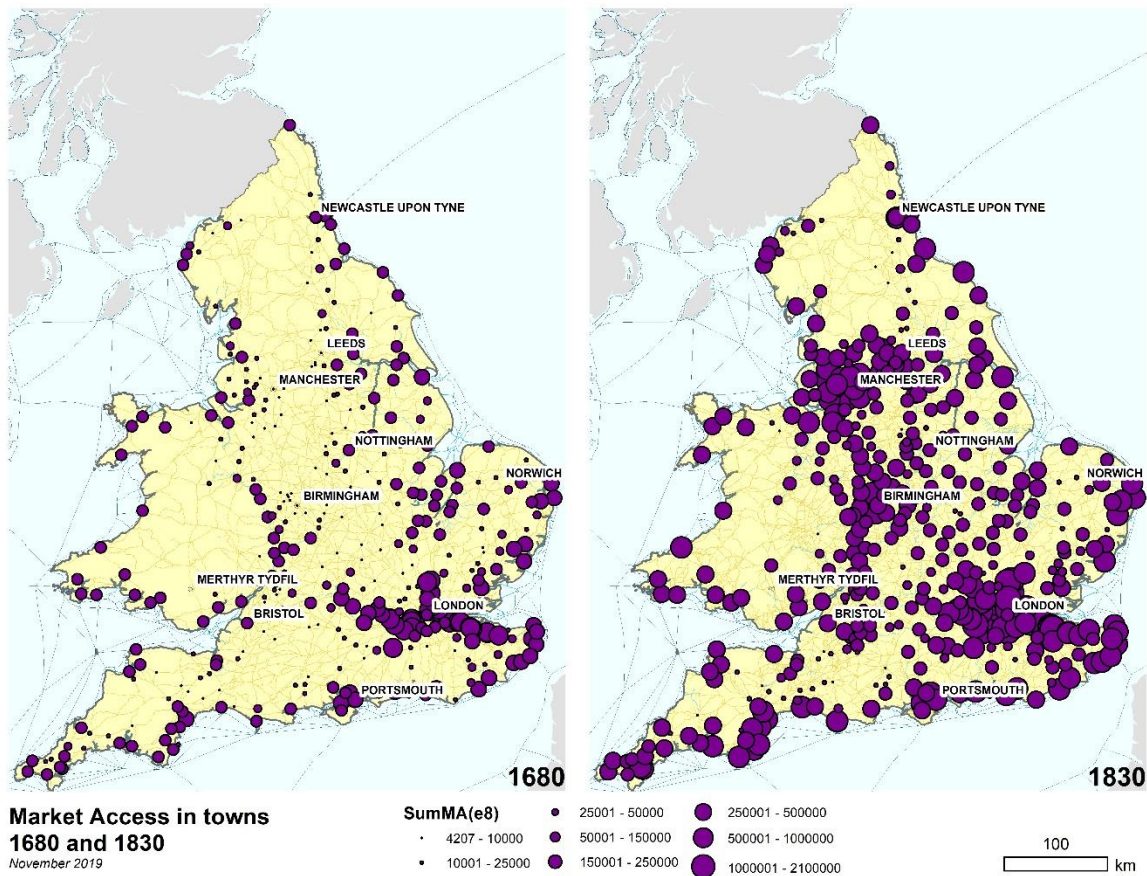
IV. Results

A. Changes in market access across space

In 1680 market access was largely determined by location and physical geography. The left panel of figure 5 shows the spatial distribution of market access (MA) in that year. Towns with the highest MA were near London. That makes sense as London was the population and production

center of the English economy. London was also located along the Thames, which gave many towns nearby low transport costs to the capital. Coastal towns also had higher MA in 1680. They could access each-other and London via cheap sea transport. By contrast MA was strikingly small for most inland towns in 1680.

Figure 5. Market access in 1680 and 1830.



Source: authors calculations, see text.

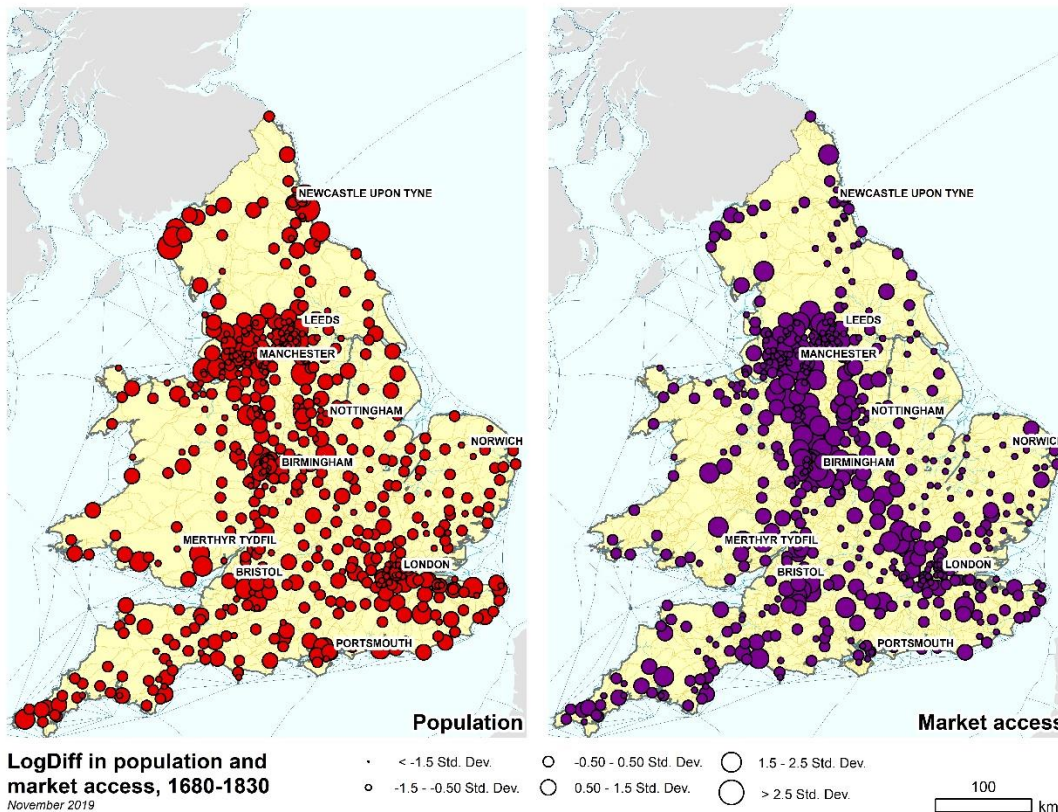
Notes: Market access is given by the formula $MA_i = \sum_{j=1, j \neq i}^{458} pop_j \tau_{ij}^{-8}$, where τ_{ij} , is the ratio of the transport cost from i to j, tc_{ij} , divided by the average estimated transport cost between all towns i and j, \bar{tc} , plus one, or $\frac{tc_{ij}}{\bar{tc}} + 1$.

By 1830 England experienced revolutions, which changed its economic geography. The right panel of figure 5 shows the spatial distribution of MA in that year. Coastal areas remained high MA but strikingly towns in the northwest and west Midlands now had large MA, roughly similar to the southeast near London. What accounts for the change? One major factor was a transport revolution, mainly the expansion of canals and improved rivers, which were

significantly cheaper than road transport. The canal network linked the major industrial towns like Liverpool, Manchester, Leeds, and Birmingham with each other and with London. Other factors were endowments, like coal, and the urbanization that came with the industrial revolution. Industries relying on energy were largely located in the midlands and northwest which had coal deposits.

The regression analysis in the next section examines the link between changes in market access and changes in town population. Figure 6 provides a preview by illustrating the spatial relationship between the log difference in town population between 1680 and 1841 and the log difference in market access between 1680 and 1830. Population change was largest in the northwest, west midlands, and the southeast. MA change was largest in the corridor from Manchester to London. There was a close overlap between the two variables.

Figure 6. 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.

B. Summary statistics

Our main variables are summarized in table 2. We only consider those towns with population observations in 1680 and 1841. That means we are left with 458 towns of out of the original 590. Panel A summarizes population variables. The average log difference in town population was 1.676, or a 434% increase in town population over the 150-year period. The 25th and 75th percentiles were 1.079 and 2.098 respectively indicating substantial variation in population growth. In panel B the market access variables are calculated for the 458 towns. The log difference in market access is calculated as in equation (2) using theta equal to 8, and when holding 1680 population fixed and using a 50 km buffer around towns. For the baseline variable, the average town experienced a 1.592 log increase in market access, or a 391% increase between 1680 and 1841.

Panel C summarizes the coordinate and NUTS 1 regional indicator variables. We chose to include London as part of the Southeast because the capital was not its own region in 1680 as it is today. For that reason, 20% of our towns were in the southeast region. Overall the regional distribution reflects the distribution of towns in this period, notably the small number in the Northwest, Yorkshire, and Humber. Panel D summarizes the first nature control variables. Towns have a wide variety of geographic features. Most notably 28% are on the coast and 22% are on the exposed coalfield.

Table 2: Summary Statistics

	(1)	(2)	(3)	(4)	(5)
Panel A: Population vars.	N	mean	sd	min	Max
$\Delta \ln$ Town population 1841-1680	458	1.681401	0.811658	-0.30656	5.467073
\ln Town population 1680	458	7.029718	0.811708	4.867535	12.64736
Panel B: Market access vars.					
\ln MA 1680	458	10.043	1.673	3.497	12.798
$\Delta \ln$ MA 1830-1680, ($\theta = 8$)	458	1.592	1.366	-0.407	6.997
$\Delta \ln$ MA 1830-1680, ($\theta = 8$) fixed 1680 pop.	458	-0.436	1.183	-2.100	5.010
$\Delta \ln$ MA 1830-1680, ($\theta = 8$) 50 km buffer	458	1.289	1.314	-0.619	7.113
Panel C: coordinate and regional vars.					

Longitude	458	430311	105112	147275	655050
Latitude	458	265417	131975	27475	652900
Southeast & London	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 D: 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

Sources: see text.

C. Regression results

Table 3 reports our estimates from the log difference specification in equation (5). The standard errors are clustered on regions to adjust for heteroskedasticity and correlation within regions over time. They are similar if Conley standard errors are used. Market access variables are reported using the formula: $MA_i = \sum_{j=1, j \neq i}^{458} pop_j \tau_{ij}^{-8}$. Column 1 is the baseline and reports estimates using 9 region fixed effects and cubic polynomials in latitude and longitude as controls. The market access coefficient is positive and implies that a 100% increase in market access increased town population by 10.4%. The standardized coefficient (not shown) is 0.175, meaning a one standard deviation increase in market access was associated an 0.175 standard deviation

increase in town population. This implies a sizeable effect from market access. Column 2 adds the first nature controls like coal. The coefficient on market access is similar albeit slightly smaller at 0.096. Column 3 uses the ‘model derived’ market access measure. The market access coefficient is smaller, but broadly similar considering market access is calculated in a different way.

Table 3: Market access and town population growth, 1680 to 1841

	1	2	3	4	5	6
	baseline	first nature controls	Model derived MA	fixed 1680 pop. in MA	50 km buffer MA	Weighted 1680 pop.
	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.	Coeff.
	(Stan. err.)	(Stan. err.)	(Stan. err.)	(Stan. err.)	(Stan. err.)	(Stan. err.)
Log diff. market access	0.104 (0.036)**	0.096 (0.036)**	0.077 (0.034)*	0.106 (0.039)**	0.085 (0.041)*	0.118 (0.039)**
n	458	458	458	458	458	458
First nature controls	N	Y	Y	Y	Y	Y
R-squared	0.25	0.34	0.34	0.34	0.34	0.33

Notes: The dependent var is natural log difference 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. Standard errors are clustered on regions. In 5, observations are weighted by 1680 population. *, **, and *** represents statistical significance at the 10, 5, and 1% levels.

Columns 4 and 5 of table 3 address two endogeneity concerns. It is possible that the market access variable reflects agglomeration, specifically a feedback process between population growth in neighboring towns, even holding transport costs constant. To address this issue, we use the log difference in market access holding 1680 population fixed. The results are remarkably similar to column 2 reducing concerns about feedback processes. Another concern is that a town’s population growth encouraged the development of infrastructure in its hinterland, suggesting that changes in market access were partly caused by population growth of towns nearby. We address this issue by calculating the change in market access only for towns more than 50 km away. The estimates suggest a smaller impact of market access, but still significant

and broadly in line with the baseline model. Finally, column 6 shows that weighting our observations by 1680 population does not significantly affects the baseline estimates.

Table 4 reports specifications using different market access parameters for theta. The market access formula is $MA_i = \sum_{j=1, j \neq i}^{458} pop_j \tau_{ij}^{-\theta}$ in columns 1 through 5. All specifications include first nature control variables. It is clear 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 higher values of theta. The standardized coefficients also get larger. As our ability to explain the variation in population growth is similar across different thetas, we continue to use theta = 8, which make our results more comparable to other studies.

Table 4: 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. (Stan. err.)	Coeff. (Stan. err.)	Coeff. (Stan. err.)	Coeff. (Stan. err.)	Coeff. (Stan. err.)
Log diff. market access	0.697 (0.350)*	0.369 (0.168)*	0.189 (0.079)**	0.096 (0.036)**	0.067 (0.024)**
n	458	458	458	458	458
First nature controls	Y	Y	Y	Y	Y
R-squared	0.33	0.34	0.34	0.34	0.34

Notes: The dependent var is natural log difference 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. Standard errors are clustered on regions. Observations are unweighted. *, **, and *** represents statistical significance at the 10, 5, and 1% levels.

D. Counterfactuals

We can now estimate how urban population would have evolved in England if transport changed differently between 1680 and 1841. Such counter-factual have been long studied as early as Fogel (1964), but not with the type of data we have developed. We will consider several counterfactual scenarios for different normalized transport costs in 1830 labelled as τ_{ij}^c . In each

case, this will which will imply 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 normalized transport costs τ_{ij}^c , we need to use the functional form of our model. Recall that our regression model implies the following relationship between town population, market access, and series of town specific factors and common time shocks interacted with those specific factors.

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

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.

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

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 $i = 1, \dots, n$ equations:

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

The first counterfactual we consider is a case where transport networks and technology did not change between 1680 and 1830, but towns retained the same fundamentals in 1830 and the transport sector faced the same input prices of 1830. One approximation of this scenario is to use 1680 transport costs, tc_{ij}^{1680} , in the formula for counterfactual normalized transport costs $\tau_{ij}^c = \frac{tc_{ij}^{1680}}{tc_{1830}} + 1$ and market access. However, if the transport sector faced the same input prices in 1830 then we are understating transport costs using tc_{ij}^{1680} . In the appendix we show that the ratio of transport input prices in 1830 relative to 1680 was 1.75. Therefore, in our first counterfactual scenario we use $\tau_{ij}^c = \frac{1.75 * tc_{ij}^{1680}}{tc_{1830}} + 1$ as the counterfactual normalized transport

cost. Naturally these will be much higher than actual normalized costs in 1830. For example, the average normalized transport cost τ_{ij} increases from 2.00 to 4.16 under the counterfactual.

Our model estimates imply that the total urban population would be substantially lower in the first counterfactual, where transport networks and technology did not change between 1680 and 1830 and the transport sector faced the same input prices of 1830. The total urban population would be 5.58 million in 1841 instead of 7.02 million, or a 21% 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, retains 94% of its 1841 population under the counterfactual. The major coastal towns like Liverpool and Newcastle retain 82 and 92% 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 65%, 60%, 56%, and 56% of their 1841 levels. In other words, the largest towns of inland Britain would have been much smaller in size.

VI. Conclusion

This paper studies the role of market access for one of the most precocious economies in history: 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 the measures of transport costs derived from the multi-modal transport model. The changes in log market access between 1680 and 1830 are then related to the 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 0.175 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 21% 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 are the first to analyse the period before 1850. Our estimated effects are similar to studies despite very different contexts. Our findings 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 one of the most important engines 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

To see more details, appendix table 1 draws on Langton and 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		Rank 1841
	1680	Pop 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

To be written

Appendix 4: multi modal model

To be written

Appendix 5 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

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

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

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

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 $\beta=0.016$. 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

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

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

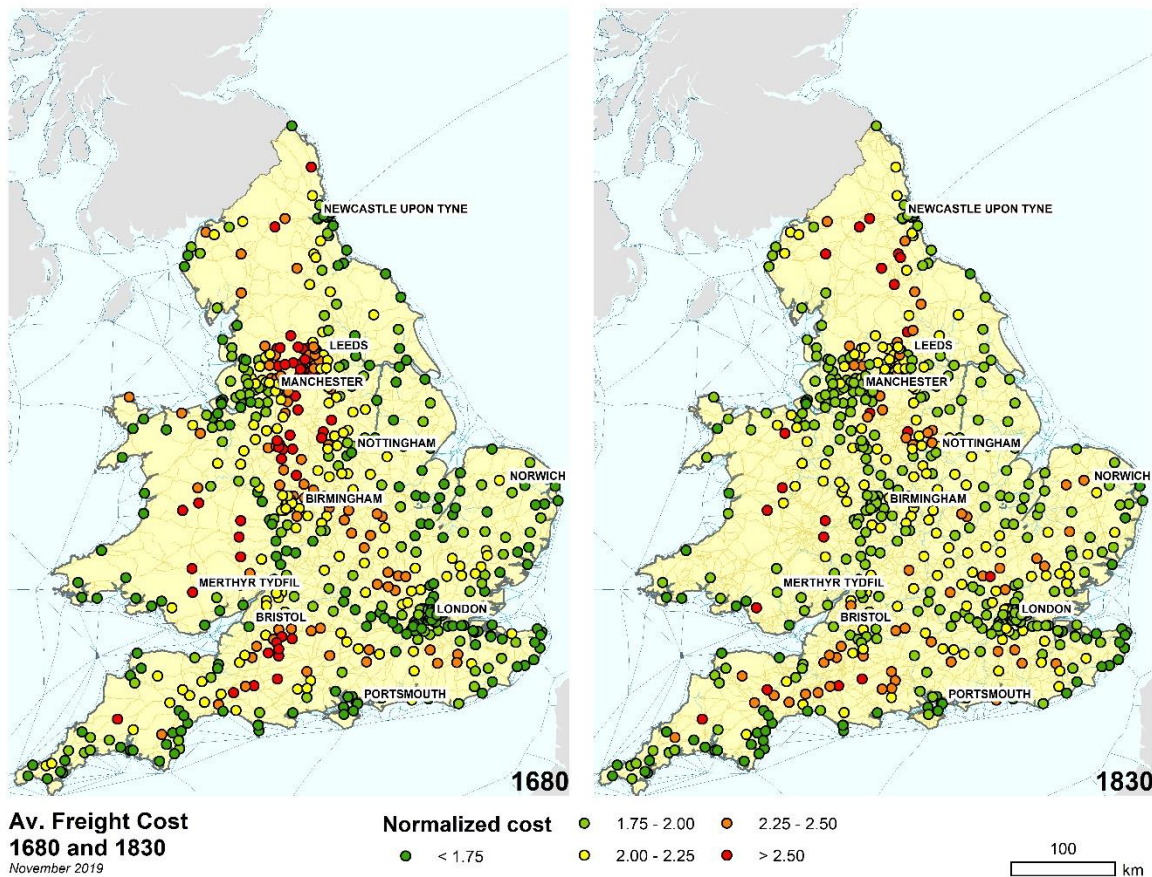
$$0.016 * \frac{4}{3} \left(\frac{2240 + 4 * 2240}{93} + \frac{4 * 2240}{40} + 32 * 3.7 + \frac{h}{l} (2240 + 4 * 2240) \right) = TC$$

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 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 , \bar{tc} plus one, or $\frac{tc_{ij}}{\bar{tc}} + 1$. The average normalized costs is $\sum_i^N \tau_{ij}$.

Appendix 7 additional results

To be written

Appendix 8 Transport input prices in 1680 and 1830

In this appendix, we calculate how road and shipping transport cost parameters in 1680 should be adjusted if the sector faced the same input prices of 1830. We use the price dual methodology, where productivity is related to the ratio of input and output prices. Let the ratio of transport productivity of transport in 1830 a^{1830} relative to 1680 a^{1680} be defined by

$$(a^{1830}/a^{1680}) = \frac{(w^{1830}/w^{1680})^\alpha (r^{1830}/r^{1680})^\beta (c^{1830}/c^{1680})^{1-\alpha-\beta}}{(p^{1830}/p^{1680})}$$

where w^{1830} is the wage of transport workers in 1830, r^{1830} is the rental rate of capital in transport in 1830, c^{1830} is the cost of fuel in 1830, and p^{1830} is the price of transport services in 1830. If we assume the productivity of wagons and ships were the same 1680 and 1830 then $a^{1830}/a^{1680} = 1$. The equation for the ratio of transport prices in 1830 and 1680 then becomes

$$(p^{1830}/p^{1680}) = (w^{1830}/w^{1680})^\alpha (r^{1830}/r^{1680})^\beta (c^{1830}/c^{1680})^{1-\alpha-\beta}$$

This implies that if the transport sector in 1680 faced the wages, rental rates, and fuel prices of 1830 and all else was the same then transport costs in 1680 should be multiplied by the factor $(w^{1830}/w^{1680})^\alpha (r^{1830}/r^{1680})^\beta (c^{1830}/c^{1680})^{1-\alpha-\beta}$. We can estimate the terms on the right-hand side through a series of steps.

The first step is to identify the weights for our 3 inputs in freight services, labour, capital, and fuel. The main sectors were road, coastal, and inland waterway. One could separately estimate input weights for shipping and road transport but as a first order approximation we model a single transport sector as an average of between road and shipping. Therefore, the weights are based on average of the cost shares provided by Gerhold (1996) for road transport and Solar (2013) for shipping. The cost share weights in our analysis are 0.4 for capital, 0.21 for labour, and 0.39 for fuel.

The second step is to estimate the ratio of input prices using secondary sources. As our wage rate for labour, we use Clark's (2010) series on the daily wages of craftsman. The day wage is 17.7 pence around 1680 and 42.1 pence around 1830. This implies $(w^{1830}/w^{1680})^\alpha = (42.1/17.7)^{0.21} = 1.199$. For fuel we use the price of oats, the main source of provender for horses. Oats are 1.45 shillings a bushel around 1680 and 2.8 shillings a bushel around 1830 (Clark,

2010). This implies $(c^{1830}/c^{1680})^{1-\alpha-\beta} = (2.8/1.45)^{0.39} = 1.292$. For the rental rate of capital, we use the formula $(r+d)*(pk)$, where r is the interest rate, d is the depreciation rate, and pk is the price of capital goods. The interest rate is around 4.75% in 1680 and 3.5% in 1830 (Clark, 2010). The depreciation rate is equal to 3% in both years. The price of capital goods are based on East India Company ships which were around 18.5 pounds a ton in 1680 and 30 pounds a ton in 1830 (Chaudhuri, Solar 2013). Thus, the rental rate of capital is $(4.75+3)*18.5=143.3$ in 1680 and $(3.5+3)*30=195$ in 1830. This implies $(r^{1830}/r^{1680})^\beta = (195/143.3)^{0.4} = 1.131$. Putting the three elements together implies $(p^{1830}/p^{1680}) = 1.199 * 1.292 * 1.131 = 1.75$. In other words, transport costs in 1680 should be multiplied by 1.75 assuming the sector faced the wages, rental prices, and fuel prices of 1830.

$$(p^{1830}/p^{1680}) = 1.199 * 1.292 * 1.131 = 1.75.$$