Rivers vs. Roads? A route network model of transport infrastructure in Northern Italy during the Roman period

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Abstract

Northern Italy has often been characterised as an isolated and marginal area during the Roman period, a region constricted by mountain ranges and its distance from major shipping lanes. Historians have frequently cited these obstacles, alongside the lack of a major seaport on the Po, as a barrier to the region's economic development and connectivity to the rest of the Roman world. However, how isolated was the interior of Northern Italy in reality? To answer these questions, this paper analyses the results of a route network model of Northern Italy's transport network during the Roman period. Containing over 136 nodes, it enables a significantly more detailed analysis of the region's transport network than previous modelling. The model explores which were the most cost-effective routes for imports arriving from the Adriatic and Ligurian coasts, alongside which ports were the most accessible from sites in the upper and middle valley. The paper's results confirm the importance of the Po-Veneto water network in facilitating the cost-efficient movement of goods from the Adriatic coast to areas hundreds of kilometres inland and vice versa, suggesting that prior assumptions of its isolation have been over-estimated.

Keywords: Networks; Roman Transport; Northern Italy; Rivers; Roads

Introduction

Over the past three decades, network analyses have been increasingly used by the archaeological community to map past exchanges, interactions, and identities (Collar et al. (2015); Knappett (2013); Mills (2017)). The ability of network analysis to handle and visualise large, complex datasets, alongside its compatibility with more established tools such as GIS, has helped drive its adoption amongst researchers, especially in the study of ancient transport systems (Brughmans (2010); Brughmans (2013); Knappett (2013)). As transport infrastructure exists within spatial networks in real space, it readily lends itself towards reproduction in network graphs, where each edge represents a section of the route (such as a road, river, or sea-lane) and each node a junction between them. Network modelling has been applied extensively to the study of Roman transport at a variety of levels, ranging from the entirety of the Roman Empire, in the case of the Stamford ORBIS model (Meeks (2015); Scheidel (2014)), to that of a single city (Livarda and Orengo, 2015). Modelling has been used to identify the configuration of transport networks, highlighting important routes and junctions within the network alongside mapping areas of high and low connectivity. Theoretically, the lower the cost in time and money to reach one place from another, the greater the level of that region's connectivity, and the greater the scope for goods and people to access it from further afield (Brughmans (2013); Cioffi (2016), Horden and Purcell (2000)). Archaeological and geomorphological investigation has helped to reconstruct the landscape and physical routes of the ancient transport networks used in these models, while extant literary and epigraphic evidence, in particular Diocletian's Edict on Maximum Prices, has been used to give estimates of the time and cost of different transport modes (De Soto, 2019).

Although network modelling is increasingly applied to ancient transport networks, its coverage across the Roman world remains somewhat uneven. While ORBIS covered the extent of the Roman Empire, it did so at low resolution, with detail sacrificed to maintain the legibility of such a large-scale model. More detailed transport models exist at provincial or sub-provincial level, although their coverage of the Roman world remains patchy. In particular, the Italian peninsula, despite the extent and evolution of its Roman transport network being well-documented, has seen limited model application, with only a handful of published studies applying it to the region (Carreras and Soto (2013); Flückiger et al. (2022); Scheidel (2014)). Several shortcomings of prior modelling are especially apparent in the north of the country. Here, previous studies have often been conducted at low resolution, with significant pieces of infrastructure, including many of the region's minor roads and a major para-littoral canal between Ravenna and Aquileia, missing from network graphs. Natural waterways are also underrepresented, with the Po frequently assumed to be the only navigable river in the region and, even then, only navigable as far as Piacenza. The results of prior modelling have been used to highlight the isolation of Northern Italy (and the Po valley in particular) from the rest of the Italian peninsula and Rome, something that has also been commented on by historians such as Harris (2011), Patterson (2006), and Scheidel (2014). Yet how poorly connected was the interior of Northern Italy in reality? An analysis of the available archaeological evidence suggests that Northern Italy's transport network was extensive and complex. Located far inland, the western reaches of the Po valley were hundreds of kilometres from the nearest seaport yet consumed goods from across the Roman world. A robust and extensive transport network was necessary to convey these imported goods from the coast inland and transport local exports in the opposite direction. Creating a dedicated network model provides a way to test assumptions of marginality and connectivity by mapping the cost of reaching inland areas from the coast.

This paper analyses the results of a route network model of Northern Italy's transport network during the Roman period. Containing over 136 nodes, the model enables a significantly more detailed analysis of the region's transport network than previous studies. The model answers several questions about the transport network of Northern Italy, exploring which were the most cost-effective routes for imports arriving from the Adriatic and Ligurian coasts, alongside which ports were the most accessible from sites furthest inland. The results of the analysis confirm the importance of the Po-Veneto water network in facilitating the cost-efficient movement of goods from the Adriatic coast to areas hundreds of kilometres inland and vice versa, suggesting that prior assumptions of its isolation have been over-estimated.

Material and methods

The network analysis is based on the methodology developed by De Soto (2019), with additions in the form of transhipment, slope, and canal costs. The network presented here encompasses the peak extent of the transport network within Northern Italy during the second century AD and tracks a hypothetical cargo of 1000 kg. The hypothetical cargo begins its journey on land. The model assumes that transport was taking place during optimum weather and hydrological conditions on the region's rivers. It also assumes that transport travelled at a constant speed, and applies the maximum cost given by the Price Edict to transport. ArcGIS was chosen as the software to analyse the network, using the program's Network Analyst suite of tools. The network model itself is comprised of a series of four vector datasets, containing the roads, navigable rivers, canals, and sea-lanes within the study area which provide the nodes and edges for the network analysis (Page, 2023b).

For the road network, a relatively complete map of the region's major roads can be constructed from the archaeological record. The road vector dataset was originally imported from the Ancient World Mapping Centre's (AWMC) shapefile resource page (http://awmc.unc.edu/wordpress/map-files/ Accessed 13/03/23). Although the AWMC vector data offered a useful starting point, it needed significant alterations to be usable in the model. While the main pathways of the roads were broadly accurate, they did not take into account the topography of the region (some roads are mapped as traversing near-vertical surfaces in the Alps). As a result, most of the AWMC vectors were redrawn in their entirety. This involved tracing the pathway of roads over a digital elevation model (DEM) using satellite imagery, alongside georeferencing high resolution survey maps in GIS. The Copernicus EEA-10 DEM was the used to provide elevation data (https://doi.org/10.5270/ESA-c5d3d65). This resulted in far more accurate road vectors that followed realistic paths through the region's topography and matched the surviving archaeological evidence. This was especially true in the Alpine and Apennine areas of the model, where road gradient did not exceed 13 percent after the redrawing of the vectors. Due to the sharp changes in elevation over short distances and circuitous nature of routes through the mountains, it is possible some minor errors in the path and gradient of the trans-Alpine road network remain. However, given the scale of the model, they are unlikely to significantly impact on its results. The AWMC dataset was then supplemented by other road data taken from regional publications, which were manually added to the shapefile (Marini Calvini (1992); Calzolari (1992); Labate (2019); Ortalli (1992)).

The river network was created from the data for navigable rivers during the Roman period (see Page (2022a) Chapter 3, for a discussion of the evidence). The paths of the Po, Adige, and other rivers during the Roman period were taken from the AWMC river vector shapefile and corroborated with more recent geomorphological research (Bosio (1979); Calzolari (2007); Uggeri (2016)). These geomorphological investigations have mainly used a combination of aerial photography and LiDAR data to highlight traces of paleochannels in the landscape. In some cases, this was coupled with coring surveys to check the validity of the aerial photography and LiDAR, as well as providing material for dating the paleochannels. In some cases, historical data from the Roman and post-Roman period has been used to establish the connections between rivers, such as Early Medieval accounts of the Reno being a tributary of the Po (Racine, 2000). Additional rivers not included in the AWMC vector file, such as the Fiume Stella, were manually added to the shapefile. There is inevitably a degree of assumption on the course of these smaller, less intensively studied rivers during the Roman period, although their broad route is accurate. Only rivers known to have been navigable were included, although it is likely there were significantly more navigable waterways within the region.

Transport Type	Cost (kg wheat/T/km)
Maritime	0.093
Fluvial (downstream)	0.33
Fluvial (upstream)	0.66
Canal	0.66
Overland	4.92
Transhipment	10.00

Table 1. The values for the cost of transport used within the network model. Cost is expressed as kilograms of wheat, per tonne, per kilometre.

The canal network vectors were manually created. Given the limited archaeological evidence for the para-littoral canals (canals running parallel to the coast) of the *Fossae Augusta*, *Claudia*, and *Flavia*, a degree of guesswork was necessary in constructing the vectors. Reconstructions of the path of the canals were taken from several sources and compared with the ancient topography (Manzelli (2000); Grazia Maioli (2018); Rousse (2013); Uggeri (1978)). From this, a possible route for the canals was created between Ravenna and Aquileia. Canal vectors were also placed in areas where ports (such as those at Milan, Tortona, and Vercelli) were connected to the river network by manmade channels (Page, 2022b). Finally, canal vectors were also used to model travel across the glacial pre-Alpine lakes of the region, as craft using these lakes would have incurred similar challenges and costs.

The maritime network vectors included in the model represent movement along the Adriatic and Ligurian coasts. A para-littoral route was selected, with connections to the region's major ports. Although fluvio-maritime vessels, such as the Comacchio and Parco Teodorico wrecks, had the ability to move interchangeably on inland and coastal waters, allowing near-seamless movement between maritime, para-littoral canal, and fluvial contexts, it was decided to keep a firm separation between fluvial/canal and maritime transport (Beltrame (2002); Willis and Capulli (2018)). This separation removed the possibility of the network modelling river vessels that did not possess seaworthy attributes (such as flat-bottomed barges) as being able to use maritime routes.

The locations where the vector polylines join form the major nodes of the network, representing prominent sites within the region. At nodes where separate transport types intersected, network junctions were created which allowed transfer between them. These network junctions fell into the categories of Maritime to Land, Maritime to River, Maritime to Canal, River to Land, River to Canal, and Canal to Land.

With the network nodes and edges generated, it was then necessary to apply weights to them in the form of cost. The figures for transport cost in the ancient world have their basis in Diocletian's Price Edict of AD 301. The Price Edict text gives the maximum price of transport across 51 maritime routes, with costs ranging between 4 and 26 *denarii* for the transport of a single *kastrensis modius* (approximately 12.9 litres of wheat). For fluvial transport, the Edict gives a price of 1 *denarius* per *kastrensis modius* per 20 Roman miles of downstream travel and 2 *denarii* per *kastrensis modius* per 20 Roman miles of upstream travel (*Edict of Maximum Prices*, XXXVA.31-33). For terrestrial transport, the Edict gives the maximum prices of 2 *denarii* per Roman mile for a passenger in a carriage, 4 *denarii* for a fully laden donkey per Roman mile, 8 *denarii* for a camel carrying 600 Roman pounds per Roman mile, and 20 *denarii* for a wagon carrying 1,200 Roman pounds per Roman mile (*Edict of Maximum Prices*, XVII.1-5). The figures presented in the Price Edict have allowed the extrapolation of different ratios of cost between overland, upstream, downstream, and maritime transport, and from them, a base cost per mile/kilometre (see below). However, the Edict is a problematic piece of evidence, and it has been extensively critiqued as a source of pricing in the Roman era (Corcoran and DeLaine (1994); Duncan-Jones (1982)). It survives in a fragmentary state, and only records maximum prices relevant to the early fourth century AD. There was probably significant variation in costs below this total, and prices may have been higher or lower in the preceding and following periods. Furthermore, the decree seems to have been principally enacted in the eastern half of the empire, giving the potential for regional price variation. These concerns aside, Russell has shown that the ratios extrapolated from transport costs given by the Price Edict are not dissimilar to cost ratios between land, river, and sea transportation from other periods (Russell (2013), 96).

The figures used to weight the model are listed in Table 1. These values, based on Diocletian's Price Edict, are taken from De Soto (2019), with the addition of the cost estimates for canal transport and transhipment taken from Page (2022a). Prices are expressed in their wheat equivalents, rather than *denarii* as the value of wheat is thought to have remained relatively stable throughout the Roman period, (with demand and consumption remaining constant). Expressing transport costs as a unit of wheat allows them to be used for transport in earlier periods when the *denarius* had greater value (Corbier (1985); DeLaine (1992)). Within each layer, the length of each polyline in the shapefile was generated in kilometres. This figure was then multiplied by the transport cost to generate figures for the total cost to traverse each network edge. For roads, a cost penalty based on the average gradient across each polyline was added to generate new cost values. The methodology applied here was developed by Bell et al., and uses the equation tan(slope)/tan(1°) to generate an adjusted cost (Bell et al., 2002). For rivers, downstream and upstream travel were distinguished via tf (to-from) and ft (from-to) values respectively, allowing the assignment of separate values depending on the direction of travel. These figures were stored in the attribute table of each layer's shapefile. For network junctions, a transhipment cost was applied to all movement between water, maritime, and canals, and land. The only exception was movement between water and canals, which was likely seamless and utilised the same vessels. Consequently, no transhipment cost was assigned to water to canal junctions.

A multi-modal network model was created using ArcCatalog, with the steps taken outlined in detail in (Page, 2023b). Four layers of connectivity were created (sea-lanes, navigable rivers, roads, and canals), with network junctions enabling transfer between them at selected points. Nodes for input sites, representing the points that goods entered the region, were selected. These were Altinum, Aquileia, Ariminum, and Ravenna on the Adriatic coast, and Genoa, Luna, Porto Maurizio, and Savona on the Ligurian coast. In addition, the inland site of Turin, in the west of the Po valley, was selected to compare how goods might move out of the region. From these, access surfaces were mapped for cost using the program's Service Area Function, creating a series of vector polygons that mapped all accessible areas within a specified impedance from a set starting point or points. For cost, bands of 100 kg wheat were mapped, covering the entirety of the study area.

Results

The results of the analysis are outlined in the following section. Figure 1 maps the incremental cost of transport for a hypothetical 1000 kg cargo from the four Adriatic ports. The model suggests the maximum transport cost from the Adriatic ports to reach another part of the study area was 1800 kg wheat, 80% more than the value of the 1000 kg cargo. The model suggests that the entirety of the Adriatic coast could be reached for less than 100 kg wheat, a reflection of the low-cost of maritime and para-littoral canal transport. The importance of the para-littoral canals is shown where they are absent between Ravenna and Ariminum, with transport costs increasing to 200 kg wheat. The para-littoral canal system between Aquileia, Altinum, and Ravenna allowed goods originating from these ports to seamlessly access the Po-Veneto fluvial network, a transition further streamlined by the absence of transhipment costs between canal and fluvial transport. Inland sites along the Adriatic coast were accessible for under 100 kg wheat, while cities in the middle Po valley, such as Cremona,

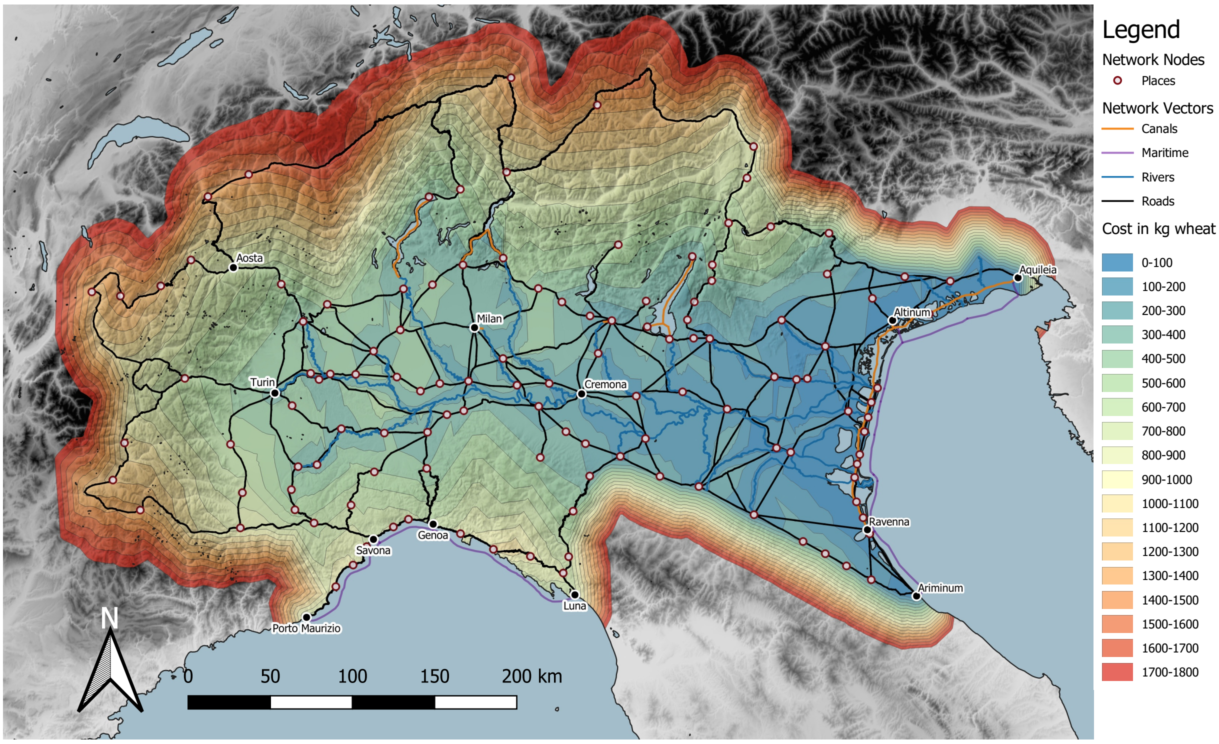

Figure 1. The incremental cost of transport from the Adriatic ports of Altinum, Ariminum, Aquileia, and Ravenna.

could be reached for a cost of under 200 kg wheat. Cost continued to accumulate as transport progressed upstream. Cities at the upper limits of the river network, such as Turin, cost 400 kg wheat to reach via fluvial routes, double the cost of transport to sites in the middle river. This formed the maximum transport cost for sites situated on a river, lake, or canal, a cost equivalent to 40% of the total value of the hypothetical 1000 kg cargo. The high density of the Po-Veneto river network helped ensure that urban centres located on the valley floor that were not on navigable waterways could be accessed for under a cost of 500 kg wheat. In the Southern Alps, the glacial lakes of Garda, Como, and Maggiore were connected to the river network. This allowed lower-cost movement into mountainous areas, which otherwise would have been significantly more expensive to access.

Transport costs sharply increased in areas where a navigable river was absent, particularly in the Alps and Apennines. 100 kg wheat could pay for 151.51 km of upstream fluvial transport, as opposed to 20.32 km of overland transport over level ground. This distance would further decrease if there was a gradient. The impact of overland transport on cost is clearly seen in the upper Po valley, where the price of transporting 1000 kg of cargo from the Adriatic coast to Aosta (800 kg wheat) doubled from 400 kg wheat over a distance of 68 km overland after it left the river network. This cost then doubled again to 1600 kg wheat in order to reach sites on the other side of the Gran San Bernado Pass in the Rhône valley. The cost of this transport exceeded the value of the 1000 kg cargo by 60%. The high prices shown here are representative of the greater cost of overland transport and especially the challenge presented by gradient in mountainous areas.

Figure 2 maps the incremental cost of transport for a hypothetical 1000 kg cargo from the four Ligurian ports. The model suggests the maximum transport cost from the Ligurian ports to reach another part of the study area was 2000 kg wheat, double the value of the 1000 kg cargo and 200 kg wheat more than the maximum transport cost from the Adriatic ports. Transport costs from the Ligurian coast are far more uneven than those from the Adriatic, with costs rapidly increasing as overland routes moved away from ports. It cost

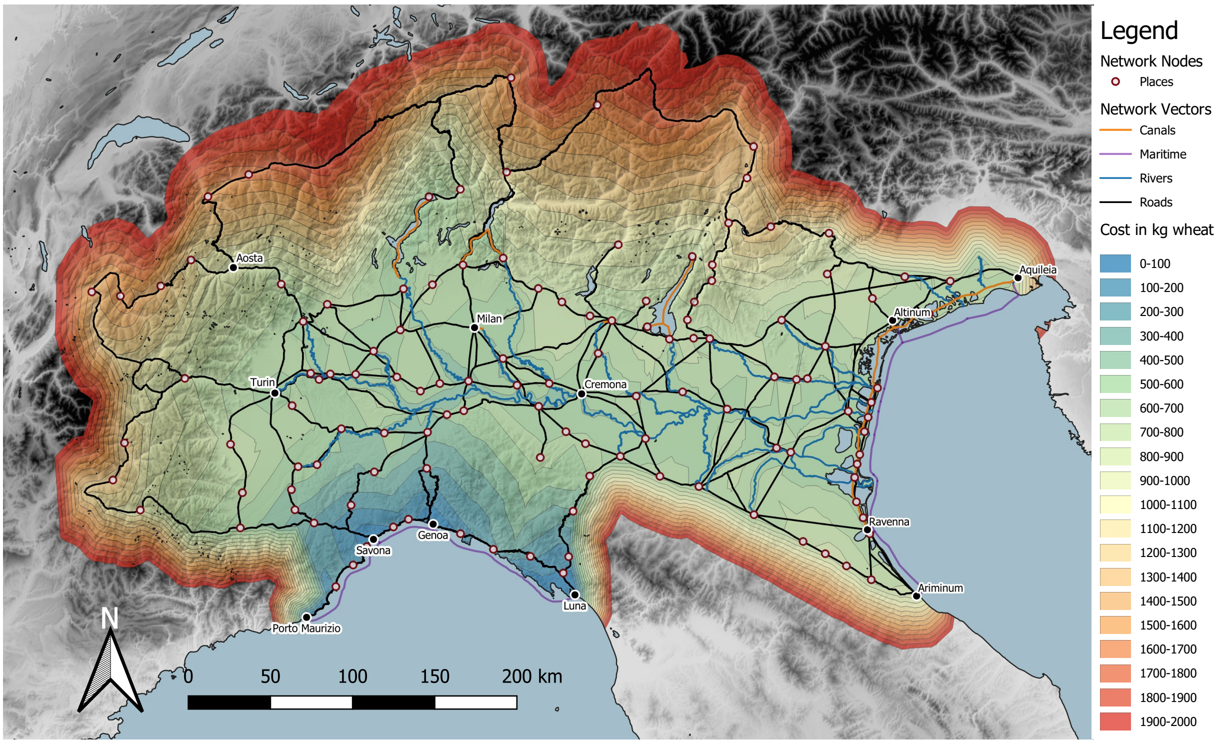

Figure 2. The incremental cost of transport from the Ligurian ports of Genoa, Luna, Porto Maurizio, and Savona.

seven times as much to transport goods overland between Luna and Genoa as it did by sea, a result of the steep and difficult roads that follow Liguria's rugged coastline.

The Apennines presented a significant cost barrier for overland travel, with prices varying between 400 and 700 kg wheat to traverse them. Beyond the mountains, the Monferrato, Langhe and Colline del Po hills forced more circuitous routes to be taken to urban centres in the south-west of the region, adding additional cost. At a minimum, these urban centres could be reached at a cost of 500-600 kg wheat, a cost of over half the value of the goods being transported. Of the Ligurian ports, Genoa and Savona seem to have been best placed from a cost perspective to access the Po valley, lying on or close to roads that crossed the Apennines which soon intersected with a navigable rivers. Although Luna also sat upon a trans-Apennine road, the model suggested it was 300 kg wheat cheaper to transfer goods via boat to Genoa, cross the Apennines using the via Postumia, and send goods into the lower Po valley along the river network, rather than use the trans-Apennine road to the eastern Po valley.

At the point that cargo reached an urban centre with a navigable river, the waterways become the primary vector of travel. The lower cost of downstream transport would have allowed goods moving from the Ligurian coast to reach ports on the Adriatic for under 700 kg wheat, up to a 200 kg wheat reduction on the cost of the same journey from an Adriatic direction. Moving off the valley floor and into the Alpine valleys and passes incurred a similar penalty to that seen in transport from the Adriatic coast. Aosta could just be reached for 1000 kg wheat, equivalent to the value of the goods transported.

Finally, Figure 3 maps the incremental cost of transport for a hypothetical 1000 kg cargo from Turin, an inland site at the supposed navigable limit of the Po. The model suggests that the maximum transport costs from Turin to another part of the study area was 1600 kg wheat. The map of costs from Turin clearly demonstrates the advantages of being on a navigable river and the possibilities offered by the low cost of downriver

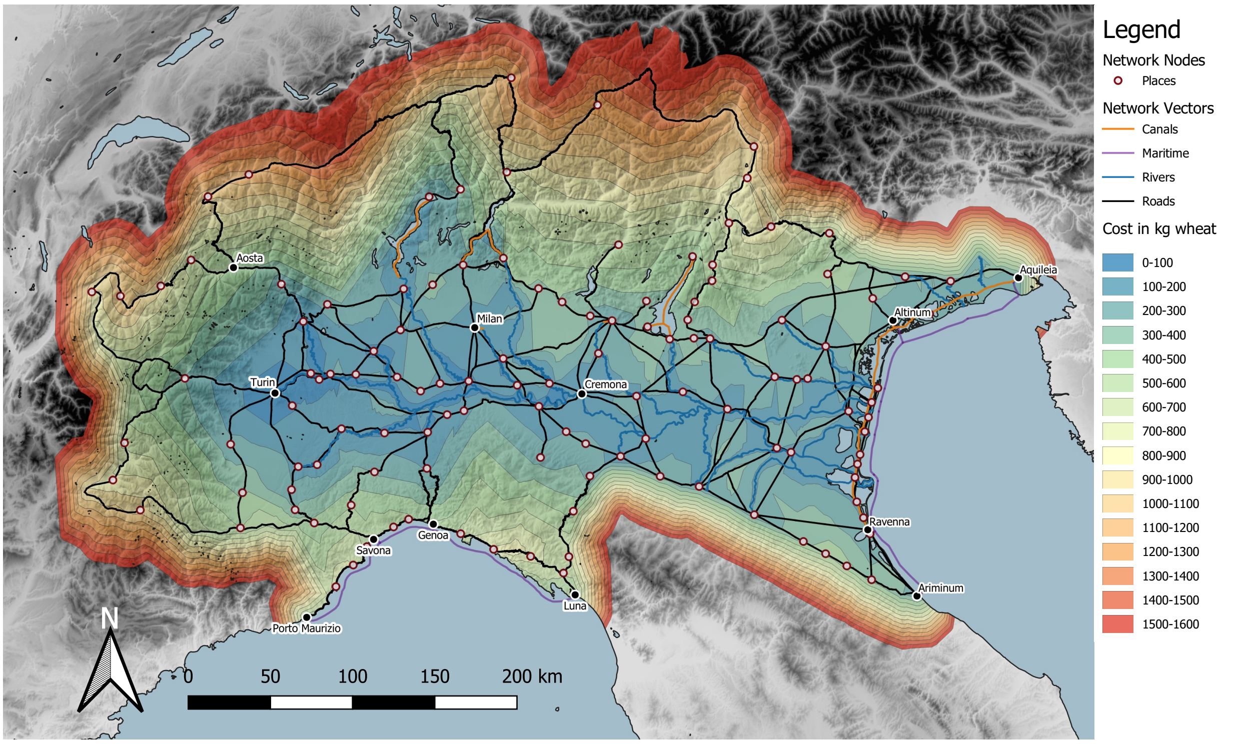

Figure 3. The incremental cost of transport from Turin.

transport. Free of the need to overcome the steep mountain gradients of the Apennines or battle upstream against a river's current to gain access to the interior, the model suggests cargo originating from Turin enjoyed low transport costs to reach other areas within the region. Almost all areas of the valley floor could be reached for under 300 kg wheat, less if they were on a navigable river. The model suggests it was possible to travel as far as Cremona for 100 kg wheat and reach the mouths of the Po for 200 kg wheat. The Ligurian ports were more expensive to reach than their Adriatic counterparts, with travel to Genoa and Savona costing between 500 and 600 kg wheat. It remained cheaper for cargo to tranship to maritime from overland routes in order to reach Porto Maurizio and Luna, with the steep coastal road adding significant costs.

Discussion

The network analysis outlined above reveals the separate challenges faced by those transporting goods from the Adriatic and Ligurian coasts, alongside inland sites, in reaching different areas of Northern Italy. Different transport modes offered various advantages and disadvantages, which the model threw into sharp relief.

Fluvial transport was shown to have had the biggest effect on how cargo moved within the model. The low cost of upstream transport allowed sites such as Turin, lying in the far west of the valley, to be reached for under 400 kg wheat from the Adriatic ports, significantly cheaper than the cost of an equivalent overland journey. Indeed, the availability of upstream transport meant that it was cheaper to reach many sites in the western valley from the Adriatic coast, despite them being geographically closer to Ligurian ports. However, while it is undeniable that the Po and its tributaries formed cost-efficient routes into the interior of Northern Italy from the Adriatic, it is worth pointing out that, in large areas of the south-west Po valley, there was less than 100 kg wheat difference in the cost of travel from the Adriatic and Ligurian coasts (see Figure 4). In this section of the valley, where the difference in transport originating from the Adriatic and Ligurian coasts was

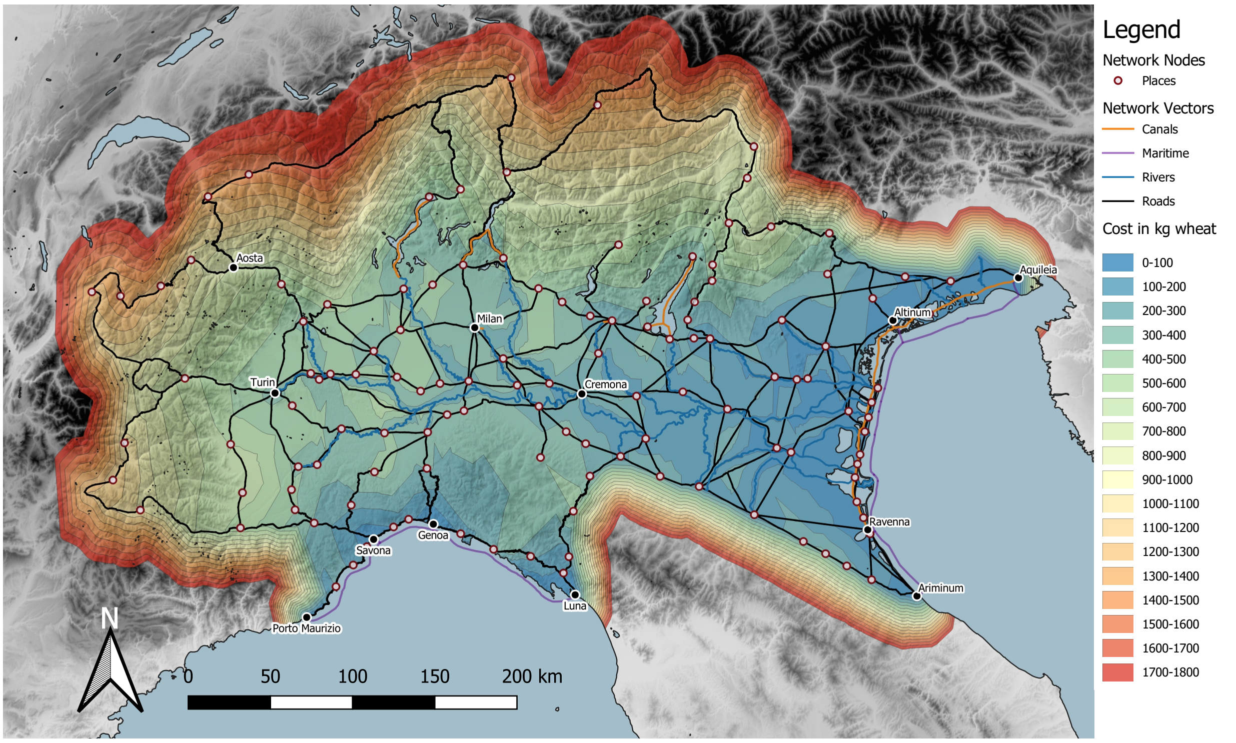

Figure 4. The incremental cost of transport from the Adriatic and Ligurian ports.

at its lowest, small changes to the price of transport or extra costs could have significantly altered the viability of one route over another. Transaction costs, such as negotiations and taxes, could significantly increase the price of cargo and transport costs would also have been accrued before goods reached ports in Northern Italy. Transport may have been charged less than the maximum, pushing back the point at which transport from one coast became cheaper or vice-versa. Goods might also be bought and sold multiple times by the time they reached their point of consumption, further complicating costs (Tchernia (2016); Terpstra (2019)). With this in mind, it is possible that transport from the Ligurian coast was more cost-efficient for a wider range of sites in the west and south-west than the network model suggests. Consequently, the dominance of the Adriatic axis of transport over the Ligurian should not be assumed across the entirety of the region. The model also demonstrated the importance of the river network in providing low cost transport from inland sites to the coast. From Turin, every site on a river connected to the Po could be reached for under 200 kg wheat, while the major Adriatic ports fell within the cost bracket of between 200-300 kg wheat. This underpins the importance of the Po as a corridor for goods produced in the western part of the region travelling to Aquileia, and beyond that, the Danubian *Limes*. Indeed, the merchant L. Tettianus Vitalis, buried in Turin, recorded on his grave monument that the Po and the Sava (a tributary of the Danube) were the two rivers most important to his business (*CIL* V.7047; V.7127; Gabucci, Mennella, and Pejrani Baricco (2000); Gabucci and Mennella (2003)).

Moving away from navigable rivers, transport became more costly. This was especially true for the more mountainous areas of the region, in particular, the northern and western Alps. While the entirety of the valley floor was traversable for well below 1000 kg wheat, cost rapidly increased as soon as attempts were made to scale any of the major Alpine passes such as the San Bernadino, the Great St. Bernard, and the Little St. Bernard, where slopes frequently exceeded 10%. Indeed, for peripheral sites in the Alps, such as Aosta, there may not have been much difference in cost between transporting goods from Gaul (in particular goods originating from the Rhône valley) and transporting goods from the Adriatic and Ligurian seaboards (Gabucci, 2017). Gradient significantly affected the cost of overland transport, although the path of roads tried to limit this as much as possible. In mountainous areas, roads routinely followed the path of valley floors before ascending and, where this was not possible, infrastructure such as bridges, viaducts, and buttresses helped to reduce the gradient (Mollo Mezzana (1992)). Of course, when ascending an Alpine pass, there was a limit to how much could be done to reduce the impact of slope, reflected in the high cost these areas of the model incur. While some areas of the Apennines, such as the road between Luna and Po valley, were also significantly affected by gradient, the via Postumia, the main trans-Apennine road between the Po valley and Genoa, followed the valley of the Torrente Scrivia for much of its path. This reduced the route's elevation and slope, which, in turn, reduced the cost of transport using it to cross the Apennines.

Crucially, the model challenges the assumption that the Apennines made transport from the Ligurian coast into the Po valley uneconomical. Although the Apennines did form a significant obstacle in terms of cost for goods arriving from Ligurian ports, this was matched by the cost of transporting goods from the Adriatic coast into the upper reaches of the valley. This presents the question as to whether different areas of the valley may have been linked into either western (served by the Ligurian ports) or eastern (served by the Adriatic ports) Mediterranean markets. Although the model suggests that, in certain areas, it was possible for goods travelling over the Apennines to compete with those coming up from the Po in terms of transport cost, the question remains as to whether or not there was specific demand to make this journey worthwhile (Page, 2023a). The proximity of Adriatic production areas to the study area and the demands from other, more accessible markets in the west for goods passing through the Ligurian ports, may have made the trans-Apennine journey unappealing to potential traders.

Although the network analysis focused on inland regions, the model suggested that maritime routes retained an important role in the movement of cargo in coastal areas. In the case of the Ligurian ports, they allowed cargo to be transported at low cost from ports such as Porto Maurizio and Luna, to harbours better placed to begin the overland journey across the Apennines. This also worked in reverse, where cargo could be transferred from overland to maritime transport to circumvent the expensive and time-consuming journey along the Ligurian coast road. The cost-efficiency of maritime transport often meant that if one port on a coastline could be reached, then other ports on that seaboard could normally be accessed within the same or adjacent cost bracket. The density of maritime, canal, and fluvial routes along the Adriatic coast contributed to the low cost of navigating this area of the network.

Transhipment penalties had a mixed effect on the cost and speed of transport. A 2% transhipment cost does not seem to have significantly impacted smaller cargoes, as the high cost of overland transport enabled waterborne goods could easily absorb the additional price. Of course, the model cannot account for quirks in human nature and non-quantifiable factors that may have influenced decision-making. For example, although high cost did not pose a barrier to transhipment in the model, the transfer of goods and materials posed significant risks, especially with large, bulky loads such as stone and marble that were difficult to handle (Russell, 2013). The potential for breakage or loss of cargo increased with each transfer, and it is questionable whether shippers would have risked transhipping cargo if it could have been avoided.

The network analysis of Northern Italy's Roman transport network suggests that, far from being a difficult and prohibitively costly region to traverse, there was good accessibility for large areas of the Po valley from coastal regions and vice versa. The model largely confirms the importance of waterways in facilitating cost-efficient travel within inland regions, with the Po and its tributaries forming an important axis for transport due to their extent and density across the valley floor. However, away from fluvial and maritime routes, the expense of overland transport, compounded by gradient, rapidly increased costs. While the cost of traversing overland routes, particularly those in the mountains, likely posed a significant obstacle to trade, this was not insurmountable. The picture of the transport network that has emerged is far more complex than previous studies of Northern Italy have accounted for, and the image of an isolated and disconnected region, with minimal choice and access to imports, is no longer viable.

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Conflict of interest disclosure

The author declares that they comply with the PCI rule of having no financial conflicts of interest in relation to the content of the article.

Data, script, code, and supplementary information availability

The vectors files used to create the route network model explored in this paper, alongside instructions on how to create the network dataset used to generate its results, are hosted online: https://doi.org/10.5281/zenodo.7937731.

References

Bell T, A Wilson, and A Wickham (2002). Tracking the Samnites: Landscape and Communications Routes in the Sangro Valley, Italy. *American Journal of Archaeology* 106, 169–86. https://doi.org/10.2307/4126242.

Beltrame C (2002). Le sutiles naves romane del litorale alto-adriatico. Nuove testimonianze e considerazioni tecnologiche. In: *Archeologia subacquea. Studi, ricerche e documenti III*. Ed. by Gianfrotta PA and Pelagatti P. Roma, pp. 353–79.

Bosio L (1979). I Septem Maria. *Archeologia Veneta* 2, 33–44.

Brughmans T (2010). Connecting the dots: towards archaeological network analysis. *Oxford Journal of Archaeology* 29, 377–303. https://doi.org/10.1111/j.1468-0092.2010.00349.x.

— (2013). Thinking Through Networks: A Review of Formal Network Methods in Archaeology. *Journal of archaeological method and theory* 20, 623–662. ISSN: 1072-5369. https://doi.org/10.1007/s10816-012-9133-8.

Calzolari M (1992). Le Strade Romane della Bassa Padania. *Atlante tematico di topografia antica* 1, 161–68.

— (2007). Il Delta padano in Età romana: idrografia, viabilità, insediamenti. In: *Genti nel delta da Spina a Comacchio: uomini, territorio e culto dall'antichità all'alto Medioevo*. Ed. by Berti F, Bollini M, Gelichi S, and Ortalli J. Ferrara, pp. 153–72.

Carreras C and P de Soto (2013). The Roman transport network: a precedent for the integration of the European mobility. *Journal of Quantitative and Interdisciplinary History* 46, 117–33. https://doi.org/10.1080/01615440.2013.803403.

Cioffi R (2016). Travel in the Roman World. *Oxford Handbooks*, 1–39.

Collar A, F Coward, T Brughmans, and B Mills (2015). Networks in Archaeology: Phenomena, Abstraction, Representation. *Journal of archaeological method and theory* 22, 1–32. ISSN: 1573-7764 1072-5369. https://doi.org/10.1007/s10816-014-9235-6.

Corbier M (1985). Dévaluation et évolution des prix, Ier - IIIe siècles. *Revue Numismatique* 27, 69–106.

Corcoran S and J DeLaine (1994). The unit measurement of marble in Diocletian's Prices Edict. *Journal of Roman Archaeology* 7, 263–273. ISSN: 1047-7594. https://doi.org/10.1017/S1047759400012617.

De Soto P (2019). Network Analysis to Model and Analyse Roman Transport and Mobility. In: *Finding the Limits of the Limes. Modelling Demography, Economy and Transport on the Edge of the Roman Empire*. Ed. by Verhagen P, Joyce J, and Groenhuijzen M. Springer Open Access, pp. 271–90. https://doi.org/10.1007/978-3-030-04576-0_13.

DeLaine J (1992). Design and construction in Roman imperial architecture : the Baths of Caracalla in Rome. Thesis.

Duncan-Jones RP (1982). *The Economy of the Roman Empire: Quantative Studies*. 2nd. Cambridge.

Flückiger M, E Hornung, M Larch, M Ludwig, and A Mees (2022). Roman Transport Network Connectivity and Economic Integration. *The Review of Economic Studies*, 1–71. https://doi.org/10.1093/restud/rdab036.

Gabucci A (2017). *Attraverso le Alpi e lungo il Po: importazione e distribuzione di sigillate galliche nella Cisalpina*. Vol. 532. École française de Rome. https://doi.org/10.4000/books.efr.3241.

Gabucci A and G Mennella (2003). Tra Emona e Augusta Taurinorum. Un mercante di Aquileia. *Aquileia Nostra* 74, 318–34.

Gabucci A, G Mennella, and L Pejrani Baricco (2000). Un mercante di Aquileia tra 'Emona' e 'Augusta Taurinorum'. *Aquileia Nostra* 71, 522–24.

Grazia Maioli M (2018). Antiche acque di Ravenna. In: *Il genio delle acque: scavi nelle piazze di Ravenna*. Ed. by Guarnieri C and Montevecchi G. Ravenna: L'Erma di Bretschneider, pp. 331–42.

Harris W (2011). Trade and the River Po: A Problem in the Economic History of the Roman Empire. In: *Rome's Imperial Economy: Twelve Essays*. Ed. by Harris W. 2nd ed. Oxford: Oxford University Press, pp. 189–97. https://doi.org/10.1093/acprof:osobl/9780199595167.001.0001.

Horden P and N Purcell (2000). *The Corrupting Sea: A Study of Mediterranean History*. Oxford: John Wiley.

Knappett C (2013). Introduction: Why Networks? In: *Network Analysis in Archaeology: New Approaches to Regional Interaction*. Ed. by Knappett C. Oxford: Oxford University Press, pp. 3–15. https://doi.org/10.1093/acprof:oso/9780199697090.001.0001.

Labate D (2019). Archeologia di una strada consolare: la via Emilia dalla fondazione all'età contemporanea. *Atlante tematico di topografia antica* 29, 195–212. https://doi.org/10.1400/269868.

Livarda A and H Orengo (2015). Reconstructing the Roman London flavourscape: new insights into the exotic food plant trade using network and spatial analyses. *Journal of Archaeological Science* 55, 244–52. https://doi.org/https://doi.org/10.1016/j.jas.2015.01.008.

Manzelli V (2000). Documentazione Archeologia. *Atlante tematico di topografia antica Supplimenti* 2, 39–196.

Marini Calvini M (1992). Strade Romane dell'Emilia Occidentale. *Atlante tematico di topografia antica* 1, 187–92.

Meeks E (2015). The design and implementation of ORBIS: The Stanford geospatial network model of the Roman world. *Bulletin of the Association for Information Science and Technology* 41, 17–21. ISSN: 2373-9223. https://doi.org/10.1002/bult.2015.1720410206.

Mills B (2017). Social Network Analysis in Archaeology. *Annual review of anthropology* 46, 379–397. ISSN: 0084-6570. https://doi.org/10.1146/annurev-anthro-102116-041423.

Mollo Mezzana R (1992). La strada romana in Valle d'Aosta: procedimenti tecnici e costruttivi. *Atlante tematico di topografia antica* 1, 58–72.

Ortalli J (1992). La Cispadana Orientale: Via Emilia e altre Strade. *Atlante tematico di topografia antica* 1, 147–60.

Page J (2022a). From the Adriatic to the Alps: An Examination of Inland Trade in Northern Italy Between the First Century BC and Fifth Century AD. Thesis.

— (2022b). Riverbed, banks and beyond: an examination of Roman infrastructure and interventions in response to hydrological risk in the Po–Venetian plain. *Papers of the British School at Rome* 90, 171–200. https://doi.org/10.1017/S0068246221000258.

Page J (2023a). 'Carrying up it all the products of the seas': The Po-Veneto water network and trade in the Roman period. In: *Rivers and Waterways in the Roman World*. Ed. by Tibbs A and Campbell P. London: Routledge, pp. 85–99. https://doi.org/https://doi.org/10.4324/9781003277613.

— (2023b). Modelling Transport in Northern Italy During the Roman Period. Dataset. https://doi.org/10.5281/zenodo.7937731.

Patterson J (2006). *Landscapes and Cities: Rural Settlement and Civic Transformation in Early Imperial Italy*. Oxford: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198140887.001.0001.

Racine P (2000). Il vescovo di Piacenza, signore della città (997). *Studi di storia medioevale e di diplomatica - Nuova Serie* 18, 79–96. https://doi.org/https://doi.org/10.54103/2611-318X/9811.

Rousse C (2013). Opérations de canalisation dans les ports fluvio-maritimes de la Regio X Venetia Histria: réflexions sur l'urbanisme et les transformations du territoire à l'époque Romaine. *Antichità Altoadriatiche* 76, 123–40.

Russell B (2013). *The Economics of the Roman Stone Trade*. Oxford: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780199656394.001.0001.

Scheidel W (2014). The shape of the Roman world: modelling imperial connectivity. *Journal of Roman Archaeology* 27, 7–32. https://doi.org/10.1017/S1047759414001147.

Tchernia A (2016). *The Romans and Trade*. Oxford: Oxford University Press. https://doi.org/10.1093/acprof:oso/9780198723714.001.0001.

Terpstra T (2019). *Trade in the Ancient Mediterranean: Private Order and Public Institutions*. Princeton. https://doi.org/10.1515/9780691189703.

Uggeri G (1978). Vie di terra e vie d'acqua tra Aquileia e Ravanna in età Romana. *Antichità Altoadriatiche* 13, 46–79.

— (2016). "La Romanizzazione dell'antico delta padano." 40 anni dopo: una revisione. *Atti dell'Academia delle Scienze di Ferrara* 93, 79–104.

Willis S and M Capulli (2018). A Report on the late 1st–2nd-century-AD Venice Lido III Sewn Timber Assemblage. *The International Journal of Nautical Archaeology* 47, 343–36. https://doi.org/10.1111/1095-9270.12322.