Growth before steam:

A GIS approach to estimating multi-modal transport costs and productivity growth in England, 1680-1830

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Preliminary Draft

May 2017

Abstract

How much did transport change and contribute to aggregate growth in the pre-steam era? This paper answers this question for England and Wales by estimating internal transport costs in 1680 and 1830. We build a multi-modal transport model of freight and passenger services between the most populous towns. The model allows transport by road, inland waterway, or coastal shipping and switching of transport modes within journeys. The lowest money cost and travel time for passenger and freight is identified using network analysis tools in GIS. The model estimates show substantial reductions in the level of transport costs and its variability across space. The model's results also imply substantial productivity growth in transport, equalling close to 0.8% per year. Plausible assumptions imply a social savings of 10.5% of national income by 1830.

[1] Data for this paper was created thanks to grants from the Leverhulme Trust (RPG-2013-093) Transport and Urbanization c.1670-1911 and NSF (SES-1260699), Modelling the Transport Revolution and the Industrial Revolution in England. We thank Alan Rosevear for extremely valuable assistance in this paper. We also thank seminar participants at the Economic History Society Meetings, 2017. All errors are our own.

I. Introduction

Transport improvements are one of the key engines of economic growth. Their significance is often measured through the effects of a single modal innovation, such as railways or steamships.[2] However, there are some limitations to this approach. Transport systems are multi-modal, with railways, ships, and road carriers inter-connecting through a network. Thus, the effects of innovations in one mode, like railways, may depend on its connections with another mode. Moreover, there can be improvements in multiple transport modes at the same time. If so, identifying the effects of an innovation in one mode holding fixed the quality of others captures only part of the effects from transport.

This paper quantifies the extent of change across a large proportion of the transportation system. It studies England and Wales from 1680 to 1830, a context where there was significant urbanization and industrialization, and also large changes in overland, inland waterway and coastal shipping. Most histories of the so-called 'transport revolution' emphasize steamships and railways.[3] But in England and Wales, there is evidence for transport improvements before steam-power. Road surfaces and gradients were improved, the inland waterway network expanded, and technology evolved in sailing ships and passenger coaches. The institutional environment also changed with wars and new methods of public finance that spilled over into transport.

Most of the research to date on the pre-steam transport revolution has focused on exclusively on shipping, turnpike roads, or canals.[4] There are two reasons. First, data on transport networks have not been sufficiently detailed in terms of spatial accuracy. Second, scholars have lacked the computing power to model a large number of transport options simultaneously. We integrate new GIS data on roads, inland waterways, ports, and coastal shipping routes into a single model of the transport network. The model also uses transport cost parameters, like freight rates per mile, estimated from samples of observed transport costs. For a given origin and

[2] Some examples are Baum-Snow (2007), Donaldon (2010), Pascali (2014), Duranton and Turner (2014).
[3] See Jackman (1962), Aldcroft and Freeman (1983), and Bagwell (2002) for overviews of the transport revolution in England.
[4] Some examples include Gerhold (1996, 2014), Bogart (2005), Turnbull (1987), Harley (1988), Armstrong (1991), and Solar (2013).

destination, it identifies the least cost route across all the possible alternative routes and infrastructures. The current analysis estimates the lowest transport costs, in both money and time, between the 100 most populous towns in 1680 and 1830. For example, we estimate the relative costs of trading with or travelling to large cities like London and Manchester. Two key findings are that transport costs declined substantially between the average town pair, and there was a reduction in the variability of transport costs across town pairs. For important cases, like London, we find fairly uniform reductions in passenger costs across provincial towns, but more varied reductions in freight costs.

The quantitative significance of changing transport costs is shown in several ways. First, we use our model's outputs to quantify the rate of change in transport costs between 1680 and 1830 relative to other price series. The rate of inflation in consumer prices is one comparison and identifies whether transport costs declined relative to key consumption goods, like food and housing. The results show that freight transport costs decreased at the rate of -0.56% per year between 1680 and 1830, while consumer prices increased at the rate of 0.36% per year. Together they imply a -0.92% annual change in real freight transport costs. The pure money passenger cost increased at an average rate of 0.18%, and thus exhibited a different trend than freight rates. But the generalized passenger cost, which incorporates the value of time, shows a similar pattern of lower costs over time. If the traveller earned twice as much as craftsmen then the generalized passenger cost declined at the annual rate of -0.02%, implying the annual change in the real passengers cost was -0.38%.

Another comparison is with the growth of input prices in transport, which yields an estimate of total factor productivity growth following the price dual method. In freight transport the average annual TFP growth rate between 1680 and 1830 was 0.937% and for passenger travel it was 0.46%. These figures show that transport experienced more substantial changes than most other sectors. The rate of TFP in the aggregate economy is much lower, typically between 0.25% and 0.3% per year.[5] The high rate of TFP growth also implies that transport improvements generated a large increase in national income, even before steam power. A plausible weighting of freight

[5] See Clark (2010), Antras and Voth (2003), Crafts and Harley (1992).

and passenger services in GDP implies a 0.067% contribution to the annual aggregate TFP growth rate between 1680 and 1830. Drawing on the methodology of social savings and growth accounting (e.g. Crafts 2004), this translates into a 10.6% increase in national income by 1830.

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 this economy.[6] 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 (Leunig 2006, Crafts 2004). We show that transport improvements were hugely important and rank close to innovations in textile manufacturing in generating income growth.

II. Background

II.A transport infrastructure

The domestic transport system in England and Wales substantially evolved between 1680 and 1830. This evolution was caused by several factors. The literature has mostly emphasized infrastructure construction, technological innovations and institutional changes. In this section, we briefly review these developments.

In 1680, inland communications were precarious. 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 in deposited sediments did not restrict the draft in excess. Meteorological conditions also affected communications both in roads and rivers, adding even more uncertainty. Costal 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. Shipping casualties were annually reported in Parliamentary Papers, giving an idea of the recurrence of sinking. All in all, this period was characterised by a clear lack of reliable transport infrastructure. This situation kept low speeds and high costs, maintaining distance as the main barrier for communications between settlements.

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[6] See Szostak (1991) fore example.

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. The increase in the number of services allowed labour specialization, emerging new occupations. And all the institutions had to adapt themselves to boost the market, to keep the infrastructure in good conditions and to finance new investments. 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. In this case, technological and institutional innovations were also fundamental to compete with roads in inland transport. The coastal network was probably the one were changes were less visible. Port infrastructure developed considerably, as well as the design of ships and vessels. However, navigation techniques and the introduction of steam was not significant by the date.

III. Data and Methodology:

III.1 Networks

In this section, we describe the databases of historical infrastructures. [7] Roads, waterways and coastal routes have been digitised (see figure 1) in both 1680 and 1830, allowing the benchmark between these two time-slices to be seen in a quantitative way.

[7] The networks were generated as a part of a larger project. For additional information, see: http://www.campop.geog.cam.ac.uk/research/projects/transport/data/

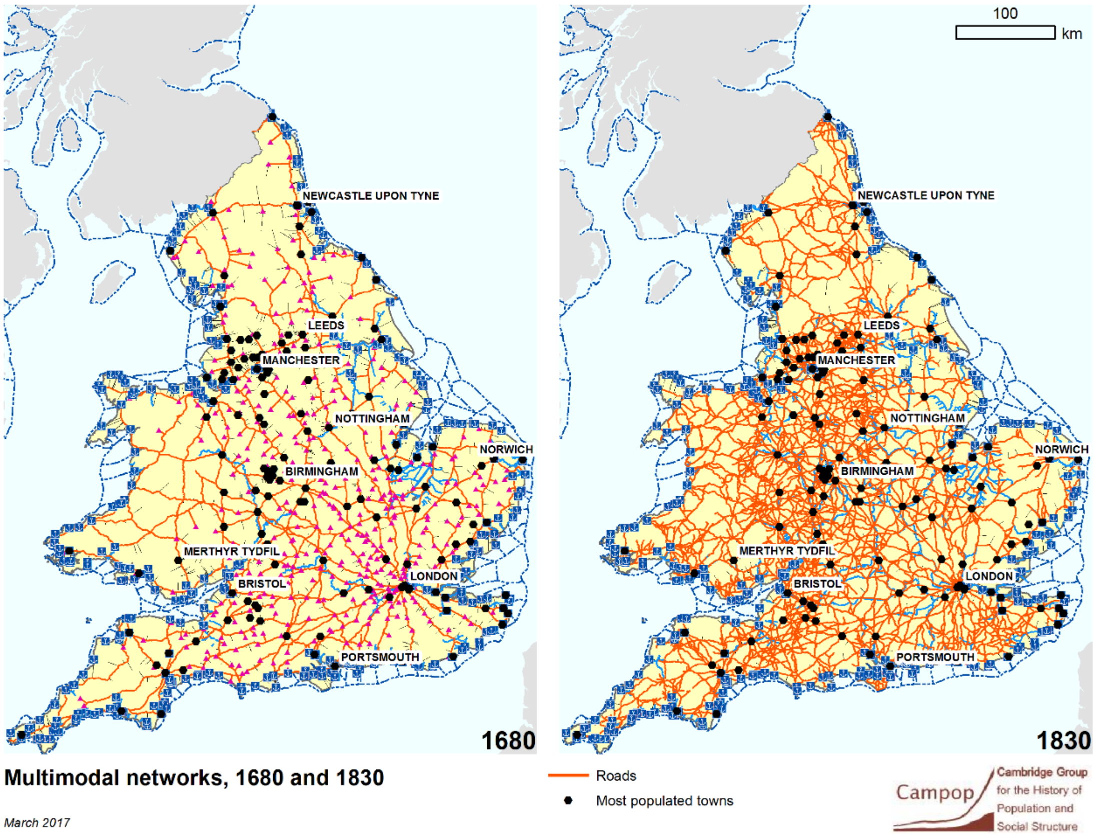


Figure 1. Multi-modal networks (roads, waterways and coastal routes) in 1680 and 1830. Most populated towns are included.

To model road transport in 1680, we use the routes contained in the strip maps of John Ogilby's atlas. The author published in 1675 an extended set of draws of the principal roads in England and Wales. Specifically, 85 routes were plotted, covering over 7,500 miles in total.[8] Ogilby's maps, though, only represented the main roads of the network. Secondary roads and cut-offs were not included by the author. For our purposes, this lack of data could create anomalies, thus we add additional connections to our dataset. Knowing the location of the most important inns and stables of the era, we assume that travellers had to stop in those locations, so they would be located next to secondary roads, if not principal. We connect then those enclaves to the previous database based on Ogilby's maps. The resulting network is what we consider the actual network of the time.

[8] See Max Satchell's digitisation of this historical collection, creating a complete shapefile of the 1680 network. http://www.campop.geog.cam.ac.uk/research/projects/transport/data/roadnetwork1680.html

For road transport in 1830, we use what is called the turnpike network, obtained from a dynamic database of roads covering the period 1695-1896. The data are described in Rosevear et. al. (2017). The data derive in part from acts of parliament that gave powers to bodies and local trustees to improve and expand the network. The law allowed them to levy tolls on the users with the aim of better maintain each segment of the road, which could be existing of newly constructed. This digitisation work was based on John Cary's *New map of England of Wales and a part of Scotland*, digitised using OS 1st ed. as a base map. In order to represent 1830s state of the network, we selected just those roads operating in that specific period of time.

For inland navigation, we have a dynamic dataset of rivers and canals from 1600 to 1948. The dataset is described in Satchell (2017). It uses several sources: the *Ordnance Survey* 1st edition, Richard Dean's *Inland Navigation. A Historical Waterways Map of England and Wales*, Hadfield regional volumes, Willan's *River Navigation in England 1600-1750*, the *Royal Commission on Canals and Waterways* and Salis' *Bradshaw's Canals and Navigable Rivers of England and Wales*. For this specific period, we selected all those waterways in operation, almost exclusively rivers by the date.

In the case of maritime and costal transport, we have created an historical database composed by ports and maritime connections between them. The dataset is described in Alvarez-Palau et. al. (2017). It uses the following sources: *Ports 1540-1700* (Sacks and Lynch, 2016), *A Collection of tracts relative to the law of England from manuscripts* (Hargrave, 1787), *Atlas of Industrialising Britain, 1780-1914* (Langton, 1780), *The Shipowner's and Shipmaster's directory to the port charges, all the depth of water in Great Britain and Ireland* (Daniel 1842), *Ship-master assistant and owner's manual* (Steel, 1826) and *Harbour authorities. Return from the authorities of the harbours of the United Kingdom* (Hopwood, 1903). All ports cited in this sources were digitised using GIS software and categorised by their hierarchical rank when possible. The connections between ports were digitised according to the navigation knowledge of the era and the physical geography of the coast in itself. Bathymetrical maps were used to determine the minimum distance the ships could navigate from the coast. In terms of penetration routes from the cabotage line to the ports, we traced connections maximising the depth and avoiding potential clogging in sandbanks.

The evolution of the size of cited inland networks is shown in figure 2. In the case of waterways, it is clear that navigable rivers were the only available infrastructure until mid c.18th, when canals started to be constructed. The total length of navigation ways almost doubled from 1680 to 1830. In the case of roads, turnpike roads started to develop at the beginning of the c.18th, but the main change in trend arrived between 1750 and 1770 when most of the network was improved. From them on, the infrastructure continued growing but at a more moderated rate. In order to compare the previous tendencies, we have also plotted Ogilby roads in 1680. The total length of turnpike roads in 1830 tripled the extension of main roads in the first period. All in all, we can conclude that in quantitative ways, waterways doubled and roads tripled their total length between our benchmarking years.

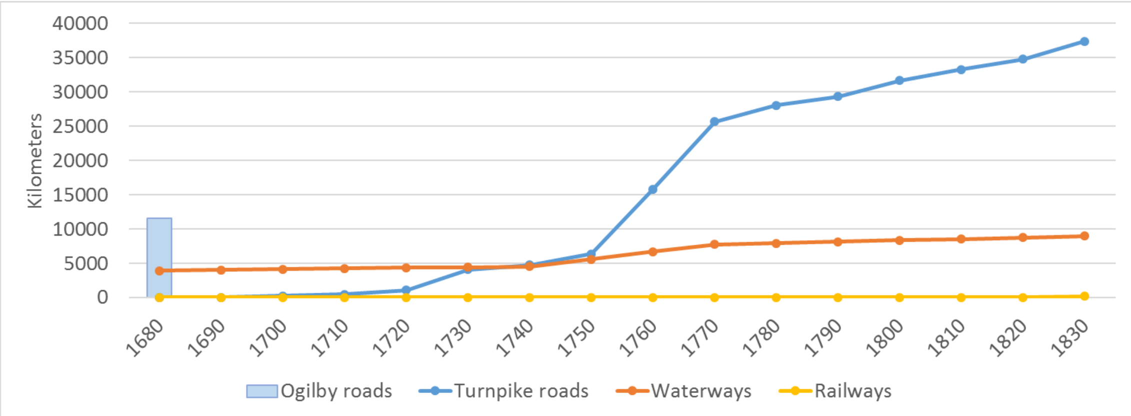


Figure 2. Evolution of inland transport systems, 1680 – 1830.

III.2 Towns

Our analysis of transport networks focuses on towns. This is not so say that rural areas are unimportant. We focus on towns more for analytical tractability. It is relatively straightforward to analyse the transport connections between several hundred points representing towns, but much more difficult to analyse connections between more than 10,000 points representing rural parishes. Therefore, for practical purposes, we focus on travel between the 100 most populous towns in 1680 and 1830. Towns in 1680 are drawn from Langton (2000)'s list, which provides estimates of town population in the late 17th century. Town in 1830 are taken from Law (1967) and Robson (2006). We use the 1841 population for our analytical purposes. The results are not very different if we used population in 1831.

There are a few items worth noting about our sample of towns. There are 46 in the top 100 in 1680 which are not in the top in 1841. Thus, we add 46 additional towns to get the top 100 in 1841. In total, we study 146 towns in one or both lists.

The 146 towns are shown as proportional circles in the figure 3. The top ten regional towns in 1801 are shown as a reference. The density of the urban network and the transport network overlap greatly especially in 1830. The towns that are large in 1680 or became large by 1841 are well connected. Notably many of the towns in the northwest that became large by 1841 do not have good transport connections in 1680.

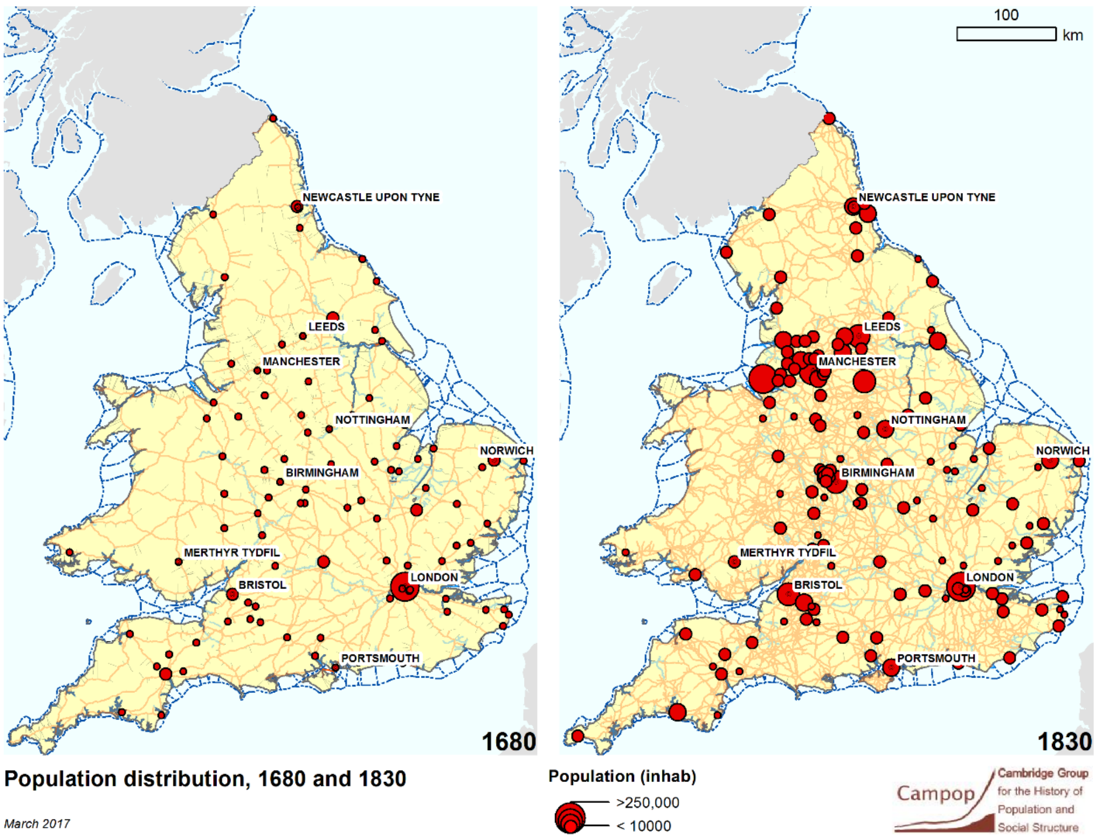


Figure 3. Population distribution in 1680 and 1830. The size of each urban settlement is proportional to their total population.

III.3 Multi-modal Model

We benefit from the development of detailed HGIS databases for each network to propose an innovative method to analyse the whole transport system: a Historical Multi-modal Network Analysis. 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 networks. Time and cost parameters for both passengers and freight are used as the impedance of the model to solve the least-cost-path equation in two time-slices: 1680 and 1830.

The framework of the multi-modal model can be observed in the figure 4. 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.

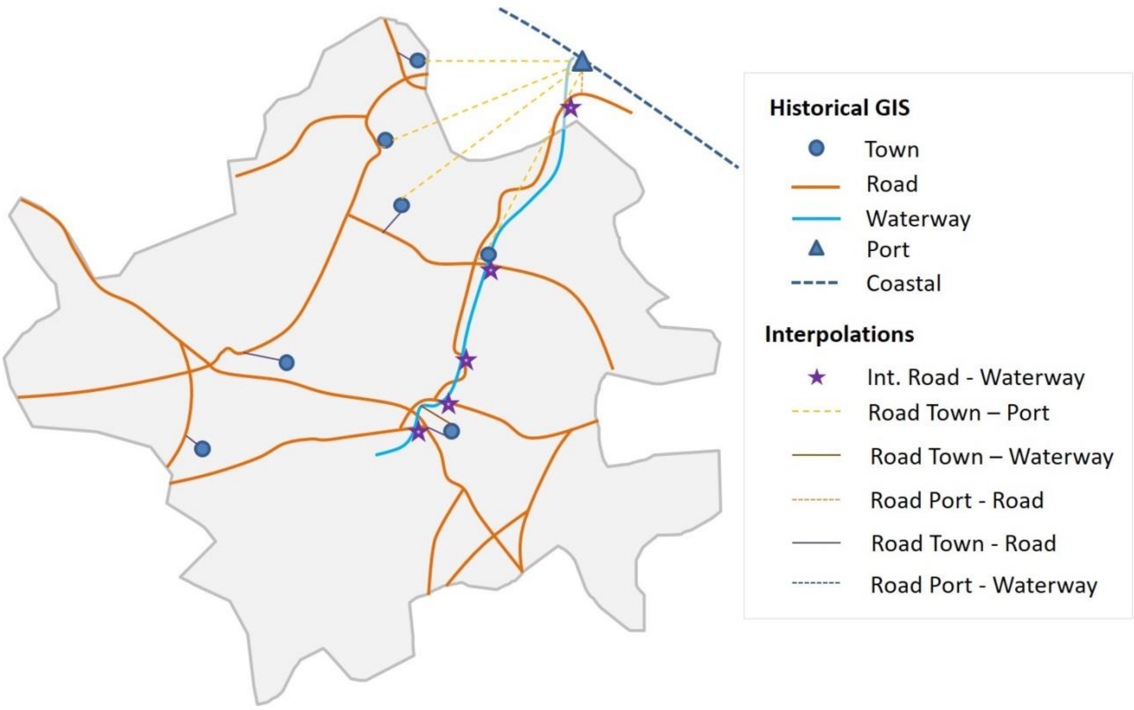


Figure 4. Multi-modal model framework: roads, waterways, coastal routes, towns, ports and their interpolated interconnections.

Following the description of the networks developed in the previous section, we build the 1680 multi-modal model. Ogilby's roads, the navigable rivers and the coastal routes have been digitised as lines and incorporated as a basis of the model. All those features have been topologically cleaned in other to avoid little gaps and disconnections due to the precision of the digitisation. The most populated towns and the historical ports have also been added with the aim to assign punctual information and determine specific routes between them. The software, however, requires an additional step to route between its origins and destinations. To ensure the connectivity of the model, and to avoid inconsistent routing problems, we create a set of interpolated lines between our point layers, towns and ports, and the respective networks; roads, waterways and coastal. This lines are created as a straight lines from the points to the nearest network, imposing certain restrictions. Each town is connected to the road network at its nearest point using an interpolated line. Thus every town is connected to one another by road. Towns may or may not be connected to inland waterways and ports with interpolated lines. Towns are connected to its nearest waterway if they are within 2km of the waterway and to ports if they are within 10 km of a port. Finally, those connections have been visually checked to avoid inconsistences. The same procedure has been implemented in 1830, creating an equivalent model with the new set of databases.

Once the model is created, 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 popular terminology, if someone is driving a packhorse in an Ogilby road, and this road intersects a river, we allow the transhipment to the river without restrictions. This policy may overestimate modal changes; thus, we are aiming to impose specific restrictions in the next version of the model. The policy of connectivity is also global. All the networks are considered at the same level and interconnected between them. The only restriction is that to allow the transhipment, both networks must have a vertex in common.

ESRI ArcGIS software is used to carry on with the analysis. The network analysis tools of ESRI are based on the Dijkstra's algorithm for finding the shortest paths.[9] More specifically, we use the OD matrix solver for distance, time and cost. Current multi-

[9] According to ESRI website:

> *"The classic Dijkstra's algorithm solves the single-source, shortest-path problem on a weighted graph. To find a shortest path from starting location s to destination location d, Dijkstra's algorithm maintains a set of junctions, S , whose final shortest path from s has already been computed. The algorithm repeatedly finds a junction in the set of junctions that has the minimum shortest-path estimate, adds it to the set of junctions S, and updates the shortest-path estimates of all neighbours of this junction that are not in S. The algorithm continues until the destination junction is added to S."*

For more information, see ESRI website: http://webhelp.esri.com/arcgisdesktop/9.3/index.cfm?TopicName=Algorithms_used_by_Network_Analyst modal networks rely on the minimization of accessibility functions composed by a sum of several factors. The accessibility between points i and j A_{ij} is given by equation (1). It is the sum of access from the origin of the journey to the network (a_i^o), the transport accessibility in the n transport modes between p and q (a_{pq}^n), the accessibility of each transhipment between modes r (a_r^t), and the access to reach the final destination (a_j^t). At the moment, transhipment costs a_r^t are discarded because of the lack of reliable historical data to assess the interconnections.

$$A_{ij} = a_i^o + \sum a_{pq}^n + \sum a_r^t + a_j^d \qquad (1)$$

The accessibility equation in terms of distance can be seen hereafter without the transhipment element. In this case, only access to the network and the transport through all the involved modes are considered as in equation (2):

$$D_{ij} = \min\left[d_i^o + d_{ab}^c + d_{bc}^r + d_{cd}^w + d_j^d\right]; \qquad i = 1 \ldots k;\ j = 1 \ldots k \qquad (2)$$

where D_{ij} is a matrix $k_x k$ with the total length between each town, d_i^o is the distance from the town i to the network, d_{ab}^c is the distance by costal, d_{bc}^r is the distance by road, d_{cd}^w is the distance by waterway and d_j^d is the distance from the network to the destination town j. Note that the variable distance can be substituted by time or cost.

Each mode of transport has been assigned a unique speed or cost value for each time-slice, or what we call the parameter value. Dijkstra's algorithm uses the parameter values to estimate the shortest or least-cost-path between the origins and destinations supplied. The parameters are reported in constant per mile units and are linearly related to the length of the network segment. In terms of time, the length is multiplied by the average speed to obtain the time spent in each segment. In terms of cost, the length is multiplied by the unit cost of moving passengers or freight.

III.4 Parameters

In choosing parameters our general approach was to identify costs and speeds reported in the secondary literature. In the future, we plan to add archival sources, which will enrich the analysis. We begin with parameters for 1680.

The assumed average passenger speed by road in 1680 is 2.0 miles per hour. The speed is based on Gerhold (2005, app. 8), who gives observations on passenger journey times in days between 1680 and 1712. The journeys included stops along the way, such as overnights at inns and rest. We do not model journeys based on when they started in the day and at what time of day they stopped. Instead we calculate speeds based on miles per journey hour, not miles per hour while traveling. Specifically, we divide the mile distance of journeys by days travelled and divide again by 24 to get miles per journey hour. The average across the observations in Gerhold (2005) is 2.0 mph. There is a distinction between journeys in winter and summer. For the moment, we do not incorporate this difference.

The assumed freight speed by road in 1680 is 1 mph. Again, this figure is based on miles per journey hour. According to Gerhold (2005, app. 4, p. 57), carrier miles per day ranged between 20 and 24. Also, in a sample of freight travel time observations the average is approximately 24 miles per day (Gerhold 2005, app. 8).

The assumed road passenger fare in 1680 is 2.2 pence per passenger mile. The estimate comes from an average of passenger fare observations given in Gerhold (2005) between 1680 and 1712. Gerhold (2005) also gives observations on wagon freight rates in pence per ton mile. The average is 10.7 pence. We use this as our parameter for all roads in 1680.

Speeds and fares on inland waterways are difficult to estimate because of limited data. Willan (1964, p. 102) reports the travel time for boats on the Welland and Ouse rivers. The speeds are 1.6 mph. We use this value for passengers and freight. Passenger fares per mile are based on London waterman rates in Delaune (1690, pp. 362-364). We calculate distances of the observations and generated an average passenger fare per mile of 0.4 pence. The average rate does not distinguish between upstream and downstream journeys. The freight cost on inland waterways is 1 pence per ton mile. It is taken from a general assessment by Willan (1964).

Coastal shipping speeds are not reported anywhere in the literature to our knowledge. But there is information in archival sources, like the Port Books.[10] For some journeys, the Port Books report the date a ship's coastal bond was posted and the date when it was cancelled. We transcribed a sample of journeys for Colchester and Maldon to London in the 1650s. After deducting 1 day for bond processing, and dividing by

[10] The Port Books are available at the National Archive in the E122 series.

distance (110 miles) we obtain an average speed of 1.1 miles per hour. We use this speed for passenger and freight travel. There is no evidence for dedicated passenger vessels in the 17th century. Note these speeds do not reflect maximum speed in water, because they include waiting for wind, and anchoring at night. Notably the fastest speed observed in our sample is 2.3 mph which may approximate the maximum speed in the water for coastal shipping in the 17th century.

There is little information on passenger fares by coastal vessel. In this case, we need to make an approximation. The waterman's rate between London and Gravesend reported in Delaune (1690, pp. 362-364) is reasonable because it is a longer journey. Dividing this waterman rate by the distance gives 0.3 pence per passenger mile. We use this as our parameter value for passenger fares by coastal vessel.

Coastal freight services are widely discussed in the literature, especially the trade between Newcastle upon Tyne and London. Hausman (1987) gives information on coastal rates and distinguishes between shipping costs and taxes. Hausman also distinguishes between war and peace years. At the moment, we average the costs in war and peace years to keep the model simple. The result is a 0.48 pence per ton mile coastal freight rate.[11] In terms of transhipment costs, Willan provides a detailed costing of a Newcastle voyage in 1729. In total, the tolls, charges, and labour in ports average to be 21.5 pence per ton.[12] We assume this cost is incurred any time a ship enters a port.

Our model also allows travel by ferry. Delaune (1690 p. 363) reports the 2 pence fare for a sculler over the Thames river directly between Limehouse and Vauxhill in London. We assume all coaches and wagons pay the 2 pence to cross at a ferry.

[11] In war years during the 1690s, Hausman reports the shipping cost is 14.9 shillings per ton and the tax is 2.5 shillings per ton. Using a distance of 381 miles by coast between Tyne and London implies a 0.48 pence per ton mile shipping cost in war years and 0.08 pence per ton mile tax. If the tax is recorded as a flat fee then the tax cost is 30 pence per ton. In peace years, Hausman says the shipping cost is 7.3 shillings per ton and the tax is 6.0 shillings per ton. The shipping cost is 0.24 pence per ton mile and the tax is 0.19 pence per ton mile. If the tax is recorded as a flat fee the cost is 72 pence per ton.

[12] The taxes paid in London are 66 pence per ton. In Newcastle, the tolls 1.1 pence per ton and charges combined 9.4 pence per ton. In London tolls are 10.9 pence. So the average is 10 pence. The labour in Newcastle is 3.8 pence per ton. In London the labour is 11.8 pence per ton. The average is 11.5 pence per ton.

III.3.b 1830 Parameters

The 1830 parameters for passenger and freight by road are taken from Gerhold (1996, 2014). They are again based on miles per journey hour, not miles per hour while travelling. The assumed passenger speed is 8.7 mph, which is the average speed in Gerhold's (2014) sample for journeys 80 miles and above. The assume freight speed by road is 2 mph reported in Gerhold (1996, p. 500, app. 4, p. 57). The assumed fare per passenger mile is 2.2 pence. Gerhold (2014, p. 821) gives an estimate of 3.0 pence per passenger mile inside and 1.5 pence per passenger mile outside. We use the average. The freight rate by road is taken from freight rates between Leeds and London. The average from 1825 to 1836 reported in Gerhold (1996) is 84 pence per hundred weight. The distance is 182 miles, implying a freight rate of 9.2 pence per ton mile. We use this figure for all roads in 1830.

The 1830 freight and passenger speed on inland waterways is 1.25 mph. The speeds are taken from Skey (1841, p. 8), who reports that bulk carriers reach 30 miles a day, travelling 16 hours a day. Following our emphasis on miles per journey hour we get a speed of 1.25. Passenger fares by inland waterway come from waterman's rates reported in the Kent's Directory (Kent Causton 1827). Incorporating our estimates of distances for the routes given, the average rate per passenger mile (upstream and downstream) is 1.0 pence.

The assumed freight rate by inland waterway is 1.3 pence per ton mile in 1830. Maw (2013) notes that freight rates by canal are typically 1/3 the rate of road. This would imply a 3.1 pence per ton mile using our freight rate per mile by road. The freight rate by tidal river is thought to be 1/10 by road. This would imply a 0.9 pence per ton mile. Approximately 19% of the waterway network is tidal and therefore subject to the lower freight rate, and 81% is non-tidal and subject to the canal rate. The weighted average freight rate is 1.3 pence per ton mile, which is what we use.

Currently we do not have robust information on coastal travel speeds and fares in 1830. Archival sources are being developed, which will greatly improve our knowledge. For the moment, we use a single archival source for speeds. The log of the Sancho, a coastal sailing vessel, reports voyage times over the year in 1848. The average miles per hour is 2.9. We use this figure for 1830. The assumed passenger fare by coastal vessel is 1.2 pence per passenger mile. We use the London to Gravesend waterman's rate reported in the 1827 Kent's directory.

The assumed freight rate by coastal vessel is 0.32 pence per ton mile. We use Hausman's (1987) estimates between Newcastle upon Tyne and London. The same source was used in 1680.

The flat rate for passengers and wagons to cross a ferry is 2 pence per ton or per person. Kent's 1827 directory (Kent Causton 1827, p. 24) reports that a sculler boat over the water between Windsor and Greenwich is 2 pence per passenger.

The full set of parameters is summarized in table 1. These are the parameters we use for each network in our model in each time-slice. Values are shown with their units and the source we rely on.

Table 01. Speed and Cost parameters used in the multi-modal models, 1680 and 1830.

	Units	1680	Source	1830	Source	Δ	Δ/year
Passenger speed							
Coastal	*mph*	1.10	*E122*	2.90	*Sancho 1848*	164%	1.09%
Waterway	*mph*	1.60	*Willam 1964*	1.25	*Skey 1841*	-22%	-0.15%
Road	*mph*	2.00	*Gerhold 2005*	8.70	*Gerhold 2004*	335%	2.23%
Freight speed							
Coastal	*mph*	1.10	*E122*	2.90	*Sancho 1848*	164%	1.09%
Waterway	*mph*	1.60	*Willan 1964*	1.25	*Skey 1841*	-22%	-0.15%
Road	*mph*	1.00	*Gerhold 2005*	2.00	*Gerhold 1996*	100%	0.67%
Transhipment time							
Port	*days*	-	-	6	*Sancho 1848*	-	-
Passenger cost							
Coastal	*pppm*	0.30	*Delaune*	1.20	*Kent's dir. 1824*	300%	2.00%
Waterway	*pppm*	0.40	*Delaune*	1.00	*Kent's dir. 1824*	150%	1.00%
Road	*pppm*	2.20	*Gerhold 2005*	3.00	*Gerhold 2014*	36%	0.24%
Freight cost							
Coastal	*pptm*	0.48	*Hausman 1987*	0.53	*Hausman 1987*	10%	0.07%
Waterway	*pptm*	1.00	*Willan 1964*	1.30	*Maw*	30%	0.20%
Road	*pptm*	10.70	*Gerhold 2005*	9.20	*Gerhold 1996*	-14%	-0.09%
Transhipment cost							
Port	*ppt*	21.5	*Willam 1964*	-	-	-	-

The comparison between parameters in both time periods suggests some preliminary conclusions. Passenger speed increases in average at a 1.06% annual rate, with huge improvements in roads (2.23%) and a slightly decrease in waterways (-0.15%) due to the lower average speed in canals in relation to rivers. Obviously, the first steamboats emerged in 1830, allowing to reach 3.50 mph. But, their diffusion was still limited. In terms of freight speed, the average annual increase is more moderated:

0.54%. Being that both waterways and coastal remained very similar, the difference with passenger speeds is due to roads. In average terms, carriers travelled at lower speeds. Passenger costs increases at 1.08%, with important increases in coastal (2.00%) and waterways (1.00%), and a slightly increase in roads (0.24%). What is striking is that both, coastal and waterways, could increase their fares at a higher rate than their speeds, whilst roads experienced the opposite effect. Improvements in the infrastructure and the gradual increase of carriers' availability seem the most reasonable explanations. In terms of freight cost, the average annual increase is 0.06%, almost negligible. It means that the increase in speeds and reliability raises passenger costs, but has little effect in freight costs.

IV Results

IV.1 Travel times and transport costs to London and Manchester

This sub-section uses the results of our multi-modal transport model to analyse transport costs for the most populated towns in 1680 and 1830. The estimated travel times and freight costs to London and Manchester is a useful place to start. London was the sprawling capital of the country and Manchester emerged as its industrial base in the 18th century.

Isochrone maps measure zones with similar travel times to a location. The results are shown in figure 5 for passenger travel to London. In 1680, moving from the centre of London to its surroundings can take almost 10 hours. Almost 25 are needed to reach Cambridge or Oxford, and 50 to reach Bristol, Birmingham, Kings Lynn or Norwich. Reaching Liverpool can take over 100 hours, and almost 150 are needed to arrive to Newcastle. It gives an idea about how slow was to travel in that period. In 1830, however, the geographical landscape is completely different. Total travel times are divided almost by 4. Kings Lynn, Birmingham and Bristol can be reached within 15 hours and just 25 hours are needed to arrive Liverpool.

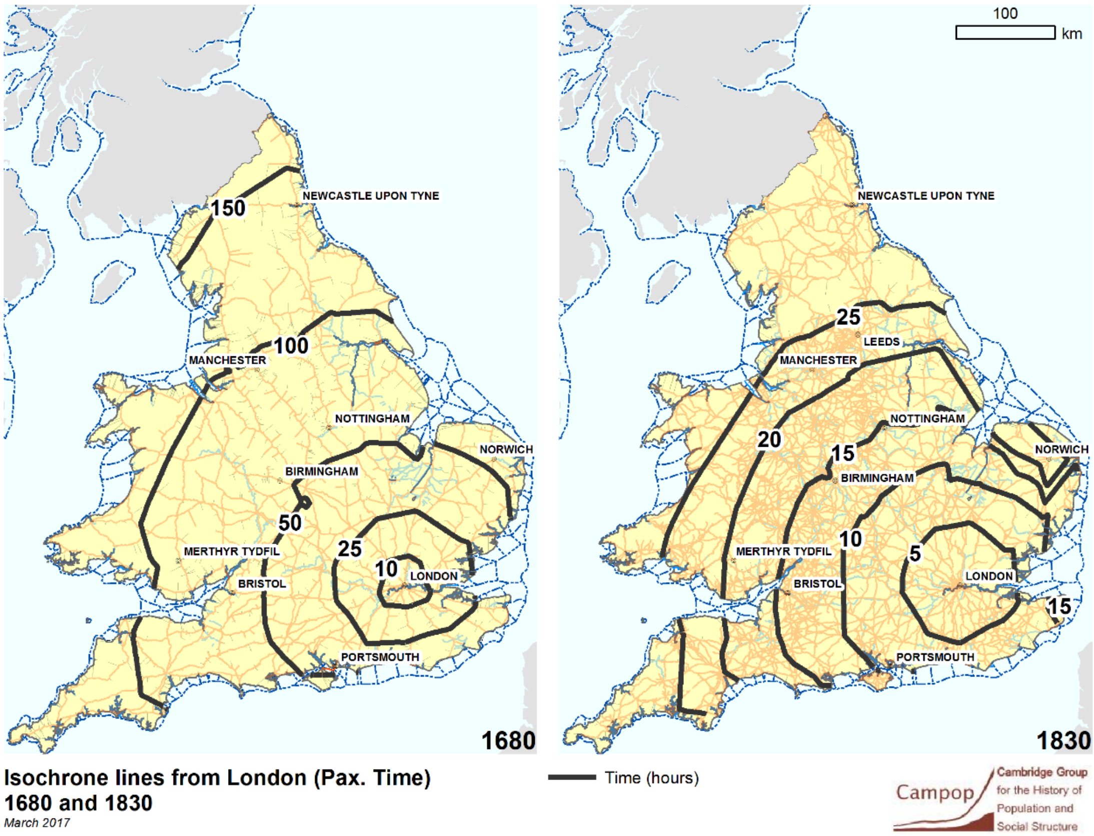


Figure 05. Isochrone lines from London for passenger time in 1680 and 1830.

The reader should be aware that London is the settlement with better connectivity due to the shape of the transport networks. Around the capital, roads are designed in a radial way, boosting the capital's accessibility. In other parts of the country, the improvements in accessibility were less, remaining more isolated.

Isocost maps measure zones with similar transport costs to a location. The results are shown in figure 6 for passenger travel to Manchester. The results are striking. In 1680, the shape of the isocost lines denote an apparent lack of connection. Manchester is relatively well connected with Beaumaris and Carlisle, but has problems to surpass the Pennines and to reach central Wales. This phenomenon is denoted by the proximity of the isocost lines. The only direction with good connections is the corridor to Birmingham, that allows the connection with the centre of England. Another striking feature is the creation of islands of poor connectivity. This is the case of southern Wales or the Wiltshire country, remaining at poorer levels than their neighbourhoods. By 1830 the landscape completely changes. The isocost lines are well defined, showing a homogeneous distribution of accessibility to Manchester across the country. This is a clear example of how the expansion of the road network helped to improve inland transports, creating reliable connections and allowing the economy to benefit from this effect.

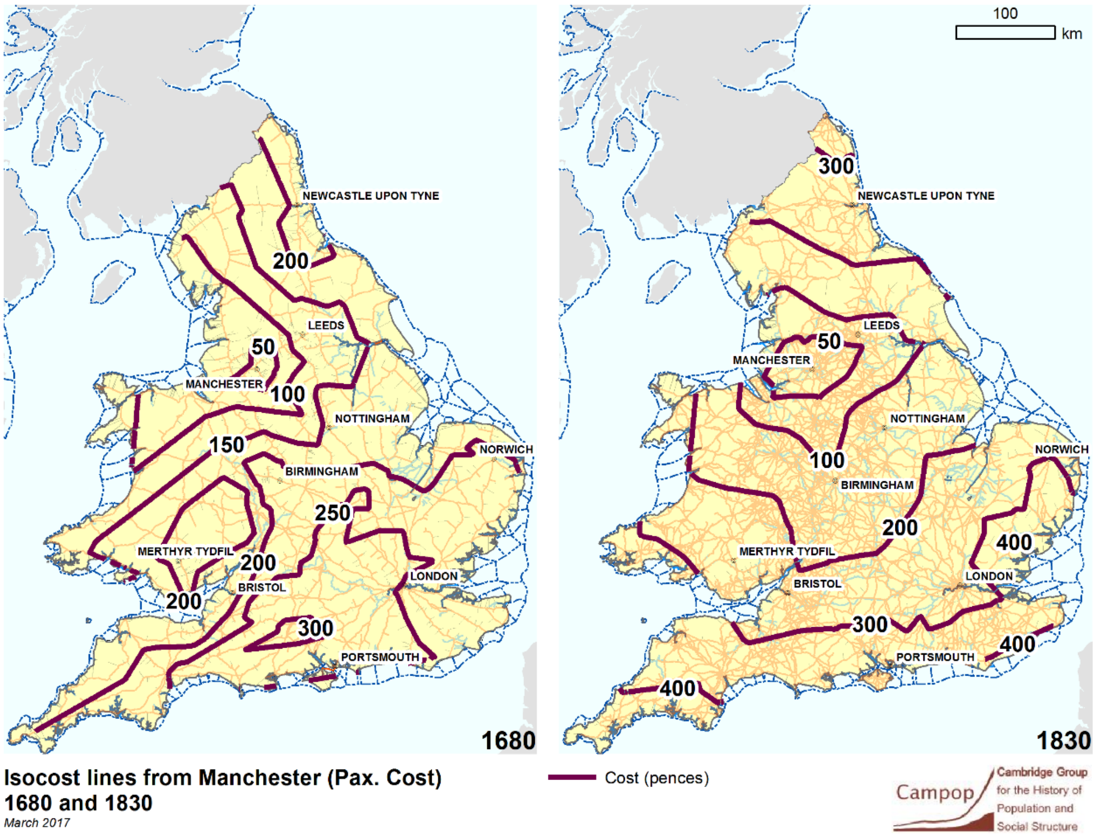
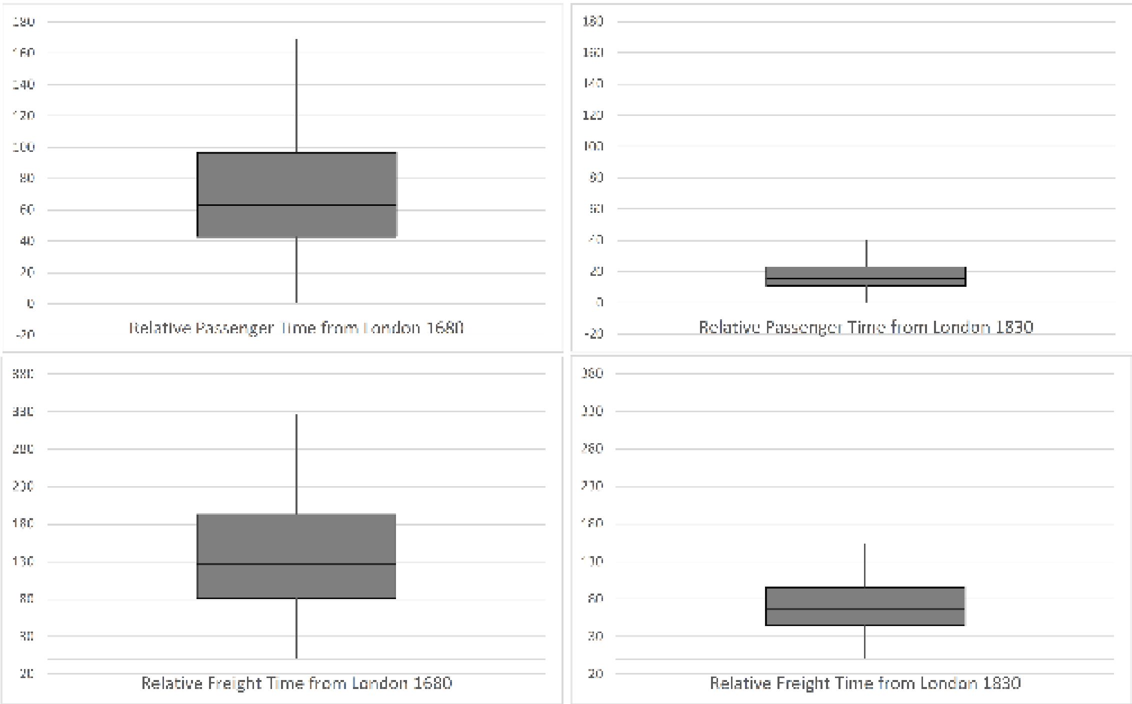


Figure 6: Isocost lines from Machester for passenger cost in 1680 and 1830.

The previous examples and the complete series of figures in the appendices help illustrate changes in the geography of transport for London and Manchester. Figure 7 gives a quantitative assessment by showing box plots for passenger time, freight time, passenger cost and freight costs to London. Regarding passenger times, in 1680 the median time from London is 62.98 hours, while quartile 1 (Q1) and quartile 3 (Q3) are 42.98 and 96.76 respectively. In 1830 the picture is notably different. The median time is 15.52 hours, while Q1 and Q3 are 10.98 and 22.96. The differences in values confirm an average drop by a factor of 4, as spotted in the graphical analysis. In terms of freight time, the median decreases from 125.97 in 1680 to 65.93 in 1830. The first and third quartiles decrease from 81.40 to 44.94, and from 192.95 to 95.74, respectively. In this case, the values halve. Regarding passenger costs, in 1680 the median cost is 152.70 pence, while Q1 and Q3 are 93.71 and 210.26 respectively. In 1830 the picture is notably different. The median cost is 201 pence, while Q1 and Q3 are 146.90 and 282.82. The differences in values confirm an average increase by a factor of 1/4. In terms of freight cost, the median decreases from 376.72 in 1680 to 221.04 in 1830. The first and third quartiles decrease from 183.96 to 159.21, and from 628.47 to 280.72, respectively. Overall, the resulting pattern is driven by two factors: an important change in average values but also a statistical convergence. The network in 1830 was much more homogeneous than in 1680, allowing the integration of the national market and reducing spatial inequalities.



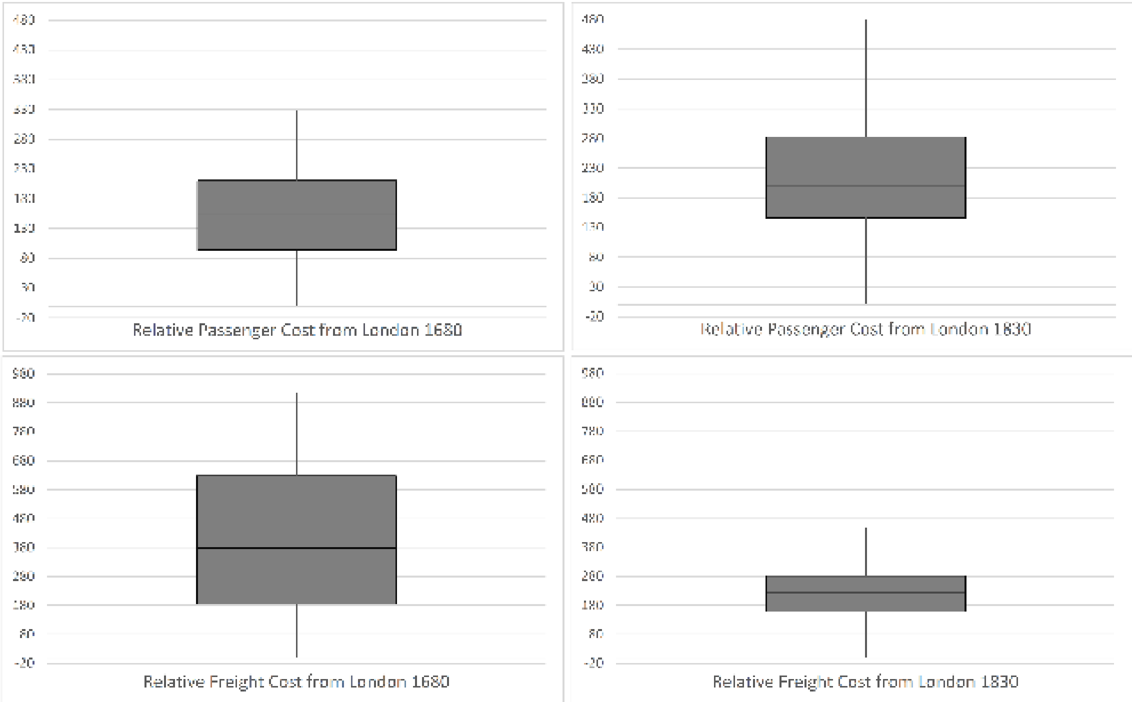


Figure 7. Box plot distribution of the variables passenger time, passenger cost, freight time and freight cost in 1680 (left) and 1830 (right).

A complementary analysis illustrates the differences between inland and costal transport. From the initial set of 146 towns, we select those located at less than 5 kilometres to the coast, assuming they have a port nearby. In total, there are 50 towns. From this list of 50, we isolate their columns in the model's time or cost matrix and select the minimum value for each row. This way, we obtain the access value to the nearest city port. This exercise is repeated for the 4 variables defined by the combination passenger/freight and time/cost.

Figure 8 plots the result of this exercise for freight time. The 1680 picture shows how the 10-hours isochrone approaches the coastline in a different manner. In London, in the Cornwall peninsula and in north Wales the lines are more separated, whilst in south Wales or Lancashire they are very close. The worst connected places are in central England and southern Wales within 50-hours intervals. Leeds, Nottingham or Birmingham are in this harsh situation, diminishing their potential to growth in economic terms. In 1830, the picture is different. The most isolated places are within 25 hours to the coast, halving the initial situation. Southern Wales, for instance, is better connected. East Anglia's situation deteriorates. The surroundings of Norwich are reasonably well connected by roads in 1680, but the development of turnpikes is lagging in the region. It created an important lack of accessibility.

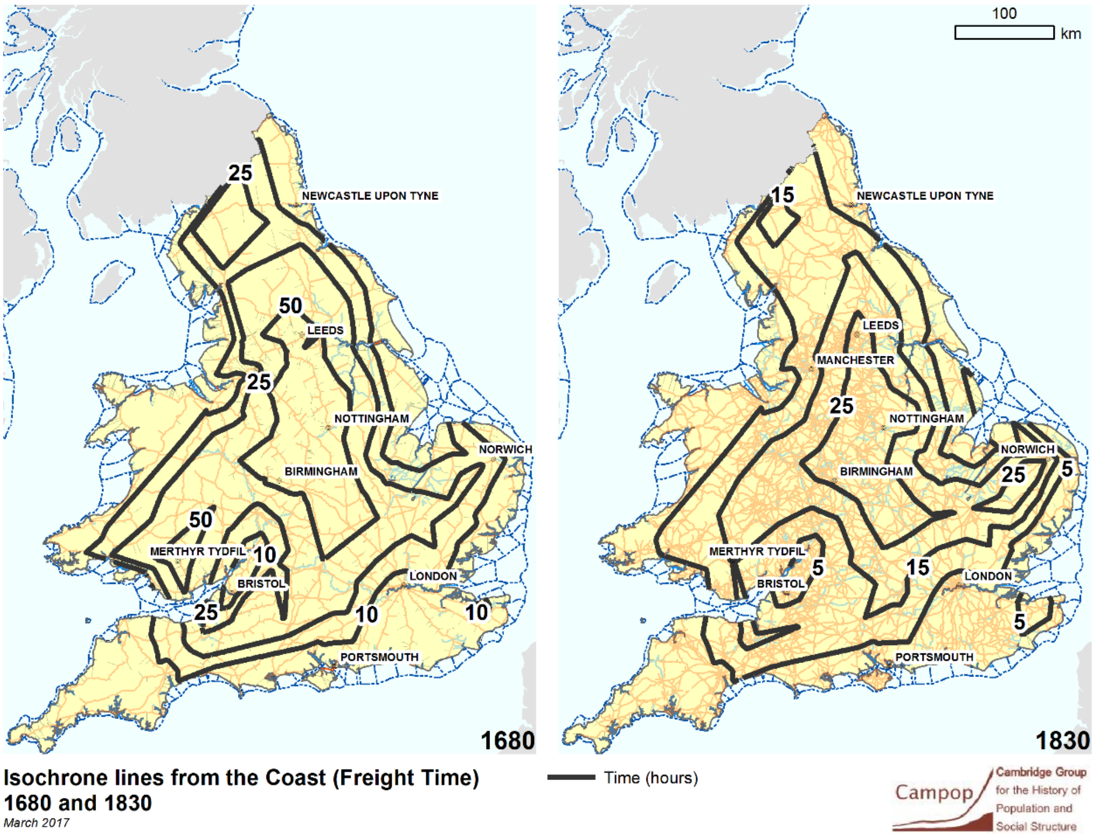


Figure 8. Isochrone lines from the coast for freight time in 1680 and 1830.

IV.2 Average travel times and transport costs across towns

In this section, we measure accessibility using common indicators from transport planning (Morris et al. 1979). In terms of passenger travel time, the Accessibility Index is defined by the average of passenger times from each town j to all the others. It can be mathematically described as follows:

$$AI^j = \frac{\sum_{i=1;\, j=1}^{k} T_{ij}}{k}$$

Where T_{ij} denotes the time spent in every OD relation and k is the total number of towns considered in the set. The same index is defined using the related indicators for freight times, freight costs, and passenger costs.

Average passenger travel times for the 146 towns are plotted in figure 9. The results are clear: accessibility improved massively. In 1680, those towns geographically central (imagine a rectangle with corners in London-Bristol-Liverpool-Lincoln) show average travel times over 50 hours, whilst the most peripheral and isolated ones are over 125 hours. In contrast, a century and a half later, the central areas have an average time under 20 hours and those peripherals do not exceed 50 hours in any case.

The same exercise has also been repeated for freight time (see figure 10). Birmingham's surroundings show the best performance in the first period, with average values between 75 and 100 hours. Manchester and London show values slightly over 125 hours, whilst the most peripheral parts of the country almost 300. In the second period, the effect is quite similar at the one described by passenger times. The central rectangle London-Bristol-Liverpool-Lincoln is connected at an average of 50 hours. The most peripheral and least connected town, Penzance, shows an average indicator slightly over 125 hours. In this case, the comparison between periods shows a clear expansion of what we call the geographically central towns, but also a huge decrease at the periphery, halving the initial values.

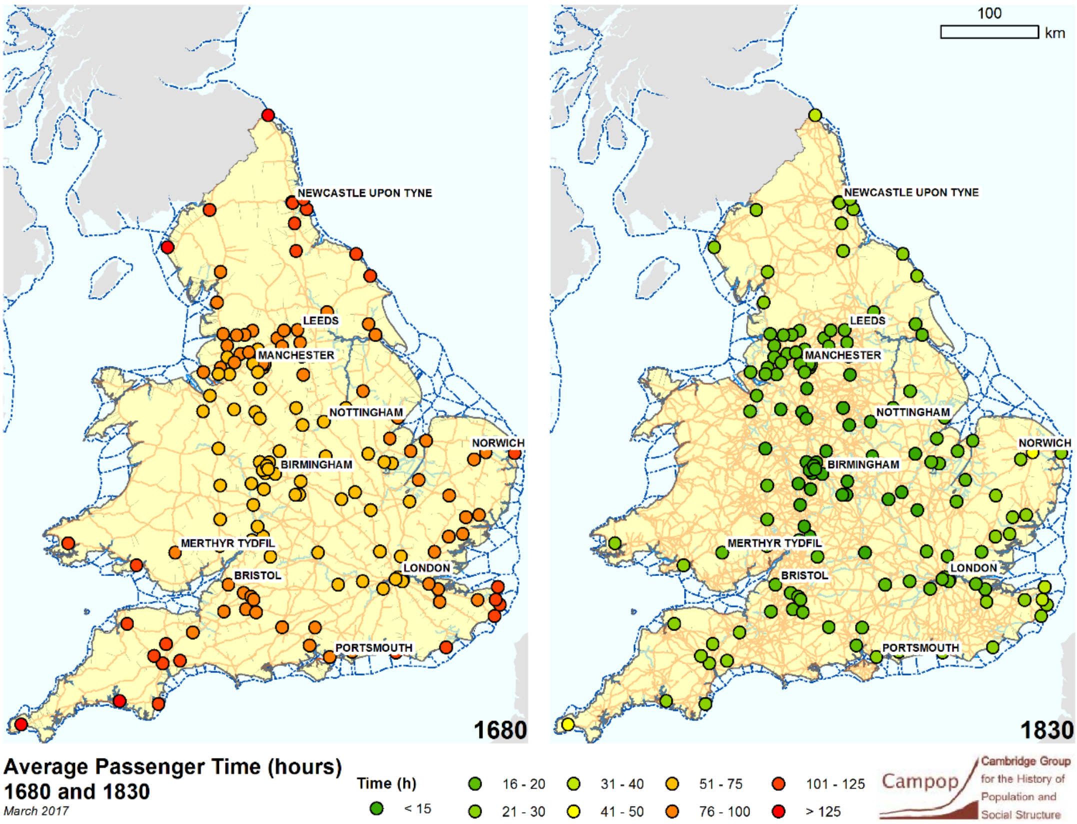


Figure 9. Average passenger times in 1680 and 1830.

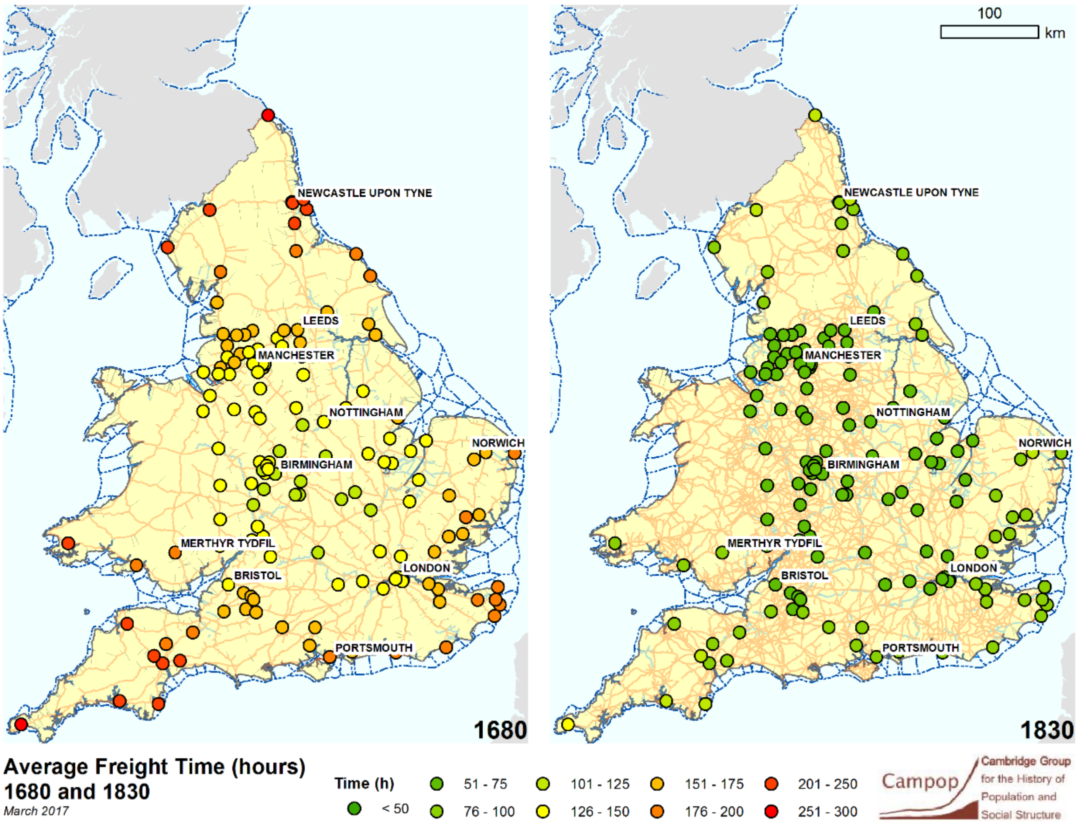


Figure 10: Average freight times in 1680 and 1830.

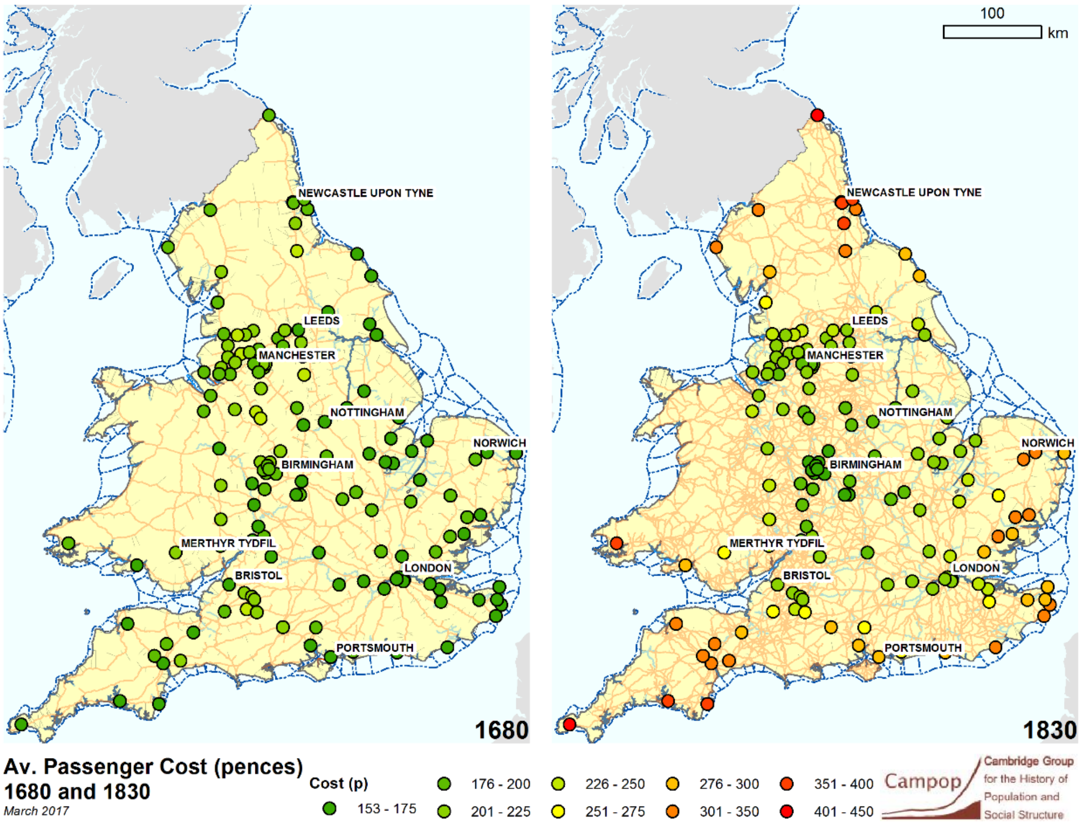


Figure 11: Average passenger costs in 1680 and 1830.

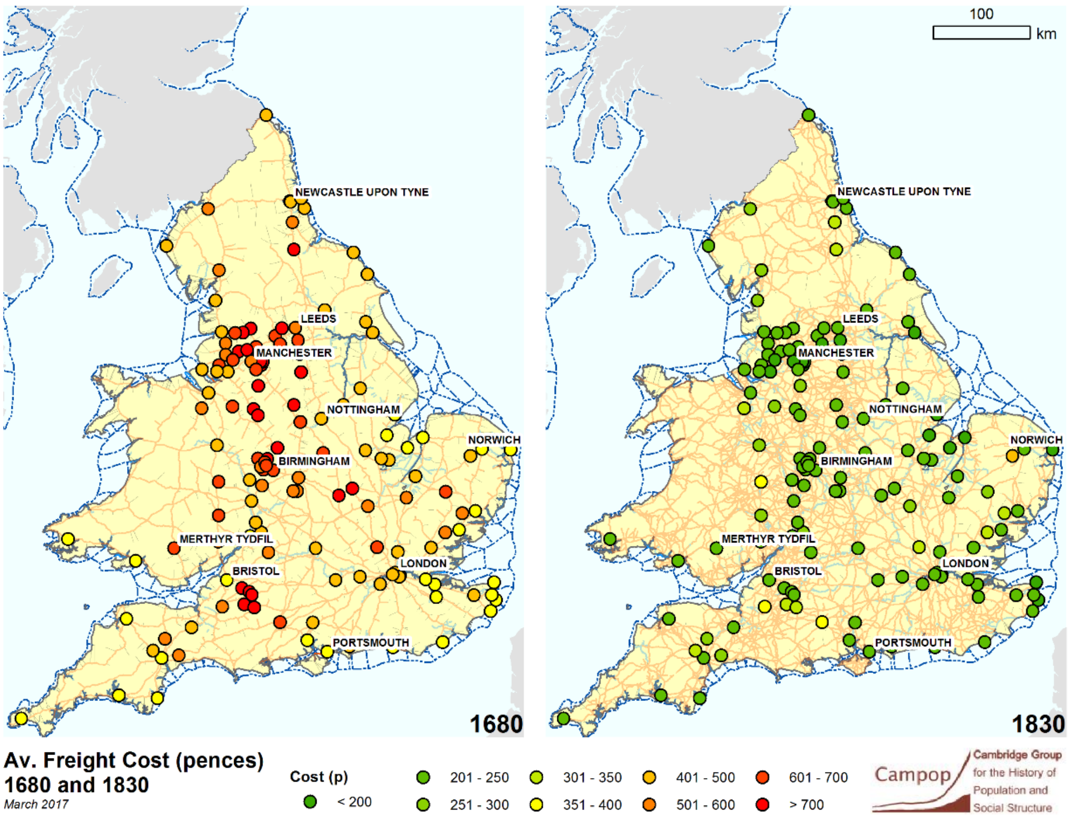


Figure 12: Average freight costs in 1680 and 1830.

The accessibility indices based on passenger costs show a different pattern. As explained in section 2.3, passenger costs notably increased between 1680 and 1830, driven by more expensive fares in both roads and canals. The results of the analysis reflect this tendency. In 1680, most of the country shows costs under 225 pence, although not homogeny distributed in geographical terms. The pattern in 1830 is much more clear. Towns in the rectangle London-Bristol-Liverpool-Lincoln keep costs under 200 pence but, beyond, the prices start to raise sharply, reaching values about 450 pence.

The accessibility indices for freight costs exhibit patterns similar to the first two indicators. Costs in 1680 were notably lower, whilst in 1830 more homogeneity and lower costs are shown. In the first period, coastal routes are the cheapest mode of transport by large. It means the costs near ports are lower, and gradually increase while moving inlands. It can explain the hotspot around Birmingham, were average costs almost reached 700 pence. The east coast registers the lower values, under 400 pence. In the second period, waterways and canals allow the transport of goods inlands. In this case, costs start to converge, staying almost all of them below 350 pence.

The aggregated values of the accessibility indicators give the overall tendency across years. The aggregates are the average travel time or cost across the towns, or the overall averages. Table 2 summarizes results. With the exception of passenger costs, accessibility changes are considerable within the studied period. The final column shows the percentage change in annual terms.

Table 2: Estimates of average transport costs and travel times between major towns

	1680	1830	Annual percent change
Average Time Passenger travel in hours	83.66	18.88	-0.988
Average Time Freight travel in hours	158.99	74.38	-0.505
Average Cost pence per passenger	184.56	242.06	0.181
Average Cost pence per ton	535.17	230.21	-0.561

IV.3 Rates of change in transport costs

In this section, we estimate the rates of change in transport costs relative to the rate of change in consumer prices. We will emphasize the generalized transport cost.

For freight, the generalized cost will include the freight cost per ton and the inventory cost per ton. For passengers, the generalized cost will include the passenger fare and the value of lost time for passengers. The identity of the representative passenger is crucial in this calculation because it determines the value of their time.

We begin with freight. The baseline price of freight services is taken from the average freight rate between all town pairs calculated in our model. The average annual percentage decrease in freight rates between 1680 and 1830 is -0.561% as seen in table 2. According to Clark (2010), consumer prices increased at the rate of 0.36% per year between 1680 and 1830. Together they imply a -0.92% annual change in real freight transport costs. This is substantial, and as we will see below, it implies large change in the relative price of transport.

How does this conclusion change if inventory costs are added? Inventory costs are a function of the time goods spent in transit, the interest rate, and the price of goods. If the hourly interest rate in % is r, the price of the good is p in tons, and the hours spent in transit is t then the inventory cost is (r/100)*p*t. According to our network model, the average hours in freight transit is 159 in 1680 and 74 in 1830. The hourly interest rate in 1680 is 0.00054% and 0.0004% in 1830, which are calculated by dividing the interest rate by 365*24. Thus the term (r/100)*t is 0.00029 in 1830 and 0.00086 in 1680. The last key variable is the price of goods. We examine two cases. The first is wheat, a low value to weight good. Its price in 1680 is 4.6 shillings a bushel or 2208 pence a ton assuming 40 bushels in a ton. In 1830 the price of wheat was 7.7 shillings a bushel or 3696 pence a ton. The implied inventory cost of wheat is 1.9 pence per ton in 1680 and 1.1 pence per ton in 1830. These figures are quite small in comparison to the money cost of freight, which is at least 232 pence per ton.

The second good is refined sugar, a medium value to weight good. The price of refined sugar in 1680 was 48,000 pence per ton in 1680 (20 shillings per 12 lbs. Beveridge 1965 vol 1, p. 429). The price of refined sugar was 43,200 in 1830 (18 shillings per 12 lbs). Thus, the inventory cost of refined sugar is 41.4 pence per ton in 1680 and 12.8 pence per ton in 1830. Adding these figures to the money price implies a total freight price of 576.6 in 1680 and 243.0 in 1830. The implied percentage decrease in freight rates, including inventory costs, is -0.574%, which is a small change compared to -0.561%, when inventory costs are excluded. Thus, inventory costs do not change the calculations for freight unless the product has a very high value to weight ratio.

The estimates from our network model imply that average passenger fares were 184.6 pence in 1680 and 242.1 pence in 1830. This implies an annual increase in fares of 0.181% (see table 2). Expressed in real terms, the passenger fare decreased by -0.179% (=0.181-0.36).

The previous figure is surely an under-estimate of the real change in passenger fares because it does not add the time costs. Gerhold (2016) makes this argument, and develops a methodology for adjusting an input cost index to account for greater speed. We take a different approach and estimate the time cost using wages and assumptions about the value of time saved. It is standard to assume the value an hour lost in passenger travel is equal to half the hourly wage (Leunig 2006). If we assume that passengers are craftsman and work 10 hours a day, then their hourly wage is 1.77 pence in 1680 and 4.21 pence in 1830. Multiplying by 0.5 gives the value of an hour lost in passenger travel. According to our network model, the average hours spent travelling between towns is 83.66 in 1680 and 18.88 in 1830. Thus, the average time cost is the value of an hour times average travelling time or 0.885*83.66 or 74.0 pence in 1680 and 2.105*18.88 or 39.7 pence in 1830. Combining the fare and the time cost to calculate a generalized cost equals (184.6+74) or 258.6 pence in 1680 and (242.1+39.7) or 281.8 in 1830. The new annual rate of change in nominal passenger fares is 0.057% and in real terms the rate of change is -0.303% (=.057-.36).

One could argue that this figure is also an under-estimate because most coach passengers earned more than craftsman. If we assume passengers earned doubled the wages of craftsman, the time cost rises to 148 pence in 1680 and 79.5 pence in 1830. In this scenario, the rate of change in nominal passenger fares is -0.023% and in real terms -0.383%. Incorporating the value of time for the representative passenger clearly makes a difference.

IV.4 Productivity growth in the transport sector

In this final section, we estimate the productivity growth of the domestic transport sector (excluding international shipping). We use the price dual method, where productivity is estimated by the difference between input price growth and output price growth. The starting point for the dual method is the assumption of perfect competition, constant returns to scale, and zero profits. Specifically, let the output in a sector be denoted by Yt and Pt is the price. The inputs are labour and capital, Lt and Kt, and the rental rate of capital and wage rate of labour are rt and wt. Using the zero profit condition, revenues equal costs, or Pt*Yt=rt*Kt + wt*Lt and differentiating with respect to time and dividing the right side and left side by Pt*Yt one gets Δpt + Δyt=a*(Δrt + Δkt) + (1-a)*(Δwt + Δlt), where Δx denotes variable X's annual growth rate, a=rt*Kt/Pt*Yt and (1-a)=wt*Lt/Pt*Yt. Notice that a is the share of revenues paid to the owners of capital and (1-a) is the share of revenues paid to labour, or alternatively the shares of each input's payment in total costs. Rearranging this expression gives the 'primal' and 'duel 'expression for productivity growth ΔAt.

$$\Delta At=\Delta yt-a*\Delta kt-(1-a)*\Delta lt= a*\Delta rt+(1-a)*\Delta wt - \Delta pt$$

It is important to acknowledge that the previous equation relies on the assumption of perfect competition and constant returns to scale. Without this assumption, it is thought that the duel measure understates the true rate of productivity growth (Lee 2004). This is not a large issue for us because it biases our TFP growth rates downwards.[13]

We now turn to the estimates of TFP growth for a large portion of the transport sector (mainly excluding international shipping). We start with freight services and then move to passenger services. In each case, we calculate a baseline TFP growth rate and an extension using inventory costs and the value of time. The last sub-section compares to the TFP growth in the whole English economy.

[13] There is a debate in the literature on whether the primal or duel provides a better measure of productivity growth. The answer depends on the context (see Hsieh 2002 for debate about productivity growth in East Asia). In historical research, the options are often limited. In most studies of British economic history, one does not observe outputs and inputs directly, but there is data on interest rates, prices of capital goods, wages, prices of goods over time. For this reason, there is a long tradition estimating productivity growth using the dual method (for the original application see McCloskey 1968, for a recent application see Clark 2010). In studies of historical transport productivity, the price dual has been used by North (1968), Harley (1988), Gerhold (1996), and Solar (2013).

IV.3.A TFP growth in Freight and passenger services between 1680 and 1830

The first step is to identify the weights for our 3 inputs in freight services, labour, capital, and fuel. The weights are based on average of the cost shares provided by Gerhold (1996) for road transport and Solar (2013) for shipping. We average because our index is meant to capture most of the transport sector prior to the steam age. The main sectors were road, coastal, and inland waterway. We lack good data on cost shares for boatman on inland waterways, but most likely they represent some average between the more capital intensive shipping sector and the more fuel intensive roads. The cost share weights in our analysis are 0.4 for capital, 0.21 for labour, and 0.39 for fuel.

The price of inputs are taken from 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. 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, farm prices). 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. The rate of growth of the three input prices is given in rows 1-3 of table 5. The weighted average growth rate is 0.376% (see row 4), implying input prices increased by 0.376% on average every year.

The price of freight services is taken from our network model as discussed in the previous section. The TFP growth estimate is reported in row (6) and calculated by subtracting (5) from (4). Our baseline estimate gives an average annual rate of TFP growth in freight equal to 0.937%. TFP growth is slightly larger at 0.95% if the inventory costs for a medium value good, like sugar, are added to the baseline freight cost (see row 10).

	Table 3: Freight TFP estimates		
		annual rate of change 1680 to 1830 in %	weights
1	rental rate of capital	0.206	0.4
2	wages	0.579	0.21
3	fuel prices	0.44	0.39
4	input prices combined	0.376	
5	freight rates	-0.561	
6	TFP (baseline)	0.937	
7	freight rates, including inventory costs for wheat	-0.56	
8	TFP with inventory costs for wheat	0.936	
9	freight rates, including inventory costs for refined sugar	-0.574	
10	TFP with inventory costs for refine sugar	0.95	

Notes: see text for calculations.

Turning to passenger services, the input weights for passenger services are taken from Gerhold (2016). They amount to a share of 0.8 to fuel, 0.14 to wages, and 0.06 to capital. The resulting increase in input prices of passenger is 0.445% per year as shown in row 4 of table 06. The estimates from our network model imply that average passenger fares were 184.6 pence in 1680 and 242.1 pence in 1830. This implies an annual increase in fares of 0.181% (see row 5). The estimate of annual TFP growth for passenger services is 0.264%. TFP growth is larger if the time costs are added. If passengers are assumed to earn a wage equal to craftsman, then the TFP growth is 0.388% per year (see row 8). A more plausible scenario where they earn twice the craftsman's wage, the TFP growth rate of passenger services rises to 0.468% per year.

	Table 6: Passenger TFP estimates		
		annual rate of change 1680 to 1830 in %	weights
1	rental rate of capital	0.206	0.06
2	wages	0.579	0.14
3	fuel prices	0.44	0.8
4	input prices combined	0.445	
5	passenger fares	0.181	
6	TFP	0.264	
7	passenger fares, including time cost for craftsman	0.057	

	Table 6: Passenger TFP estimates	
8	TFP with time cost for craftsman	0.388
9	passenger fares, including time cost for traveler with 2X value of craftsman's time	-0.023
10	TFP with time cost for traveler with 2X value of craftsman's time	0.468

How large are these TFP estimates? It is useful to start with a comparison to the whole economy. Clark's aggregate productivity estimates imply that the ratio of productivity in the British economy in 1830 to 1680 is 1.43. This figure implies an annual rate of 0.24% per year between 1680 and 1830. Thus, freight TFP growth is much larger at 0.94% per year. Passenger TFP growth is also larger at 0.39-0.47% per year. In fact, some additional assumptions suggest that transport productivity growth accounts for a large share of all TFP growth in the English economy between 1680 and 1830. Assume that passenger services represent 2% of GDP and freight represents 6% of GDP. These weights imply that transport contributed 0.02*0.43+0.06*0.97 or 0.067% to aggregate TFP annually. As annual TFP growth is estimated to be 0.24% for the whole economy, it follows that transport accounts for 27.9%=(0.067/0.24) of all TFP growth.

It is also useful to calculate the social savings that arose from TFP growth in transport. According to Crafts (2004), the social savings are equal to the compounded effect of the annual TFP contribution. In our case, transport improvements contributed 0.067% to aggregate TFP annually between 1680 and 1830. Over 150 years this would increase annual income by 10.5%. We take this finding as strong evidence that transport improvements were a major driver of improvements in living standards even in the pre-steam era.

V. Conclusion.

Transport improvements are one of the key engines of economic growth in England during the Industrial Revolution. This paper quantifies the extent of change across a large proportion of the transportation system. It integrates new GIS data on roads, inland waterways, ports, and coastal shipping routes into a single model of the transport network. It estimates the lowest transport costs, in both money and time, between the 100 most populous towns in 1680 and 1830. The results show fairly uniform reductions in passenger costs across provincial towns, but more varied reductions in freight costs.

We use our model's outputs to quantify the rate of change in transport costs between 1680 and 1830 relative to other price series. Freight transport costs decreased at the rate of -0.56% per year between 1680 and 1830, while consumer prices increased at the rate of 0.36% per year. The pure money passenger cost increased at an average rate of 0.18%, and thus exhibited a different trend than freight rates. But the generalized passenger cost declined at the annual rate of -0.02%, implying the annual change in the real passengers cost was -0.38%. A comparison with input prices shows that freight transport the average annual TFP growth rate between 1680 and 1830 was 0.937% and 0.46% for passenger travel. A plausible weighting of freight and passenger implies a 0.067% contribution to the annual aggregate TFP growth rate between 1680 and 1830 and a 10.6% increase in national income by 1830.

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 this 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 (Leunig 2006, Crafts 2004). We show that transport improvements were hugely important and rank close to innovations in textile manufacturing in generating income growth.

V. Bibliography

Alvarez-Palau, Eduard Dan Bogart, Oliver Dunn, Leigh Shaw-Taylor, "Ports and Coastal Shipping network of England and Wales, 1680-1911." 2017. http://www.campop.geog.cam.ac.uk/research/projects/transport/data/ports.html

Armstrong, John. "The significance of coastal shipping in British domestic transport, 1550–1830." International Journal of Maritime History 3.2 (1991): 63-94.

Alder, Simon. "Chinese roads in India: The effect of transport infrastructure on economic development." Work. Pap., Univ. North Carolina, Chapel Hill (2014).

Antras, Pol, and Hans-Joachim Voth. "Factor prices and productivity growth during the British industrial revolution." Explorations in Economic history 40.1 (2003): 52-77.

Aldcroft, Derek Howard and Michael Freedman. Transport in the industrial revolution. Manchester University Press, 1983.

Bagwell, Philip. *The transport revolution 1770-1985*. Routledge, 2002.

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

Beveridge, Lord. Prices and wages in England. Vol. 1. Psychology Press, 1965.

Clark, Gregory. "The macroeconomic aggregates for England, 1209–2008." Research in Economic History. Emerald Group Publishing Limited, 2010. 51-140.

Crafts, Nicholas. "Steam as a general purpose technology: a growth accounting perspective." The Economic Journal 114.495 (2004): 338-351.

Crafts, Nicholas FR, and C. Knick Harley. "Output growth and the British industrial revolution: a restatement of the Crafts-Harley view1." The Economic History Review 45.4 (1992): 703-730.

Daniel, J., The Shipowner's and Shipmaster's directory to the port charges, all the depth of water in Great Britain and Ireland, (Aberdeen), 269pp.

Donaldson, Dave. Railroads of the Raj: Estimating the impact of transportation infrastructure. No. w16487. National Bureau of Economic Research, 2010.

Donaldson, Dave, and Richard Hornbeck. "Railroads and American economic growth: A “market access” approach." The Quarterly Journal of Economics (2016): qjw002.

Duranton, Gilles, Peter M. Morrow, and Matthew A. Turner. "Roads and Trade: Evidence from the US." The Review of Economic Studies 81.2 (2014): 681-724.

Gerhold, Dorian. "Productivity change in road transport before and after turnpiking, 1690-18401." The Economic History Review 49.3 (1996): 491-515.

Gerhold, Dorian. Carriers and Coachmasters: Trade and Travel before the Turnpikes. Phillimore, 2005.

Gerhold, Dorian. "The development of stage coaching and the impact of turnpike roads, 1653–1840." The Economic History Review 67.3 (2014): 818-845.

Hargrave, F. A Collection of tracts relative to the law of England from manuscripts, Vol. 1, (Dublin, 1787), pp. 49-50. 650pp.

Harley, C. Knick. "Ocean freight rates and productivity, 1740–1913: the primacy of mechanical invention reaffirmed." The Journal of Economic History 48.04 (1988): 851-876.

Hopwood, F., Harbour authorities. Return from the authorities of the harbours etc of the United Kingdom, (London), 286pp.

Hsieh, C-T. (2002). "What Explains the Industrial Revolution in East Asia? Evidence from Factor Markets." American Economic Review 92(3), 502-526.

Jackman, William T. The Development of Transport in Modern England. Psychology Press, 1962.

Jaworski, Taylor, and Carl T. Kitchens. National Policy for Regional Development: Evidence from Appalachian Highways. No. w22073. National Bureau of Economic Research, 2016.

Kee, Hiau Looi. "Estimating productivity when primal and dual TFP accounting fail: An illustration using Singapore's industries." Topics in Economic Analysis & Policy 4.1 (2004).

Kent Causton, Henry. Kent's original London directory: 1827 : being an alphabetical list of more than 20,000 merchants, manufacturers, traders, &c. Henry Kent Causton & Son, 1827.

Langton, John. "Urban growth and economic change: from the late seventeenth century to 1841." The Cambridge urban history of Britain 2 (2000): 1540-1840.

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

Leunig, Timothy. "Time is money: a re-assessment of the passenger social savings from Victorian British railways." The Journal of Economic History 66.03 (2006): 635-673.

Maw, Pete. Transport and the industrial city: Manchester and the canal age, 1750–1850. Manchester University Press, 2013.

McCloskey, Donald N. "Productivity Change in British Pig Iron, 1870–1939." The Quarterly Journal of Economics 82.2 (1968): 281-296.

Morris, J. M., Dumble, P. L., & Wigan, M. R. (1979). Accessibility indicators for transport planning. Transportation Research Part A: General, 13(2), 91-109.

North, Douglass C. "Sources of productivity change in ocean shipping, 1600-1850." Journal of Political Economy 76.5 (1968): 953-970.

Pascali, Luigi. "The wind of change: Maritime technology, trade and economic development." American Economic Review (2016).

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

Rosevear, A., Satchell, A.E.M., Bogart, D, and Sugden, K., Shaw Taylor, L., 'Turnpike roads of England and Wales,' 2017. http://www.campop.geog.cam.ac.uk/research/projects/transport/data/turnpikeroadnetwork.html

Sacks, D.H., and Lynch, M., Ports 1540-1700, in Clark, P. The Cambridge Urban History of Britain, (CUP 2016), pp. 388-389.

Satchell, M. Navigable waterways in England and Wales Dynamic GIS 1600-1948, 2017. http://www.campop.geog.cam.ac.uk/research/projects/occupations/datasets/documentation/navigablewaterwaysofenglandandwales1600to1948dynamicgisdraftdatasetdocumentation.pdf

Skey, Robert S. Birmingham and Liverpool Junction Canal. Report to the Committee ... on the present state of the competition between the canal carriers using that line and the Grand Junction Railway Company. With suggestions for a more economical and effective working of the canal. Vacher & Sons, 1841.

Solar, Peter M. "Opening to the East: Shipping between Europe and Asia, 1770–1830." The Journal of Economic History 73.03 (2013): 625-661.

Steel, D., Ship-master assistant and owner's manual, (London, 1826).

Szostak, Rick. Role of Transportation in the Industrial Revolution: A Comparison of England and France. McGill-Queen's Press-MQUP, 1991.

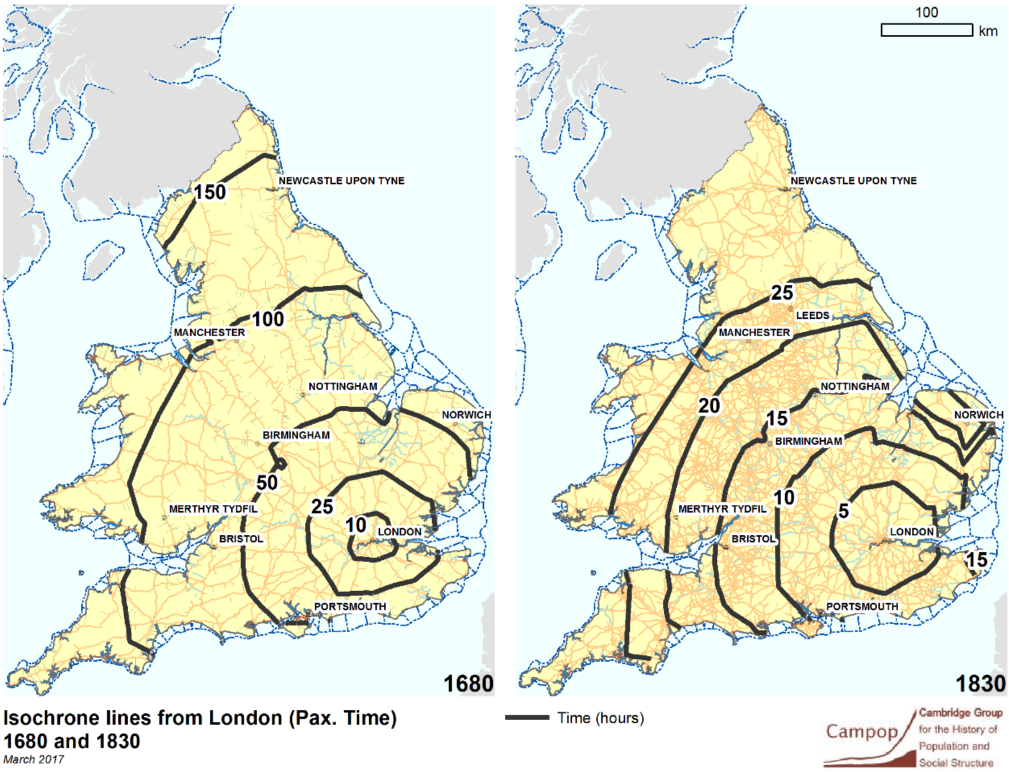


Figure 16: Relative Accessibility Index from London (passenger time) in 1680 and 1830.

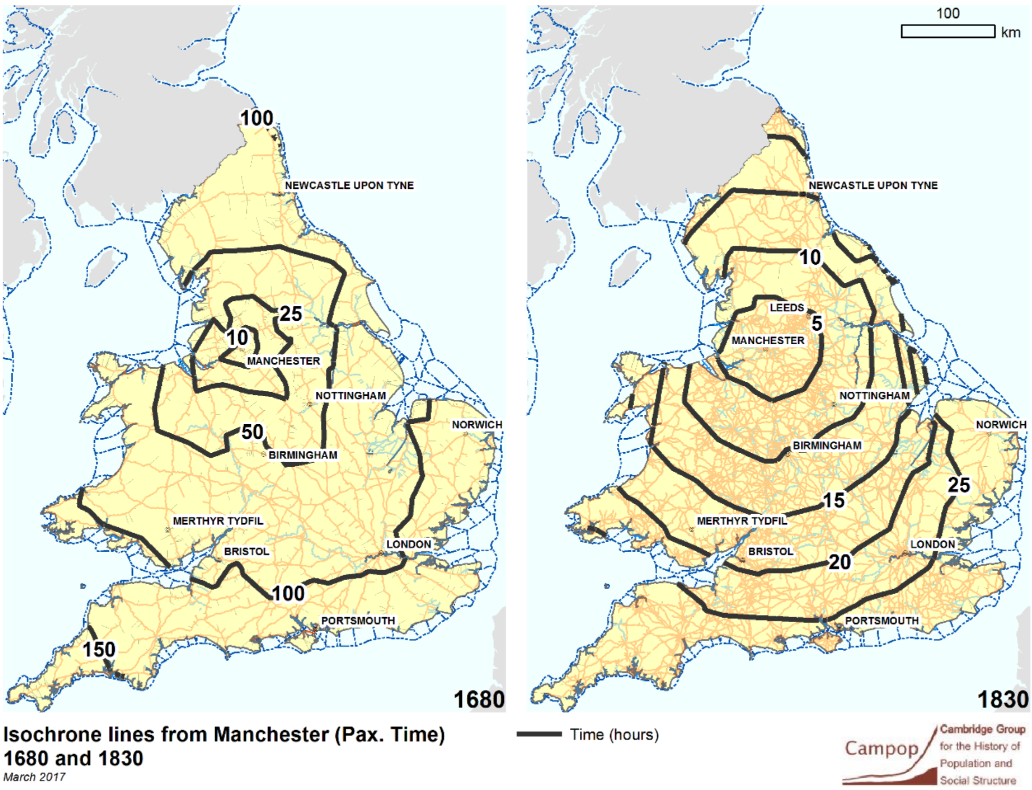


Figure 17: Relative Accessibility Index from Manchester (passenger time) in 1680 and 1830.

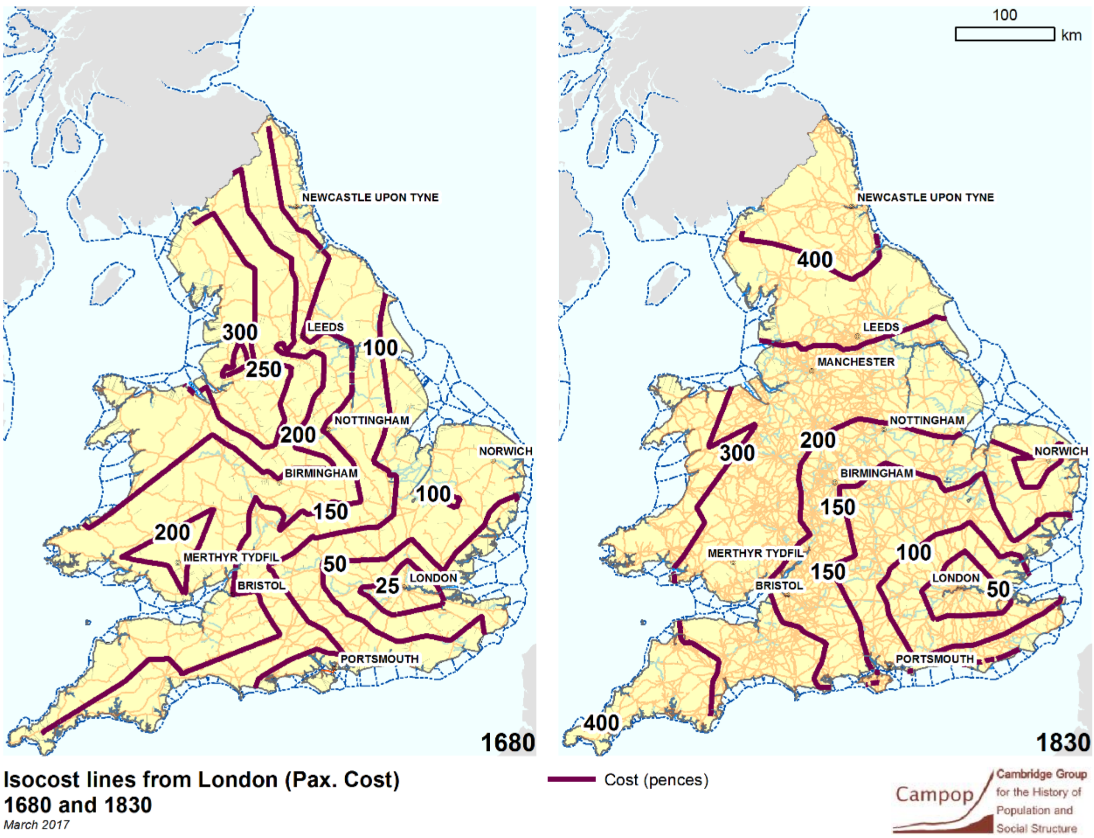


Figure 18: Relative Accessibility Index from London (passenger cost) in 1680 and 1830.

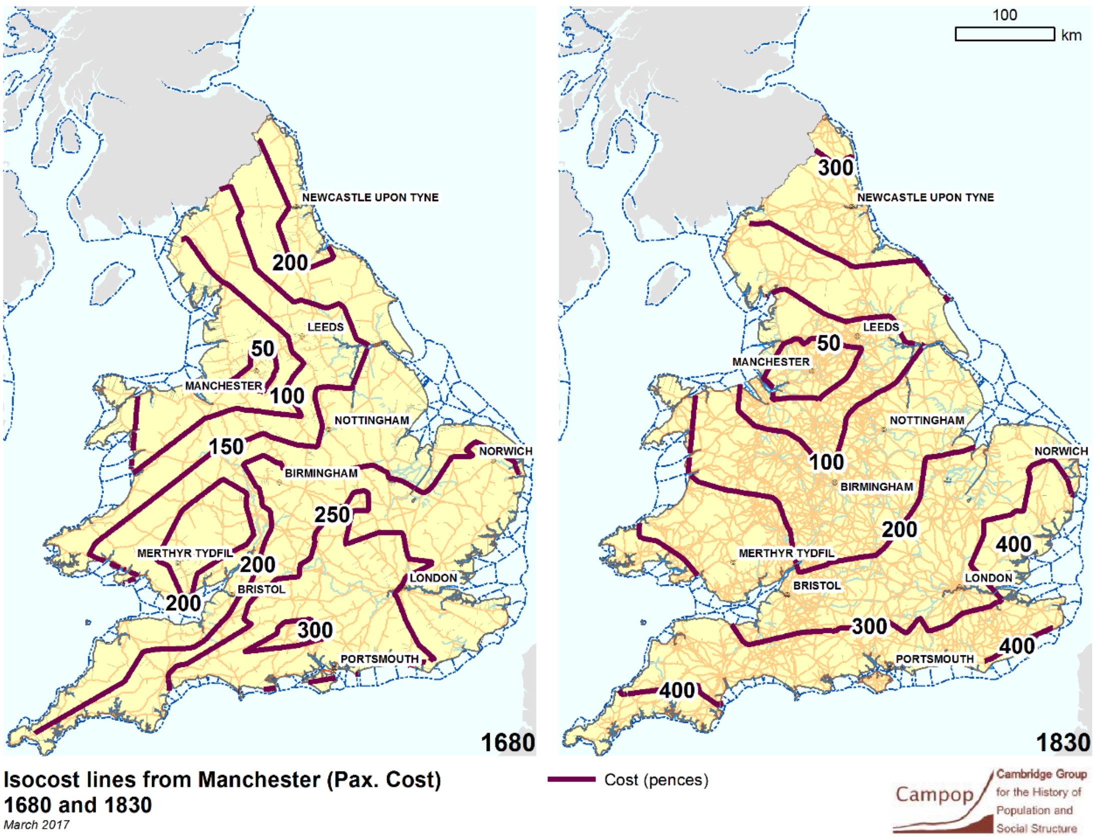


Figure 19: Relative Accessibility Index from Manchester (passenger cost) in 1680 and 1830.

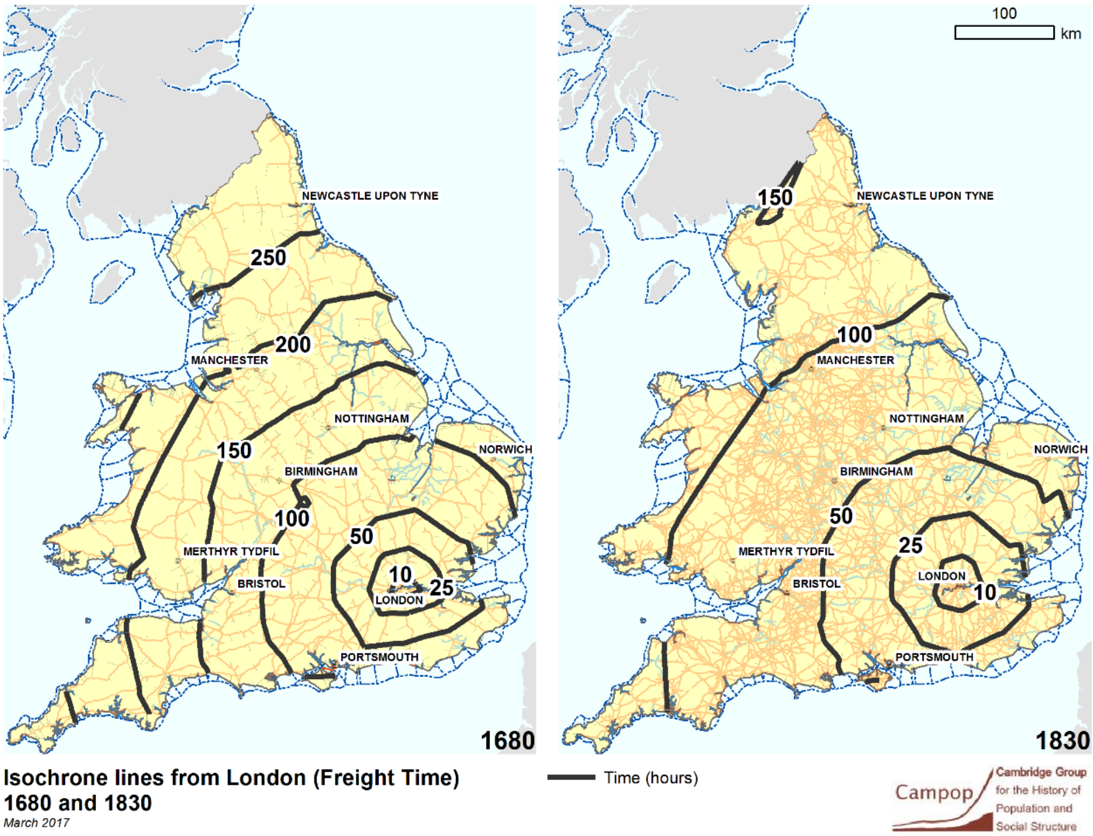


Figure 20: Relative Accessibility Index from London (freight time) in 1680 and 1830.

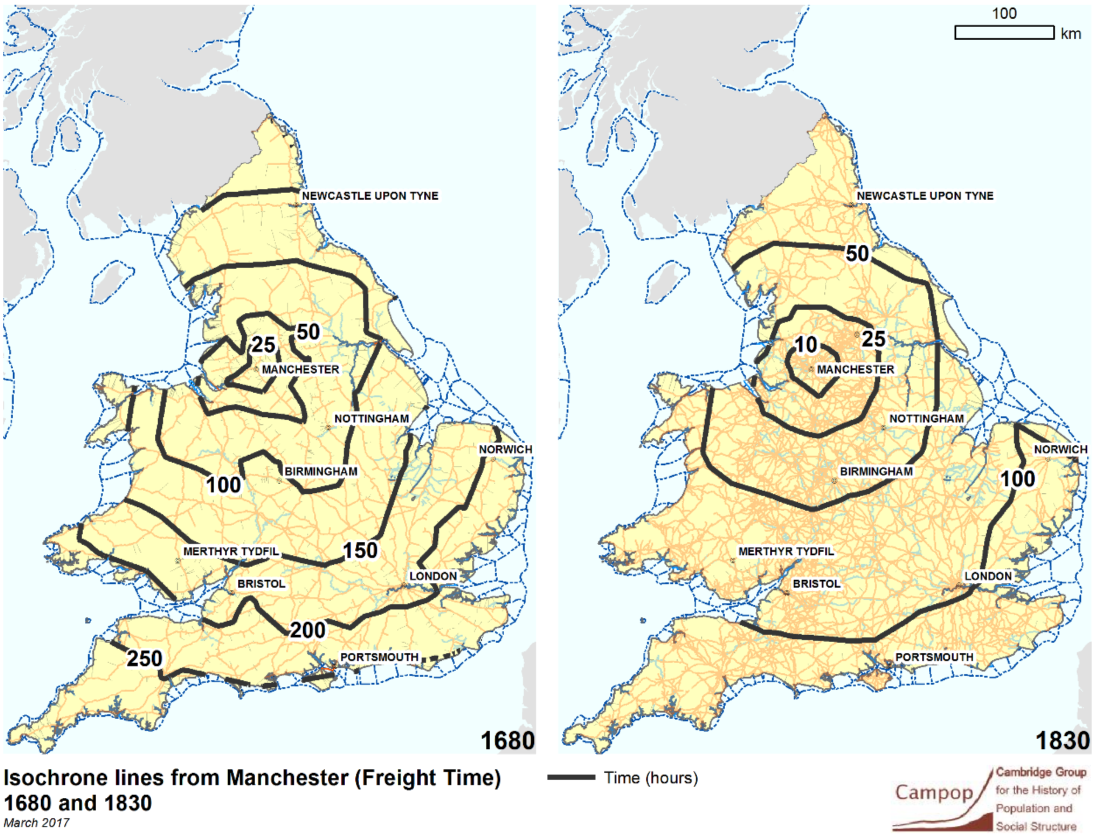


Figure 21: Relative Accessibility Index from Manchester (freight time) in 1680 and 1830.

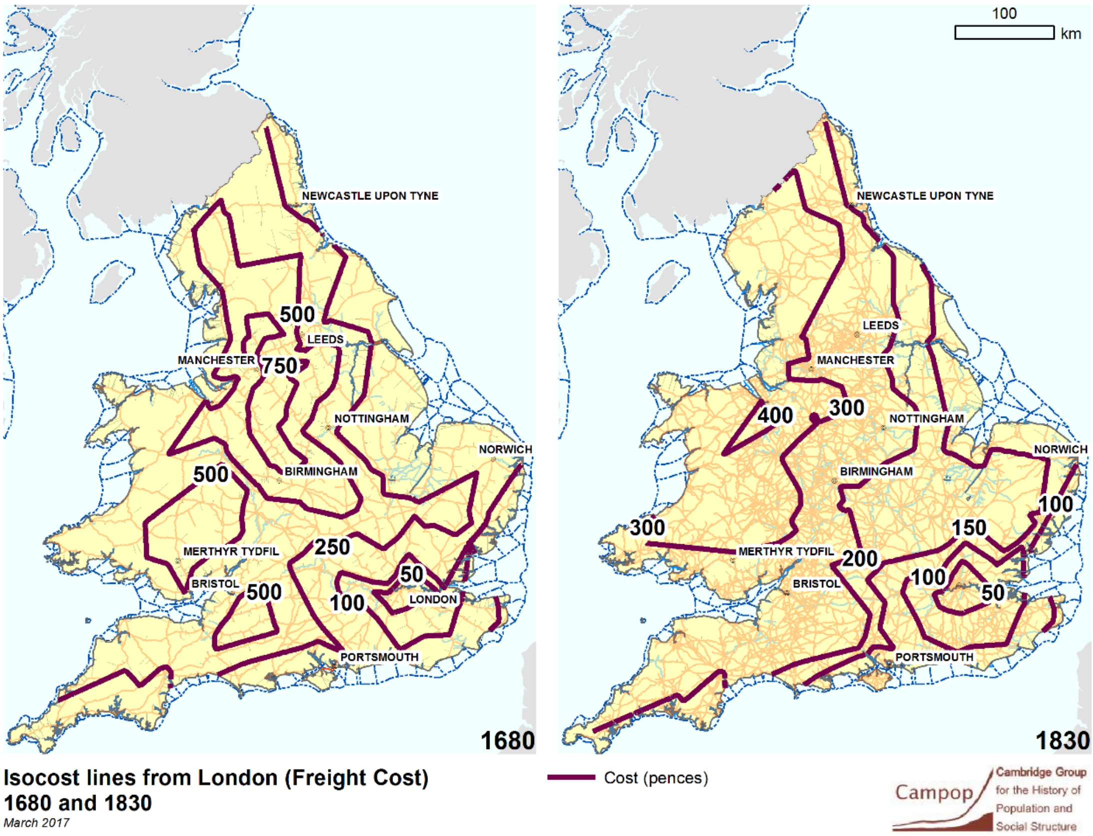


Figure 22: Relative Accessibility Index from London (freight cost) in 1680 and 1830.

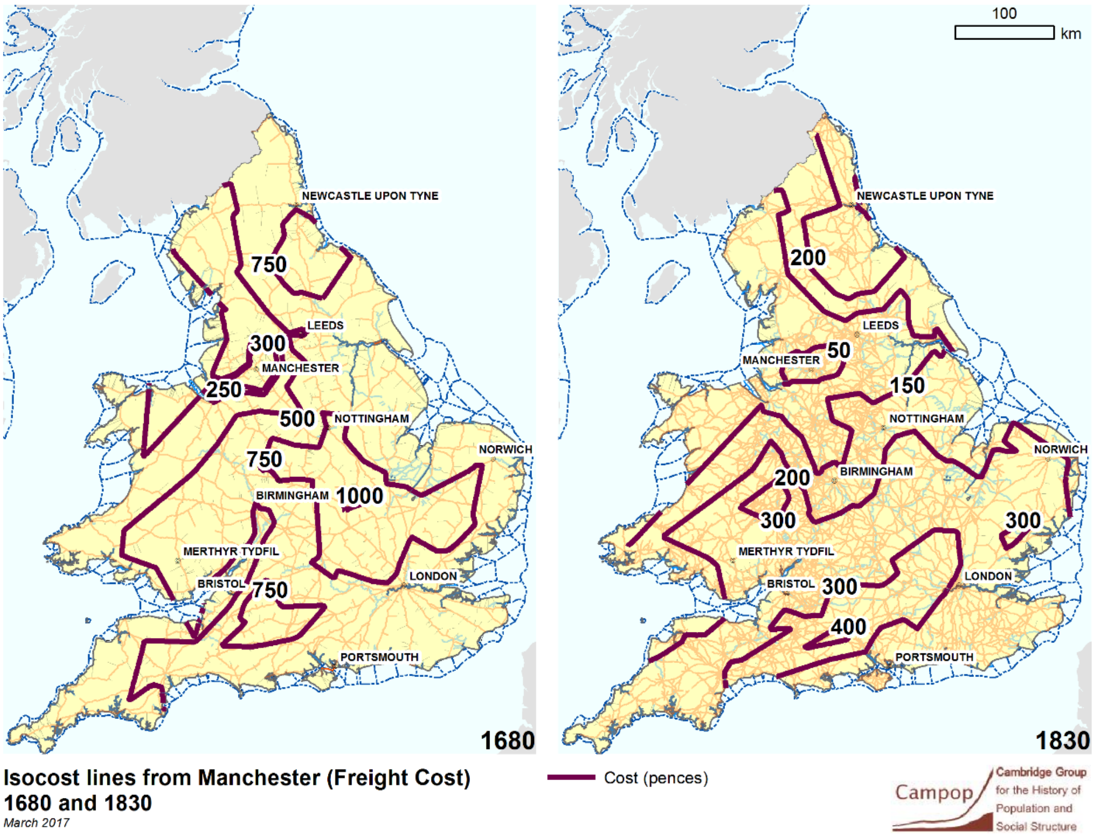


Figure 23: Relative Accessibility Index from London (freight cost) in 1680 and 1830.