Multi-modal models for pre-steam English and Welsh freight transportation systems[1]

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This dataset provides new estimates of inter-urban freight transport costs in the pre-steam era. They are derived from a multi-modal freight model with roads, inland waterways, ports, and coastal shipping networks. Technology and geography are incorporated in this model through cost parameters, like freight rates per mile, differing by the slope of the terrain and quality of infrastructure, all estimated from novel historical sources. The main output is a matrix of freight costs in pence per ton between 590 cities and towns in 1680 and 1830.

I. Historic transport networks

Historic transport networks are key data inputs for our multi-modal model. Networks comes from a wider project creating GIS maps of historic ports, coastal routes, inland waterways, and roads in E&W along with several additions.[6] Figure 1 shows the full picture of transport networks. Aside from important coastal routes, in 1680 there are many roads and inland waterways extending from the major river basins. In 1830 several canals link distant

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[6] See 'Transport, urbanization and economic development in England and Wales c.1670-1911' https://www.campop.geog.cam.ac.uk/research/projects/transport/.

basins. Also notice the additions to the road network by 1830 were often near the canals. Ports were common in both periods.

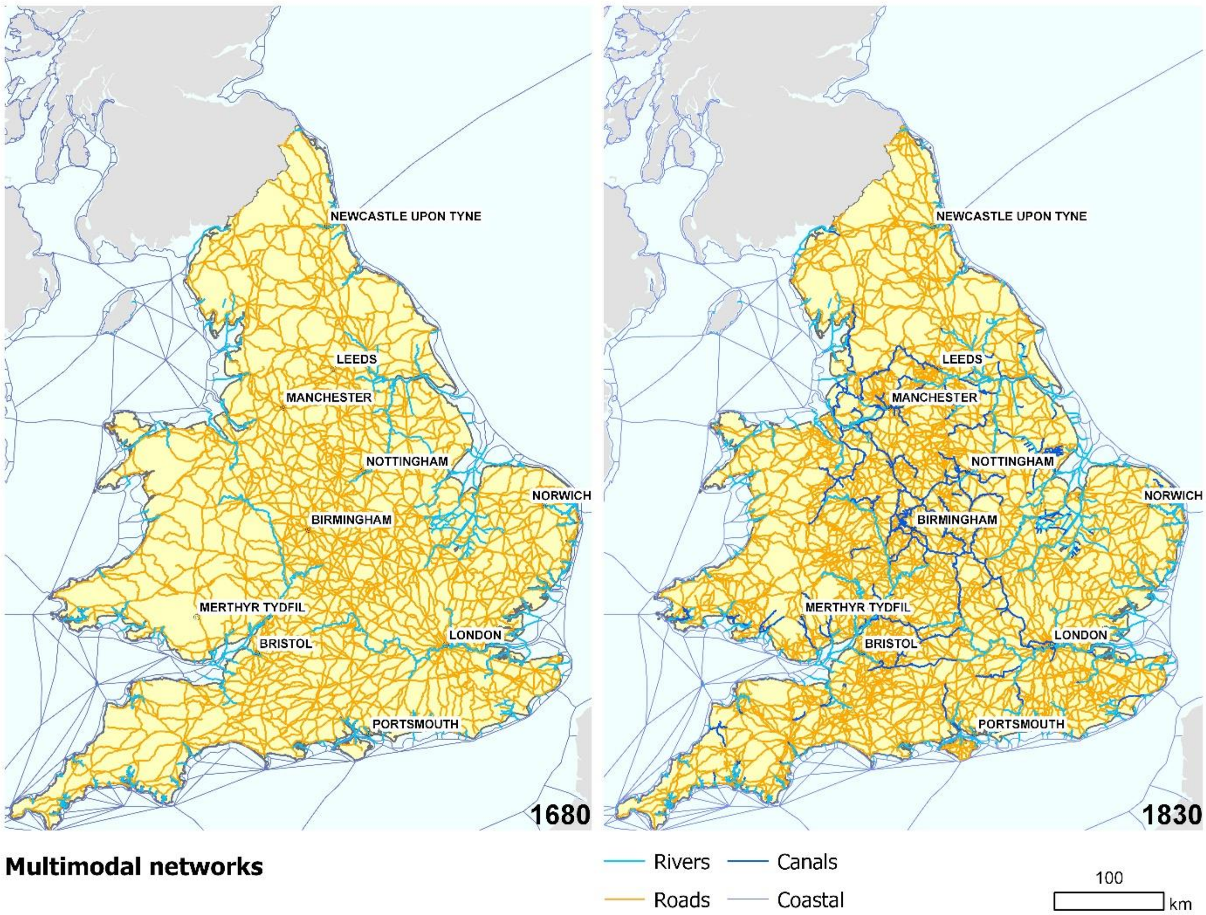

Figure 1. Transport networks in 1680 and 1830.
Source: created by authors using source in text.

I.A Ports and coastal network

In this section, we describe the database of historical ports and the database of historical coastal routes. For the GIS data on ports and routes see Alvarez-Palau and Dunn (2019) and for their description see Alvarez-Palau, Dunn, Bogart, Satchell, Shaw-Taylor (2019). Eleven different sources were used to create a list of ports and other smaller places where coasting vessels regularly landed to load and discharge goods. Some of these sources include Hargreave (1987), Daniel (1842), Hopwood (1903), Langton (2002), Sacks (2016). The existing literature provides convenient lists of the most important ports. However, coasting vessels called at a much larger range of landing locations than these suggest –including beaches, natural bays, piers, etc. To locate and record more places we drew on new sources that provided us with an array of landing locations at different benchmark dates[7].

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

In the nineteenth century, the number of reported ports of all kinds increased compared with the sixteenth century due to better information about ports in general, but also because of the expansion of the network. According to earlier sources, ports included harbours, piers, small creeks and even beaches. These were overseen by larger ports with customs houses. Figure 2 shows the geographical distribution of all 479 ports with one or more appearance in our sources[8].

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

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

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

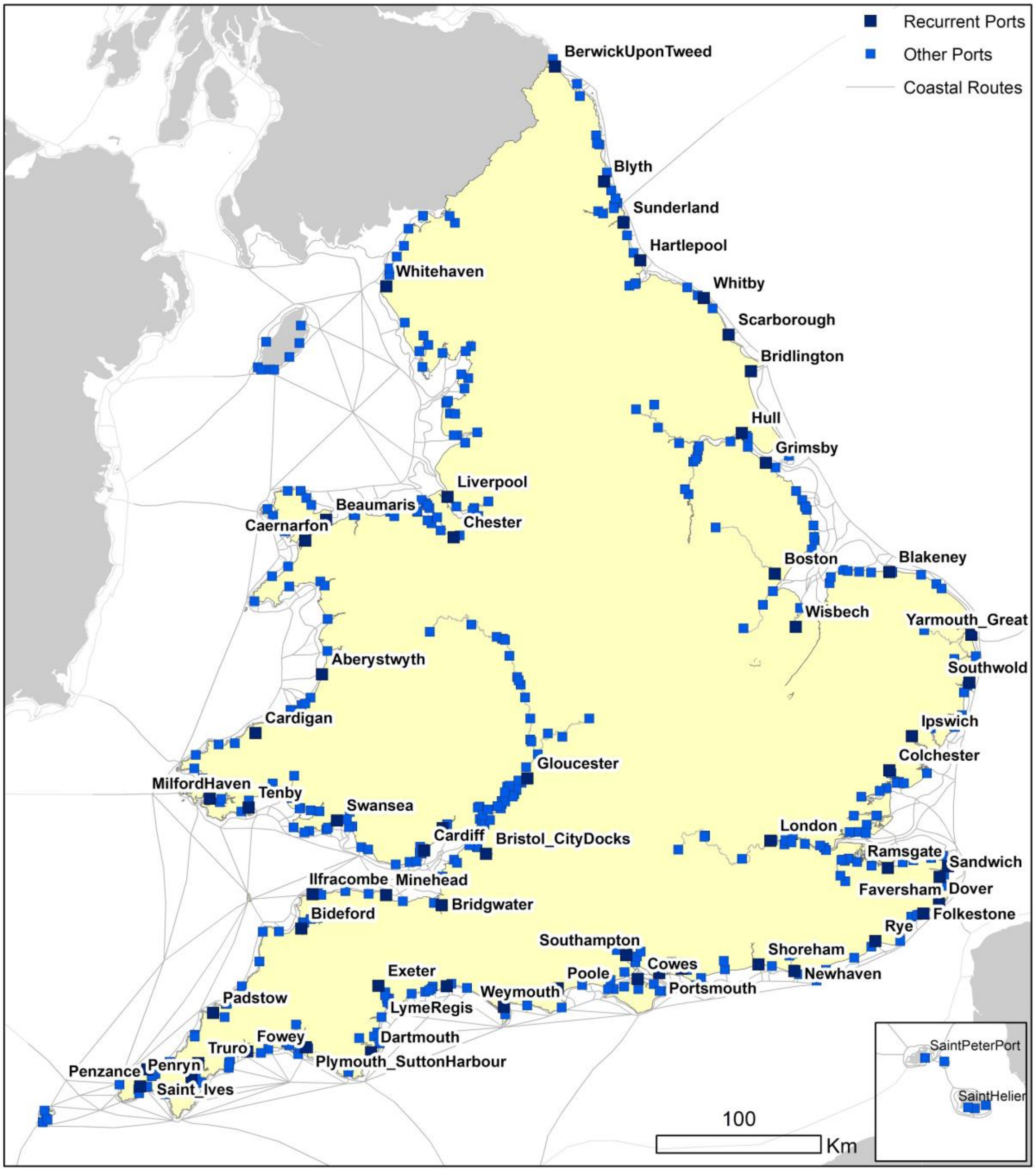

Figure 2: Ports with one or more mentions within the sources used. Those places marked as dark blue (recurrent ports) are mentioned in at least nine out of eleven sources.

Sources: Alvarez-Palau and Dunn (2019) and Alvarez-Palau, E. J., Dunn, O., Bogart, D., Satchell, M., & Shaw-Taylor, L. (2019).

The following principles were used to create coastal networks in Alvarez-Palau and Dunn (2019). In the sailing era, natural conditions constrained operations, especially storms, tides and waves, but also low light, which clearly all had adverse effects. In terms of navigation, instruments used at the time allowed travel only under certain circumstances, and good visibility was necessary for safe passage. Knowledge of bathymetry was key to avoiding damage by grounding on sandbanks or rocks. Navigational charts reported the depth of water at certain locations, but for these to be of any use it was crucial to know the exact position of the ship. Mariners used landmarks to track their position, often using triangulation, and it was thus normal to sail in sight of the coast. During the night or in poor visibility navigation became difficult. Beacons, lighthouses and light-vessels etc. served as an alternative to landmarks where available, but their presence on the coast was very limited at the beginning of our period of study.

An amalgamation of different sources were used to identify coastal routes mariners most likely followed. Specifically, Alvarez-Palau and Dunn (2019) relied on historical coastal charts, bathymetric depth rasters, topographic elevation rasters, and parliamentary reports to create our database. The main primary sources used to determine coastal routes were navigation charts included in Captain Collin's publication, Great Britain's Coastal Pilot, first published in 1693. For later years, they also looked at coastal charts published by the admiralty in 1830 at the UK Hydrographic Office, Taunton. These documents were digitised and geolocated to gain a workable understanding of the contemporary navigation techniques of each period. Charts always contain landmarks and bathymetry information so mariners could determine their position and avoid danger. Collins also gave specific directions for some routes with their distance in miles given, and this information revealed the routes the author directed ships to take when sailing round the coast.

Bathymetry data was used to distinguish those areas with sand banks and submerged rocks. Although the position of sands changed over time, it is assumed there was stability in other parts of the coast that were less affected by tides and oceanic currents. Alvarez-Palau and Dunn (2019) relied on the EMODnet Bathymetry data for the Atlantic Ocean, published by the European Marine Observation and Data Network in 2016. Specifically, they obtained a Digital Terrain Model (DTM) raster with bathymetric depth data with an approximate resolution of 200-metre cell.

Topographical data was gathered from the NASA Shuttle Radar Topography Mission (SRTM). The raster, though, was a processed version offered by the International Centre for Tropical Agriculture (CIAT); in particular, Alvarez-Palau and Dunn (2019) worked with its version 4.1. In this case, the different rasters were provided in TIFF format with a resolution of 90-metre cell. Figure 2 above shows the coastal routes.

I.B Inland waterway network

In this section, we describe how existing GIS data on inland waterways was created and how we add to it further in this dataset. For the full GIS of waterways, 1600-1948 see Satchell, Newton, and Shaw-Taylor (2017) and for 1680 and 1830 GIS time slices see Satchell, Shaw-Taylor, and Wrigley (2017a, b). See Satchell (2017 b, c) for descriptions of each. Satchell did the primary work with the help of others. Previously the extent and expansion of navigable waterways in England and Wales could only be established in a very laborious way. Estimates of national mileage at various dates had to be used, salient information had to be extracted from the regional studies of Hadfield and a variety of paper maps of varying accuracy and utility had to be consulted. The creation of the first time-dynamic GIS model of the English and Welsh waterway network was carried out by Max Satchell with the assistance of Owen Tucker, Zoe Crisp, Ellen Potter, and Gill Newton.

Digitising the major navigable rivers of England starts from geo-rectified scans of the Ordnance Survey 1:10560 first edition. Next all waterways shown on Richard Dean's *Inland Navigation. A Historical Waterways Map of England and Wales* were digitized The c.1:536,448 scale of this map meant that in itself, it was not sufficiently detailed to produce a high standard GIS. As a consequence, the Dean digitisation as a guide to locate the historical waterways on geo-rectified scans of the Ordnance Survey first edition 1:105606 inch map series (surveyed 1840-1890), and the waterways were digitised directly from this map series. For the modest number of waterways which had disappeared before being surveyed by the Ordnance Survey 1:10560 series earlier mapping principally sheets 1-90 of the Ordnance Survey 1:63,360 Old Series (surveyed 1789-c.1840). This work was done using each of Hadfield regional volumes in succession. In every instance emphasis was on establishing as far as possible when each section of the waterway was in commercial use. In addition to the sources already mentioned, usage dates were derived from T.S. Willan, River Navigation in England 1600-1750 (1936), the Royal Commission on Canals and Waterways, BPP, 11 vols, (1906-1911) and H. de Salis Bradshaw's Canals and Navigable Rivers of England and Wales (1904). Where available secondary studies of particular regions and individual waterways were also consulted. Opening, closing and commercial disuse dates for each section of waterway linked to the GIS polyline were entered in an excel table. We used this to create an Access database which enabled the network of navigable waterways for any given year from 1600 to 1948 to be generated.

Now we explain how we add to this data. Figure 3 shows the (1) coastal network, (2) inland waterway network by river and canal, (3) interpolations that were made to connect the inland waterway and coastal networks, and (4) locks. The distinction between canals and rivers is important. One must recognise that canals are different from rivers because their routes are deliberately chosen. While a canal route does not require the pre-existence of a potentially navigable river, it is constrained by modest changes in elevation. Locks are also a crucial future. In the eighteenth century, one pound lock was considered necessary for every 7ft (2.13 metres) of elevation and locks constitute a major capital expense. We add surviving locks to our database using the River and Canal Trust Locks dataset.[9] There is a potential survival bias here, but as locks were so important, they are added. Locks can be seen in the bottom right panel of Figure 3.

[9] See the River and Canal Trust, Locks, http://data-canalrivertrust.opendata.arcgis.com/datasets/locks-public. Accessed on 1 Aug. 2018. There is a potential survival bias here, but as locks were so important, they are added.

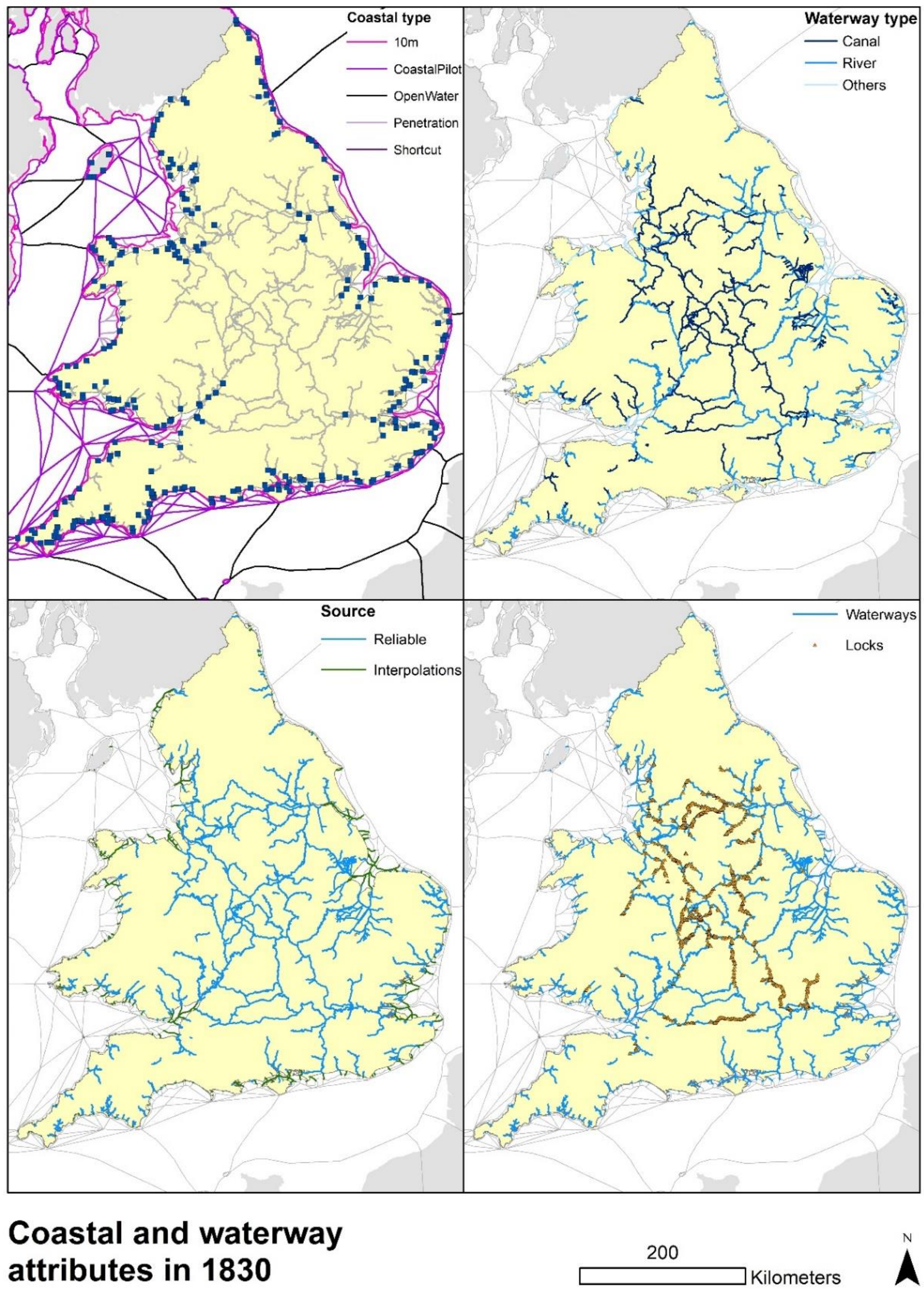

Figure 3: Coastal and waterway attributes in 1830

Source: authors creation using Satchell, Shaw-Taylor and Wrigley (2017 a, b) and locks from the River and Canal Trust.

I.C Road Network in 1680

In this section, we describe how the GIS data on 1680 roads was created and how we add to it in this dataset. See Satchell, Rosevear, Dickinson, Bogart, Alvarez, Shaw-Taylor (2017) for the original GIS data of 1680 roads and Satchell and Rosevear (2017) for more description. The primary work was done by Satchell and Rosevear with the help of others. The 1680 roads GIS contains two distinct elements: a digitisation of some 7,493 miles of road which derive from the strip maps of Ogilby's atlas and 13439.8 miles of other roads which derive from a variety of other sources. Identifying and mapping the main roads of England and Wales c.1680 is no easy task. In terms of cartographic sources, the national road network is hardly depicted at all, and certainly not with any accuracy, until John Ogilby published Britannia, his atlas of "principal roads" of England and Wales in 1675. Work by Satchell using a wide range of evidence for road transport has shown that most roads Ogilby mapped were important. Ogilby's Atlas consisted of strip maps at 1:63360 scale of 85 routes on 100 copper plates which surveyed and mapped over 7500 miles of road.

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

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

Alan Rosevear took on the formidable task of systematically integrating these disparate materials to build the rest of the 1680 road network. To assist in selecting routes and interconnections from the Ogilby Roads, he displayed following additional GIS data was over the 1st edition OS 1:10,560 base map;

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

2. Destinations in the directories by De Laune (1681) and Taylor (1637).

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

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

5. The full turnpike network

6. Carrier routes listed in the 1791 Universal British Directory

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

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

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

A map of the main Ogilby roads and non-Ogilby roads is shown in the upper left box of figure 4.

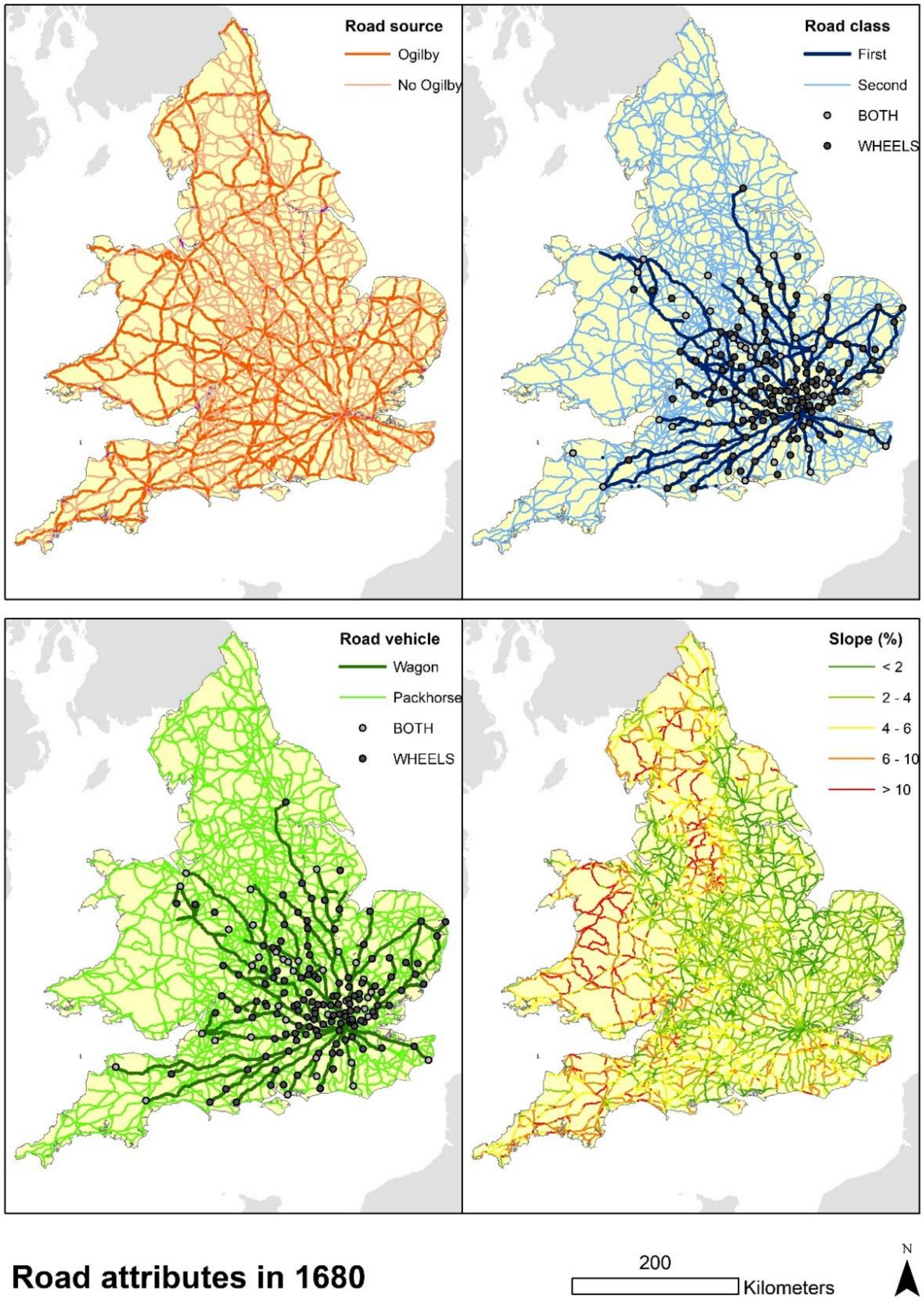

Figure 4: Roads and attributes in 1680

Source: author's creation using Satchell, Rosevear, Dickinson, Bogart, Alvarez, Shaw-Taylor (2017) and other sources in text.

This dataset enhances the 1680 roads by adding an attribute to determine whether wheeled transport or packhorses were used on the road. Our classification is derived from DeLaune's 1681 publication, which details whether packhorse (carrier) or wagon services were available from London to several towns. We have mapped packhorse versus wagon using Delaune's data. It is shown in figure 5 along with Ogilby's main roads in 1680. It is clear wheeled transport was not available everywhere. We use this information to identify a 'first class' road network where only wheeled transport was used and a second class network where packhorses or both were used. This is shown in the upper right hand box of figure 4. Wheeled transport and packhorse transport were both used in transport to some towns (both) so we assume the 1680 road network where wheeled transport was available was larger than first class roads. The full network available for wheeled transport in 1680 is shown in the lower left hand box of figure 4.

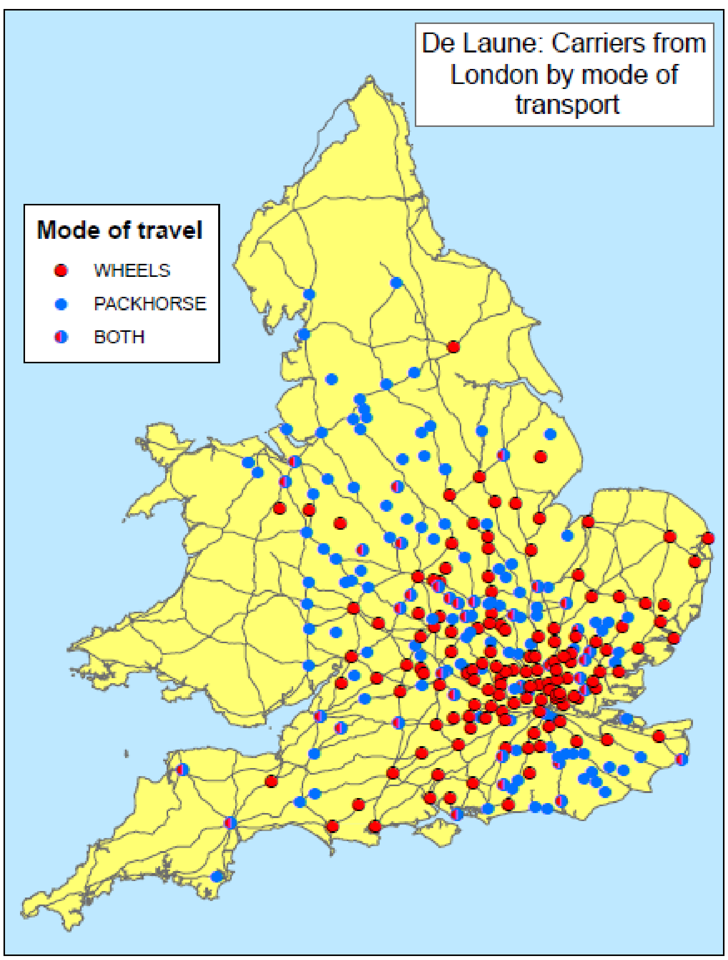

Figure 5: Delaune's map of wheeled and packhorse services from London to various towns in 1681.

Finally, slope is a crucial factor in road transport. We overlay a raster file of elevation on the map of 1680 roads to calculate segments where the average slope was fit into different categories. These segments are shown in the lower right hand box of figure 5.

I.D Road Network in 1830

In this section, we describe how the GIS data on 1830 roads was created and how we add to it in this dataset. The 1830 roads are derived from a GIS of the turnpike road network as of 1830. For the GIS data on turnpike roads see Rosevear, Satchell, Bogart, Shaw-Taylor, Aidt, and Leon (2017). For a description of turnpike roads see Bogart, Rosevear, and Satchell (2017), who did the primary work.

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

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

For England the next step used two resources that identify the territories of turnpikes trusts from surviving wayside features, parliamentary records, acts of parliament and historic county maps. The first of these was a dataset of known milestones and tollhouses created by the Milestone Society.[10] Alan Rosevear digitised these records and added the turnpike trust authority name. The second was a series of marked up county maps (generally Thomas Moule's County series ca 1830) with the roads under the jurisdiction of each trust and its opening date clearly identified. Satchell took the milestones digital data and used GIS to link these to the turnpike polylines digitised from Cary. From that the provisional road segments of each trust was acquired. Marked up county maps were then geo-rectified and used to correct and upgrade the trust data acquired from the milestones. The output of this step was a provisional time-dynamic turnpike network for England. In the final step, the trust name and dating was checked and the inter-trust boundaries were clear for each road segment and added the date of closure using parliamentary records and acts of parliament. The acts of parliament are drawn from the Portcullis database of all acts at the Parliamentary Archives in London.[11] The main parliamentary record used in this exercise is the 'Appendix to the report of the commissioners for inquiring into the state of the roads in England and Wales,' British Parliamentary Papers (BPP 1840 XXVII). The appendix records the mileage of individual trusts in each parish in 1838. Tollhouse locations found during mapping were used to confirm the allocation of sections to trusts and better specify trust boundaries. Local history studies of individual trusts were used to date and plot diversions made by the trusts where possible and the recorded trust mileage in 1820, 1838 and 1847 used to interpolate a date for improvements seen on maps where no records found. Unless specified in the Act, it was assumed that the older section of road lapsed at the date the improvement was made.

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

For Wales there was no comprehensive milestone record or marked up county maps with which to work. Rosevear took the raw Cary turnpike data and added the trust name and date of opening and closure using parliamentary records and acts of parliament described

[10] The database manager is Alan Rosevear.

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

above. The network for South Wales was refined using the maps and commentary in The Report of the Parliamentary Commission (1843) made after the Rebecca Riots.

The GIS map of all turnpike trusts was used as the starting point for selection in 1830 roads. Polylines were selected first on the basis of the start date of the Turnpike trust and all those with a date after 1830 excluded. A map of turnpike roads in 1830 is shown in the upper left box of Figure 6.

We now explain how we add to the 1830 roads GIS for this dataset. First, other main roads were added to link a small number of towns to the turnpike network, ensuring complete connection. Second, we add quality measures. The parliamentary report 'Appendix to the report of the commissioners for inquiring into the state of the roads in England and Wales,' British Parliamentary Papers (BPP 1840 XXVII)' includes an assessment of the road quality. Several classifications are given from poor, average, above average, Good, and excellent were given. We created a simple quality classification 'Good' if the road was described as good, very good, and excellent. Otherwise, it is classified as 'Bad'. The mapping of road quality is shown in the upper right box of figure 6.

There were some 1680 roads that were not included in the 1830 turnpike network. However, we are almost certain those roads were used. Therefore, we include 1680 roads in the 1830 turnpike network. 1680 roads added to 1830 turnpike roads are shown in the lower left hand box of Figure 6. Note they are classified as 'bad' on the quality metric. This assumption is reasonable as parish roads were generally of lower quality. Finally, as with 1680 roads we add slopes to each road segment. The slopes are shown in the bottom right box of figure 6.

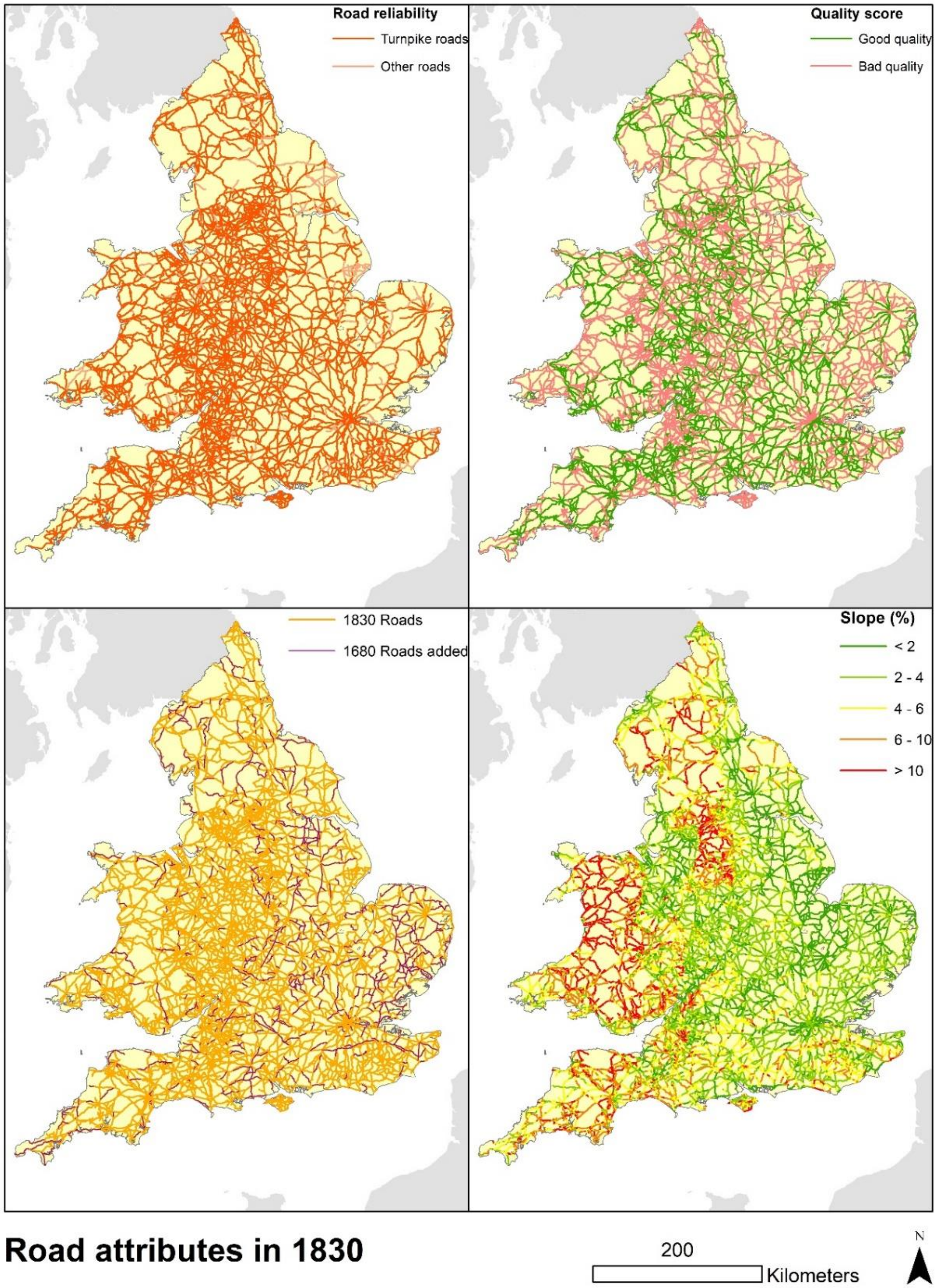

Figure 6: Roads and attribute data in 1830

Source: author's creation using Rosevear, Satchell, Bogart, Shaw Taylor, Aidt, and Leon (2017) and other sources in text.

I.E Bridges and ferries

Bridges and Ferries were also plotted into the 1830 roads GIS files. We now explain the sources and strategy for plotting data on river crossings in the GIS. Only major river crossings are considered here – loosely defined as a structure requiring large capital cost for construction and likely to have significant maintenance costs. Roads crossed streams and small rivers on structures ranging from simple culverts to small single arched bridges – these are not considered significant in the context of costing travel or determining travel speed on the GIS road network and are not plotted individually.

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

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

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

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

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

The Chadwick archive of Parliamentary Acts (covers 1799 to ca 1833) was searched through the Welcome Library web site for Acts that concerned the building of bridges. The Acts identified when a bridge would be a toll bridge (coded TB in the “was turnpike” field of the Arc GIS File) or when bridges were toll-free (coded B). Some bridges required several Acts of Parliament to increase the approval limit of building costs, and a number of bridges required new Acts for rebuilding soon after construction of a first bridge, due to collapse of the initial structure. Wikipedia entries were checked to confirm the most likely date of the first successful bridge being built – the default date used was the latest Act for building a first bridge at the site. A google search was made for bridges on the major rivers and estuaries of England and Wales – all entries that identified a toll bridge built before 1900 were recorded and the date at which tolls were lifted was noted. Finally, a visual inspection was made of all points where a turnpike road crossed a major river and any instances of a toll bridge recorded. Not all County Bridges have been separately identified in the present version of the Roads GIS.

In the Roads GIS, bridges were plotted as polylines joining roads on the adjoining banks. The OS 6 inch first edition was used to locate the bridge alinement where possible. All bridges that were not part of a turnpike trust were plotted as discrete items and associated data was that of the Bridge Trust or administrative unit. Bridges that were part of a turnpike trust were drawn as discrete polylines but the associated data was that of the turnpike trust. Where several bridges or ferries were recorded at a particular location, the bridge in use in 1830 was given priority as the straight line joining the abutting roads.

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

All instances where a bridge building Act mentions an earlier ferry were recorded and the date at which the ferry was replaced by the bridge noted. A sketch map of major Medieval Ferries was taken from Campbell and georeferenced by Max Satchell – these points were matched with potential ferry sites on Roads GIS. The OS 6 inch First series was inspected for all major rivers starting from the estuary and moving up stream along all significant tributaries. All ferries marked on this map were recorded. A google search for ferries on major rivers was used to confirm information on the possible earliest date and where applicable date of closure of ferries.

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

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

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

II. The Multi-modal model

The multi-modal model is used to estimate freight transport costs between 590 E&W towns in 1680 and again in 1830. The 590 towns are drawn from Alvarez-Palau, Bogart, Satchell, and Shaw-Taylor's (2022) new Historical Urban dataset. Briefly, the model combines several modes of transport to identify the least cost route between each town pair. Points represent towns and ports. Polylines represent networks like roads, waterways, and coastal routes. To ensure connectivity of all towns, interpolated straight lines between point layers and respective networks are created too. A 'global turns policy' is used, which means movements within and between each network are allowed. Dijkstra's algorithm finds the least cost route, minimizing a cost accessibility function C_{ij} between point i and j. In equation (1) c_i^o is the cost from the journey origin to the network, c_{pq}^n is the cost in the n transport modes between p and q, c_r^t is the cost of each trans-shipment between modes r, and c_j^d is the cost to reach the destination from the network.

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

We now give additional details. The creation of the historical GIS transport networks described in section I required topological cleaning to ensure there were no drawing errors, unwanted intersections or gaps. It ensured all networks were routable, and therefore suitable for network analysis. The next step was the amalgamation of all the different networks in just one multimodal model including all contemporary transport modes. It included transport infrastructure, such as roads, waterways and coastal routes, plus all those punctual items needed in the model, like towns and ports.

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

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

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

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

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

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

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

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

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

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

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

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

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

13. Determine XY coordinates of all intersection points.

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

15. Integrate roads and ferries.

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

17. Integrate waterways and waterway by-passes.

Once the multi-modal networks were ensembled, we proceed to create a GIS feature dataset containing a copy of all the previous features. Then we proceeded to create a network dataset including all features, allowing global turns, applying the appropriate connectivity policies (one independent group for each mode of transport), avoid elevation data (already included in the features) and defining the appropriate freight cost parameters. Figure 7 illustrates roads, waterways, coastal routes, towns, ports and their interpolated interconnections in Norfolk.

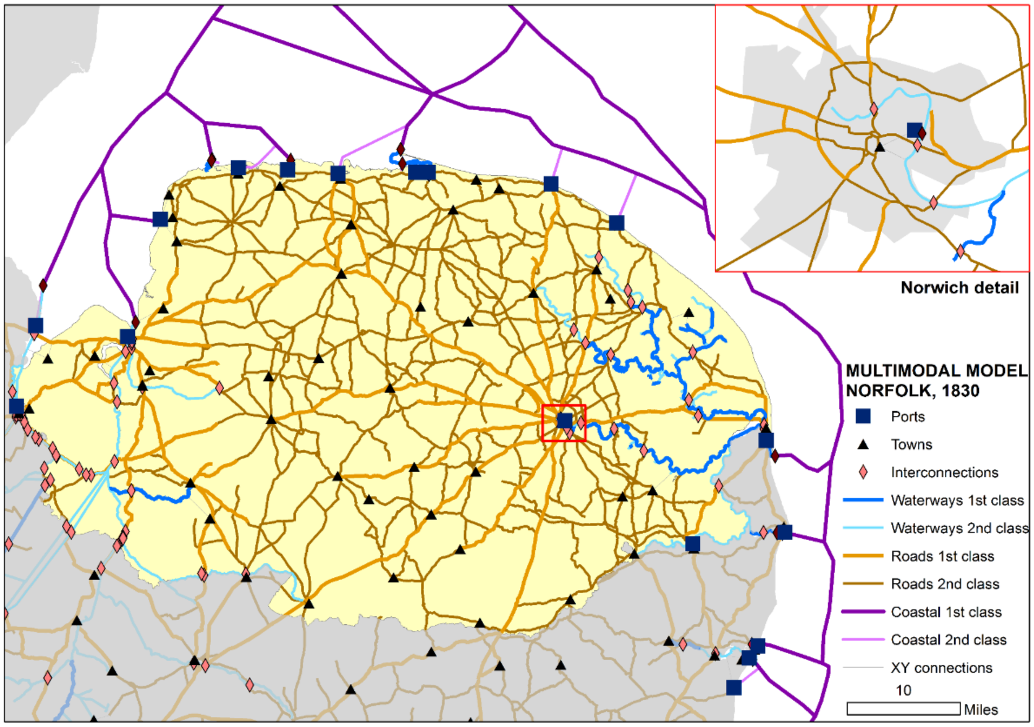

Figure 7 Multi-modal model framework: roads, waterways, coastal routes, towns, ports and their interpolated interconnections.

Table 1 gives the modal parameter values and the source basis. We now explain how they are created. Nef (1979, pp. 404-412) gives figures for coastal freight and port loading costs in the important northeast coal trade between London and Newcastle around 1690. We convert Nef's freight costs into a per ton mile rate using coastal distance between Newcastle and London and the Nef loading cost into a per ton flat figure.[12] For 1836, we use a parliamentary report on the coastal coal trade (BPP 1836, State of Coal trade, p.76). One of the most often-cited witnesses in the reports, Bentley, gives figures for loading costs and coastal freights at that time (see Ville 1986). Comparing with Nef, Bentley's testimony implies that the coastal freight rate fell from 0.21 to 0.17 pence per ton mile between around 1690 and 1830. The per ton loading coast fell from 27.1 to 22.9 pence.

Table 1: Per ton mile costs for multi modal models in 1680 and 1830.

[12] 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.

Year	1680		1830	
	parameter	source basis	parameter	source basis
coastal, pence per ton mile	0.211	Nef (1979), p. 412	0.168	Bentley in BPP
Sea port fee in pence per ton	27.1	Nef (1979), p. 404	22.9	Bentley in BPP
Trans-shipment fee, road to water in pence per ton	17.14	Nef (1979), p. 404	13.9	Bentley in BPP
inland waterways in pence per ton mile	1	Willan (1964)	2.25	Allnut (1810), p. 20
lock fee in pence per ton	n.a.		1	Priestly (1831)
Low quality road, pence per ton mile (function of height/length)	11.2+(h/l)*(298.67)	Gerhold (2005), MacNeil (BPP 1833, p. 12)	9.87+(h/l)*(238.93)	Gerhold (1996), MacNeil (BPP 1833, p. 12)
High quality road pence per ton mile as a function of height/length	9.97+(h/l)*(298.67)	Gerhold (2005), MacNeil (BPP 1833, p. 12)	7.5+(h/l)*(238.93)	Gerhold (1996), MacNeil (BPP 1833, p. 12)
ferry pence per ton	1	Willan (1964)	2.25	Allnut (1810), p. 20

Notes: (h/l) means height/length of the segment or slope. For more details see the text.

Willan (1964) summarizes inland waterway freight rates around 1700 as being 1 pence per ton mile. This figure applies to tidal rivers, like the Thames, which were then the main waterway. For 1830 a contemporary, Allnut, summarized freight rates on the river Thames as being 2.25 pence per ton mile.[13] Allnut also gives figures for several canals. They were more expensive than tidal rivers. One key factor was the number of locks, which we have included in our network data. Priestley (2014) gives a case where the cost of passing an individual lock was 1 pence per ton. We use the per lock cost to augment the 2.25 per mile cost of using canals.

Road freight rates in the late seventeenth century are generally summarized in Gerhold (2005) separately for wagons and packhorses. The average for wagons was 10.6 pence per ton and the average for packhorses was 11.9. For 1830 Gerhold (1996) reports a road freight rate of 7.5 pence per ton mile between London and Leeds. This rate comes from a large overland trade

[13] Bogart, Lefors, and Satchell (2019) discuss Allnut as source in more detail.

in woolen textiles, and along one of the best roads in England at the time. However, not all road transport was a cheap as between Leeds and London due to varying road quality. Contemporary engineers, like John McNeil, noted that draught animal power changed significantly with road quality and slope. In testimony to parliament, McNeil provided a formula based on several field experiments. The formula computes draught power based on road condition and slope. McNeil's formula is used to estimate the freight rates per ton mile on turnpike roads of different quality and with different slopes as explained below. The quality metrics were described above. Slope was obtained by extracting elevation values in the vertices of the road segment and dividing by the length between them. Our elevation raster is the Shuttle Radar Topography Mission (SRTM 90x90m), created in 2000 from a radar system on-board the Space Shuttle Endeavor by the National Geospatial Intelligence Agency (NGA) and NASA (Jarvis et. al. 2008).

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 1833, Second report from the Select Committee of the House of Lords appointed to examine the turnpike returns, p. 129). 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 p.129 gives 6 values for c. $c = 2$ on a paved road, $c = 5$ on a well made broken stone road in a dry state, $c = 8$ on a well made broken stone road with dust, $c = 10$ on a well made broke stone road covered with mud, $c = 13$ on a gravel or flint road when wet, and $c = 32$ on a gravel or flint road when covered with mud. From this formula we can calculate draught P given a wagon load, a weight, a road type, a speed, and slope and calculate draught.

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

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

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

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

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

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

Or

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

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

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

Or

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

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

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

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

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

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

Or

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

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

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

Or

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

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

III. Model outputs

The output of our multi-modal model yields estimates of freight transport costs in pence per ton between 590 towns in 1680 and 1830. Accounting for symmetry, we estimate 174,343 unique transport costs between town pairs. To illustrate we calculated normalized average trade costs costs for each town. First, we calculate the average freight transport costs between town i and all other towns. Then we divided by the average freight transport costs between all towns. The results are mapped for each town in figure 8. In 1680, inland towns faced very high normalized trade costs compared to towns near the coast or navigable rivers. In 1830, the differences in average trade costs across towns declined dramatically. They were still lower near the coast, but not so much lower as before.

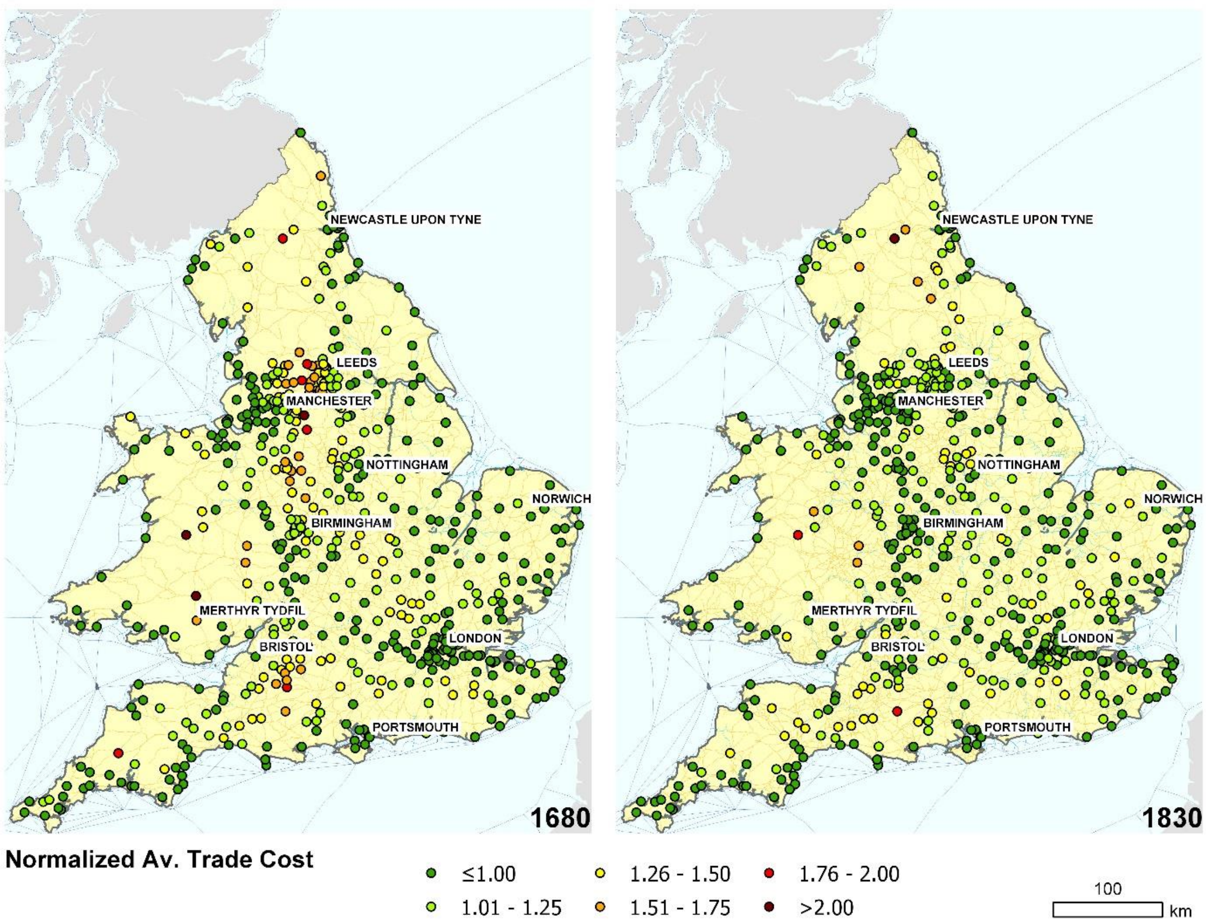

Figure 8 Normalized average transport costs for towns in 1680 and 1830.

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