ORBIS: The Stanford Geospatial Network Model of the Roman World

Version 1.0

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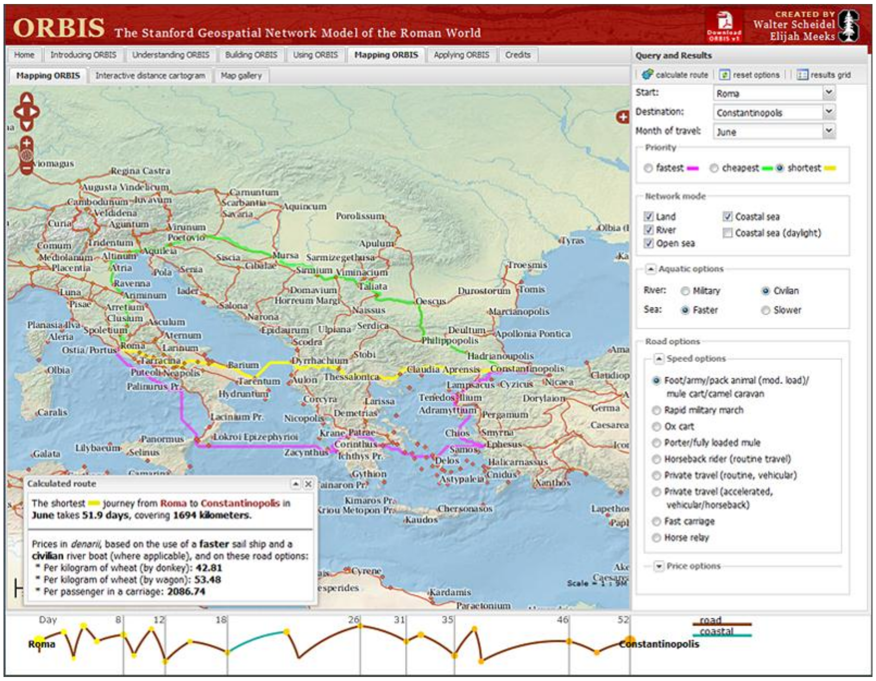
Abstract. Spanning one-ninth of the earth's circumference across three continents, the Roman Empire ruled a quarter of humanity through complex networks of political power, military domination and economic exchange. These extensive connections were sustained by premodern transportation and communication technologies that relied on energy generated by human and animal bodies, winds, and currents.

Conventional maps that represent this world as it appears from space signally fail to capture the severe environmental constraints that governed the flows of people, goods and information. Cost, rather than distance, is the principal determinant of connectivity.

For the first time, ORBIS allows us to express Roman communication costs in terms of both time and expense. By simulating movement along the principal routes of the Roman road network, the main navigable rivers, and hundreds of sea routes in the Mediterranean, Black Sea and coastal Atlantic, this interactive model reconstructs the duration and financial cost of travel in antiquity.

Taking account of seasonal variation and accommodating a wide range of modes and means of transport, ORBIS reveals the true shape of the Roman world and provides a unique resource for our understanding of premodern history.



Start: Roma
Destination: Constantinopolis
Month of travel: June

Priority
○ fastest ○ cheapest ● shortest

Network mode
☑ Land
☑ River
☑ Open sea
☑ Coastal sea
☐ Coastal sea (daylight)

Aquatic options
River: ○ Military ● Civilian
Sea: ● Faster ○ Slower

Road options
Speed options
● Foot/army/pack animal (mod. load)/ mule cart/camel caravan
○ Rapid military march
○ Ox cart
○ Porter/fully loaded mule
○ Horseback rider (routine travel)
○ Private travel (routine, vehicular)
○ Private travel (accelerated, vehicular/horseback)
○ Fast carriage
○ Horse relay
Price options

Calculated route

The shortest journey from **Roma** to **Constantinopolis** in **June** takes **51.9 days**, covering **1694 kilometers**.

Prices in *denarii*, based on the use of a **faster** sail ship and a **civilian** river boat (where applicable), and on these road options:
- Per kilogram of wheat (by donkey): **42.81**
- Per kilogram of wheat (by wagon): **53.48**
- Per passenger in a carriage: **2086.74**

Contents

Introducing ORBIS

ORBIS: The Stanford Geospatial Network Model of the Roman World reconstructs the time cost and financial expense associated with a wide range of different types of travel in antiquity. The model is based on a simplified version of the giant network of cities, roads, rivers and sea lanes that framed movement across the Roman Empire. It broadly reflects conditions around 200 CE but also covers a few sites and roads created in late antiquity.

The model consists of 751 sites, most of them urban settlements but also including important promontories and mountain passes, and covers close to 10 million square kilometers (~4 million square miles) of terrestrial and maritime space. 268 sites serve as sea ports. The road network encompasses 84,631 kilometers (52,587 miles) of road or desert tracks, complemented by 28,272 kilometers (17,567 miles) of navigable rivers and canals.

Sea travel moves across a cost surface that simulates monthly wind conditions and takes account of strong currents and wave height. The model's maritime network consists of 900 sea routes (linking 450 pairs of sites in both directions), many of them documented in historical sources and supplemented by coastal short-range connections between all ports and a few mid-range routes that fill gaps in ancient coverage. Their total length, which varies monthly, averages 180,033 kilometers (111,864 miles). Sea travel is possible at two sailing speeds that reflect the likely range of navigational capabilities in the Roman period. Maritime travel is constrained by rough weather conditions (using wave height as proxy). 158 of the sea lanes are classified as open sea connections and can be disabled to restrict movement to coastal and other short-haul routes, a process that simulates the practice of cabotage as well as sailing in unfavorable weather. For each route the model generates two discrete outcomes for time and four for expense in any given month.

Figure 1 - Sea routes in July, with coastal routes in blue and overseas routes in green.

The model allows for fourteen different modes of road travel (ox cart, porter, fully loaded mule, foot traveler, army on the march, pack animal with moderate loads, mule cart, camel caravan, rapid military march without baggage, horse with rider on routine travel, routine and accelerated private travel, fast carriage, and horse relay) that generate nine discrete outcomes in terms of speed and three in terms of expense for each road segment. Road travel is subject to restrictions of movement across mountainous terrain in the winter and travel speed is adjusted for substantial grade.

Figure 2 - Roads and rivers modeled in ORBIS.

Fluvial travel is feasible on twenty-five rivers on two types of boat. Travel speed is determined by ancient and comparative data and information on the strength of river currents. Cost simulations are sensitive to the added cost imposed by movement upriver and, where appropriate, take account of local variation in current and the impact of wind. The river routes are supplemented by a small number of canals. For each route there are four discrete outcomes for time and four for expense.

Overall, the network consists of 1,371 base segments for which the model simulates a total of more than 363,000 discrete cost outcomes. The model allows users to generate time and expense simulations for connections between any two sites across different media and for specific means and mode of transport and months of the year. A future upgrade will enable users to generate distance cartograms of all or parts of the network that visualize cost as distance from and to a central point, which can be any site in the network. A preliminary dynamic version can be found on the other tab on this page.

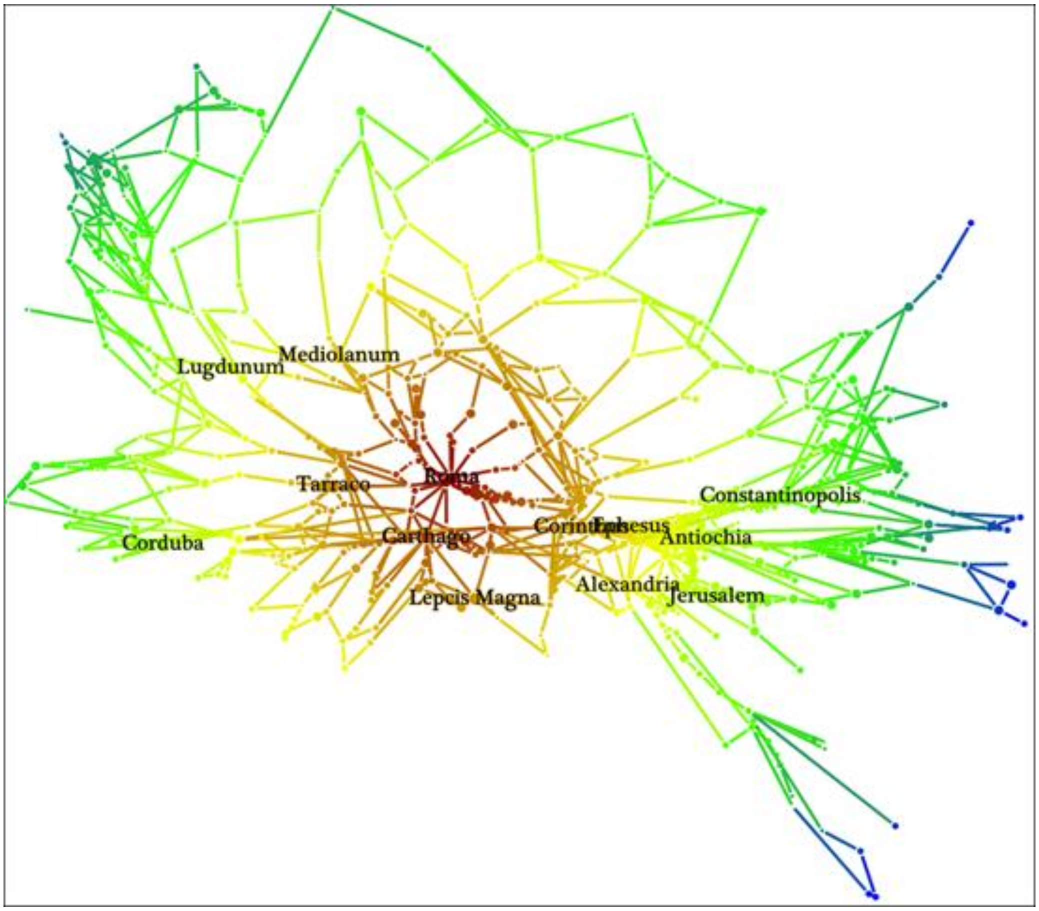


Figure 3 - A distance cartogram that distorts the location of Roman sites based on the time it would take (via all modes) to travel to that site from Rome.

This application facilitates simulation of the structural properties of the network, which are of particular value for our understanding of the historical significance of cost in mediating connectivity within the Roman Empire. We expect this function to be available on this site by the end of 2012. Cost contour maps serve the same purpose.

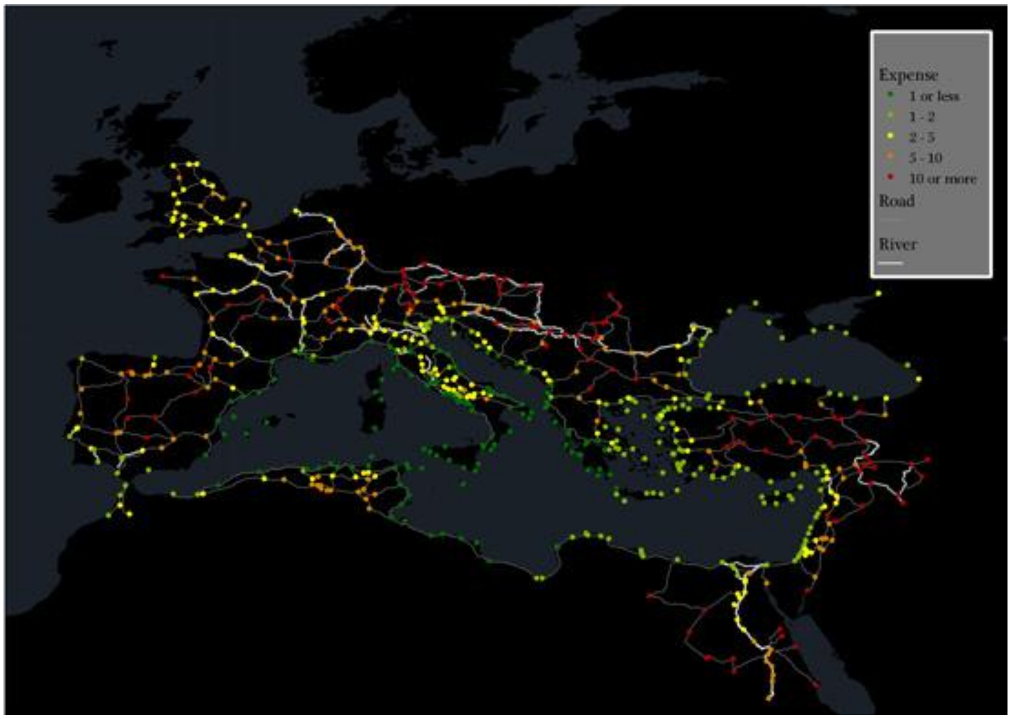
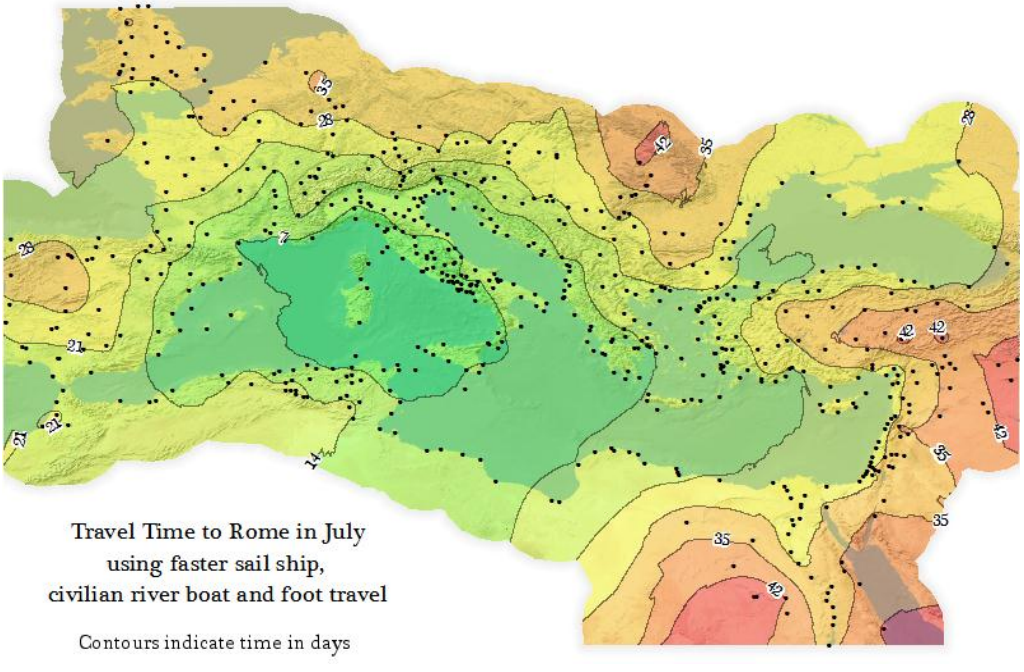


Figure 4 - A cost distribution map, with the geography of the Mediterranean world maintained but the sites colored by the cost (via all modes) of shipping grain from that site to Rome.



Understanding ORBIS

Managing expectations

It is important to appreciate what this model can and cannot be expected to accomplish. Fernand Braudel, in his famous account of the Mediterranean in the sixteenth century, highlighted the "struggle against distance," against distance as the "first enemy" of premodern civilization (Braudel 1995: 355, 357). Our model seeks to improve our understanding of how a large-scale system such as the Roman Empire worked, of the effort it took to succeed in the struggle to connect and control tens of millions of people across hundreds and thousands of miles of land and sea. This objective informs the model's perspective: it is top-down, focusing on the system as a whole. Its simulations prioritize averages over particular outcomes; large-scale connectivity over local conditions; and the logical implications of choices over actual preferences. Each of these three key features is briefly explained in the following sections, and each of them must be understood to make proper use of the model.

Particularity and structure

Our model approximates the structural properties of Roman communication networks. Simulations of the costs associated with a given route are not meant to reflect the experience of any particular traveler. Rather, they seek to capture statistically average outcomes that cumulatively shaped the system as a whole. No one traveler would encounter such outcomes except by chance. The model simulates the average experience of a very large number of travelers taking the same route in a given month using a given mode and means of transport. It is this experience that is decisive for our understanding of how Roman networks operated. Patterns of connectivity were a function of average outcomes in the long term that shaped the choices of actors and hence the overall structure of the networks themselves. For this reason, particular simulations cannot be expected to match individually documented time costs unless such costs are reported as normative and were therefore used for the calibration of the model simulations, a process described in "Building ORBIS". Instead, they convey a sense of how any given route related to other routes in terms of typical cost. The structural features of the system that are determined by these relations are best expressed not through individual route simulations but in the form of cost contour maps and distance cartograms that depict the consequences of employing specific modes and means of transportation across an entire network.

The same principle applies to simulations of expense, which not only rely on a dataset of debatable value (the price controls of 301 CE) but are inevitably crude in eliding real-life variation in transportation prices. In the economic sphere, expense matters even more than speed, which makes it essential to attempt at least a rough approximation of the cost differences between particular modes of transport. The resultant projections should be taken in the spirit in which they are offered, as a preliminary sketch of the dramatic contrasts between terrestrial, fluvial, and maritime transportation expenses and the patterns they imposed on the flow of goods within the system overall. In as much as the Roman Empire critically depended on transfers driven by tributary redistribution and market exchange, even a highly schematic approximation of their underlying costs promises to make a significant contribution to our understanding of its achievements and limitations.

Resolution and scope

In keeping with its focus on systemic features, the model is in the first instance confined to the main arterial roads and other essential connectors of the Roman road network instead of seeking to reproduce it in its (known) entirety. Many minor rivers that are not included would have been navigated by rafts and shallow boats. The number of potential sea routes is vast, constrained only by the number of points of anchorage that might be connected across maritime space. By necessity and design, ORBIS models a simplified version of Roman connectivity. By necessity, given the workload associated with any serious attempt to track down every single Roman road and every navigable river, and especially with the computational burden of simulating discrete outcomes for tens of thousands of often only marginally different sea routes. Much the same is true of the cost of incorporating more detailed wind data or ubiquitous low-velocity surface currents, or of continually adjusting terrestrial speed for grade and river speed for variation in current (see “Building ORBIS”).

Yet the model is also limited by design. The most fundamental concern is not workload as such but return on investment: more fine-grained coverage would not significantly contribute to the overall objective of this project, which is to understand the dynamics of the Roman imperial system as a whole. The inclusion of minor land, river and sea routes or of more detailed terrain constraints would have little if any discernible effect on the broad picture. The model’s utility is a direct function of the level of resolution: the smaller the scale of the simulation, the less likely the model is to approximate reality. Short-distance movement from one valley to the next or between adjacent islands may not be captured at all if low-tier connections are lacking, or only very crudely. The reliability and usefulness of the model increase with scale. It is therefore essential to ask appropriate questions, focusing on longer-range connectivity. In this respect, ORBIS differs from existing models that archaeologists and anthropologists employ in order to simulate local conditions. Our approach is not merely different but complementary: ORBIS is sufficiently flexible to accommodate detailed and more precise case studies of local movement simply by adding information for a given area, and we are planning to do so in the future.

Finally, in restricting coverage to the more important elements of the Roman communication system, the model not only maintains its emphasis on systemic features but also helps approximate ancient constraints. For instance, while much of the sea is in theory navigable without major restrictions, sailors would often follow established routes, and certain roads and rivers were more heavily used than others and hence more vital to the functioning of the system. The model’s parsimonious coverage takes account of such preferences in order to avoid the simulation of a counterfactually optimized environment characterized by specious efficiencies and excessive choice.

Options and constraints

The model maximizes user options by keeping absolute constraints on movement to a minimum. Sea routes are assumed to be navigable at all times of the year unless a strong likelihood of rough weather (determined by wave height) shuts them down. River travel is similarly unconstrained, even though rivers may sometimes have been too shallow for navigation in the warm season or frozen in the winter. Roads are routinely classified as accessible although in practice they were seasonally vulnerable to snow, flooding, or sand storms. Minor restrictions on winter travel across certain mountain routes are the only constraints imposed on terrestrial movement. The model’s tolerance of unfavorable conditions is consistent with historical evidence that shows that travel was on occasion undertaken even in highly adverse circumstances: ships braved rough seas and armies crossed the Alps in the depths of winter. At the same time, this tolerance fails to give due weight to ancient preferences that might effectively have curtailed travel at certain times of the year.

This is not a serious problem. Any trip, however and whenever taken, was prone to unpredictable obstacles that cannot be accommodated within a generalized model. Simulated outcomes are based on projected averages that do not tell us about the probability that any particular route would have been taken at any particular time of the year. This should be seen as a strength rather than a weakness of the model: it places users in a position not entirely different from that of ancient travelers who had to make choices and cope with their consequences. It is true that unlike modern observers, these travelers had access to local knowledge that cannot readily be factored into the model. To address this deficit, simulations of trips that were likely to encounter seasonal hazards will soon be accompanied by pertinent warnings. It is feasible in principle to incorporate ancient preferences into the model: agent-based modeling would allow us to discriminate between routes depending on seasonal and other constraints and refine our understanding of hierarchies within the system. The current model is designed to provide infrastructure for such probabilistic simulations and we hope to expand our project in this direction (see “Building ORBIS: The future of the project”).

Building ORBIS

Historical evidence

This section offers a general overview of the data and assumptions on which our model simulations are based. In most cases, it would have been possible to include much more detailed information. Even so, in the interest of accessibility we have sought to keep this survey to a manageable length and refrain from detailed discussion of the finer points of historical interpretation or technological issues. We expect that several features and implications of the model will be reviewed in greater depth in a number of publications by individual contributors, which will be referenced here as they become available.[1] Building ORBIS is an ongoing process and we welcome and encourage comments, queries, and constructive criticism addressed to orbisproject@stanford.edu.

Sites

The network is organized around 751 sites. Most of them represent urban settlements of the Roman period, supplemented by a number of promontories and other landmarks that were significant for travel. With few minor adjustments, labeled sites are named in accordance with our map source (Talbert 2000). Labeled sites have been ranked in five categories of size and importance in keeping with the classification system in the map key of the same reference work. In some cases, rankings have been adjusted to correct for inconsistencies between different maps in Talbert 2000.[2] On the network map, the size of sites reflects their relative standing. Sites that are not settlements were consistently assigned the lowest of the five ranks.

268 of the sites function as sea ports. In antiquity, most of them were located on the coast, although a few of them no longer are, due to changes in the coastline. Nineteen of the sea ports are connected to the sea by rivers but were accessible to seagoing ships. Except in a very few cases in which these ports are relatively far removed from the coast, these fluvial connections have not been separately classified as river routes. Owing to the impact of the tides that supported upriver navigation, sea ports situated on rivers were common on the Atlantic shores of the Roman Empire. A number of sites on rivers or the coast are connected to the network by more than one mode of transportation.

The sites included in the network account for only a small fraction of the thousands of sites recorded in Talbert 2000. In selecting them, priority was given to cities of considerable size and importance: most of the sites that Talbert 2000 ranks in the top two tiers and actually belong in this category are part of the network. Other sites are included either thanks to their regional or historical importance or, and above all, due to their function within the Roman road network. In keeping with the overall perspective of this project, the model privileges sites that were situated at the intersection or the end of major roads.

We are exploring ways of providing richer historical context for this selection of nodal sites, such as the addition of a large number of other Roman-era settlements in order to facilitate orientation and navigation on the network map at high levels of resolution.

Sea transport

Routes

The model allows movement along 900 maritime connections between coastal sites, which can be ports or landmarks such as promontories or river mouths. These routes were established by privileging sea lanes that are documented in ancient sources, drawing in the first instance on the evidence gathered by Pascal Arnaud for the Mediterranean (Arnaud 2005) and the Black Sea (1992).[3] These connections were supplemented by creating short-distance routes that link adjacent coastal sites along coasts or across island chains and by a small number of additional medium-distance routes inspired by comparative historical data that address gaps in the ancient coverage. Due to the lack of usable evidence, Atlantic sea routes were in their entirety supplied by linking relevant ports in a deliberately conservative fashion.[4] The Red Sea (and, by extension, part of the Indian Ocean) may be included at a later date.

The resultant network roughly approximates the preferred routes of sailors in the Roman period. By adopting this template, the model follows Arnaud's persuasive interpretation of ancient maritime networks of commerce as relying on a modest number of segmented routes that combined high sea crossings with coastal connections and thereby imposed structured connectivity on seascapes (e.g., Arnaud 2005, 2007). This approach seems preferable to one that we considered at an earlier stage of the project, which would have allowed direct connections between any two coastal sites within a given radius, generously set at 500 miles to approximate the distance between Alexandria and Crete. This method would have created over 10,000 discrete routes and was abandoned when it became clear that it would take months of continuous computing to simulate all these connections and therefore require access to high-speed computing resources. More importantly, this approach would have created a speciously efficient sailing environment that reduced cost and friction below historically plausible levels. It turned out to be unfeasible for us for the same reason why it would have been unmanageably complex for ancient sailors: in both cases, information costs – the ancient cost associated with commanding knowledge of the properties of a vast number of direct routes as well as the modern cost arising from heavy computational loads – were too high.

Sea routes are treated as accessible at all times of the year but cannot traverse areas where wave heights of at least 12 feet are encountered for at least 10 percent of the time in a given month, a condition that serves as a proxy of stormy weather (National Imagery and Mapping Agency 2002). In the Roman world, such weather events were limited to the Atlantic and, in the winter, the northwestern Mediterranean south of France.[5] Thanks to this absolute constraint, the model severely curtails sailing options in the Atlantic during the winter months. Sea ice would not normally have been present.[6] The fact that outside specified areas of particularly rough weather, sea lanes are considered usable throughout the winter does not mean that sea travel was equally likely to occur at different times of the year. Both ancient and subsequent premodern sources emphasize the hazards of winter sailing and envision more or less formal constraints on maritime movement in that season (e.g., Ramsay 1904: 376; Goitein 1967: 316-7; Leighton 1972: 132; Meijer 1983; Ohler 1989: 11; Jehel 1993: 315-6; Braudel 1995: 248-9; Horden and Purcell 2000: 137-43; McCormick 2001: 444-68). However, as there is no evidence of a generalized closure of the seas at any time of the year, the model seeks to mirror reality by providing the option of travel even under unfavorable conditions and at times when it would have been effectively rare. Pending a future upgrade, an output field at "Mapping ORBIS" will provide information on the seasonal hazards of selected routes.

For purely pragmatic reasons, the model considers five of the sea routes to have been continually operational. Three of them are essentially “ferry routes” across the Bosporus, the Dardanelles and the Strait of Messina, which are needed to connect Europe to Asia and Sicily to Italy. The two others cross the Strait of Gibraltar and the Strait of Dover to maintain links between Europe and North Africa and between mainland Europe and Britain. These routes are considered operational even when the option of travel by sea is otherwise disabled for the purpose of route simulation. This assumption is consistent with meteorological data in that none of these connections (with only one minor exception) would have been routinely interrupted even during the winter.

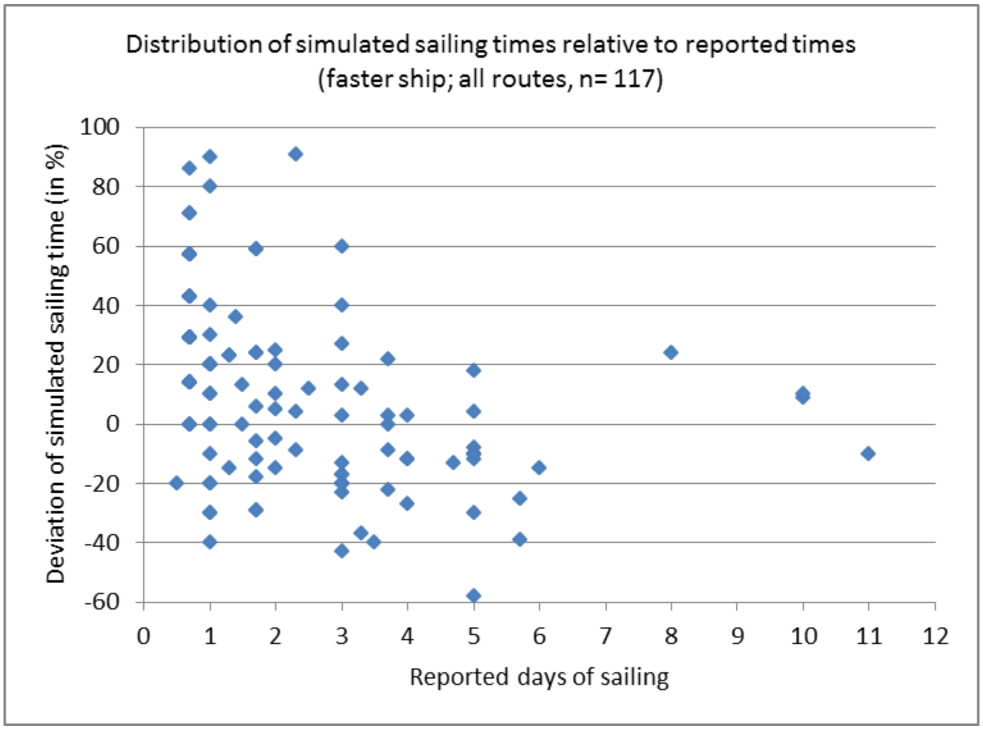
Time

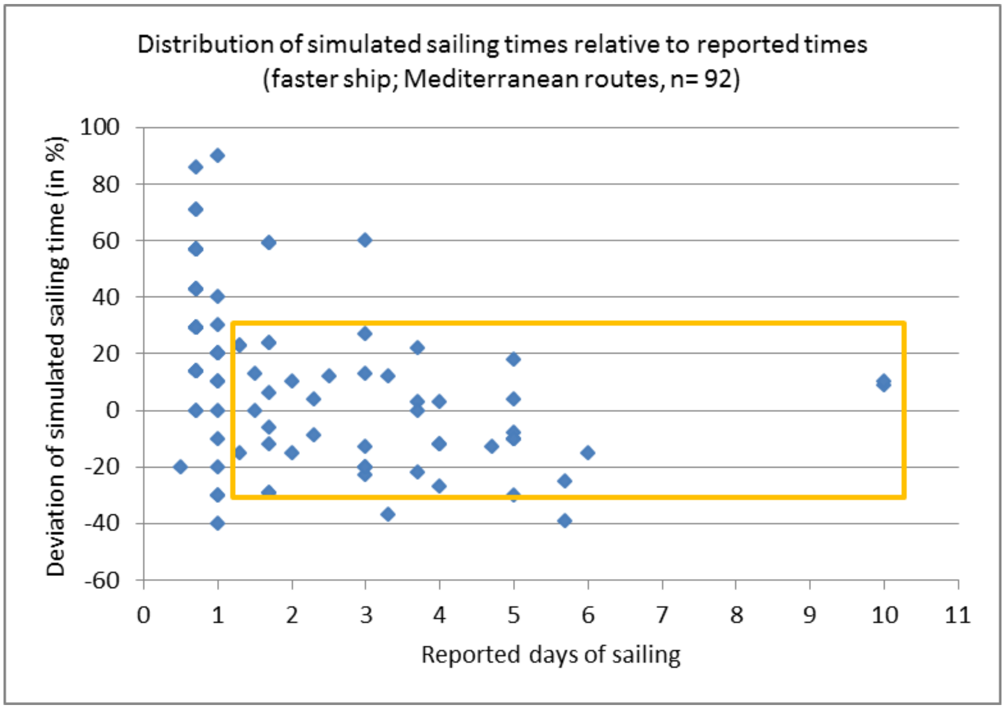
Time cost is determined by three factors: winds, currents, and navigational capabilities. Monthly wind data for the Mediterranean and the Atlantic were derived from National Imagery and Mapping Agency 2002. Data for the Black Sea were only available in a somewhat different format (Great Britain, Meteorological Office 1963), which might account for slight discontinuities in simulation outcomes.[7] Winds were incorporated into the model in the way described by Scott Arcenas in “Applying ORBIS:” meteorological information about the speed and direction of winds in different sectors of the sea was combined with experimental data concerning the performance of square-rigged vessels in a variety of wind conditions and historical evidence for maximum sailing velocity made good in order to model the movement of Roman-style sailing ships across the sea. Current constraints were only included in areas where they were unusually powerful: in descending order of significance, in the Bosporus, the Dardanelles, and the Strait of Gibraltar.[8] Seasonal costs for storm conditions were applied to transits through the Strait of Messina in the winter months002E[9] Currents in the Strait of Bonifacio (between Corsica and Sardinia) and in the Strait of Dover were insufficiently significant or regular to be included.[10] In most parts of the Mediterranean and the coastal Atlantic, surface currents do not normally exceed 0.5 knots except in strong winds, a background influence that would not make a large difference to our simulations and was therefore excluded from our model.[11] Although feasible in principle, the inclusion of currents raises modeling challenges because they act on seaborne vessels differently from wind and, more importantly, the force of surface currents themselves is to a significant extent determined by wind strength in ways that may also affect their direction. Future development of the model may include experiments with the impact of currents and its interaction with wind.

The parameters underlying the model’s simulation of sailing capabilities are explained by Arcenas in “Applying ORBIS.” The model offers the option of maritime travel using two different types of sailing ship which differ in terms of their ability to sail against the wind. We refrained from adding a separate option for oar-propelled vessels given that sailing was the principal means of maritime travel.

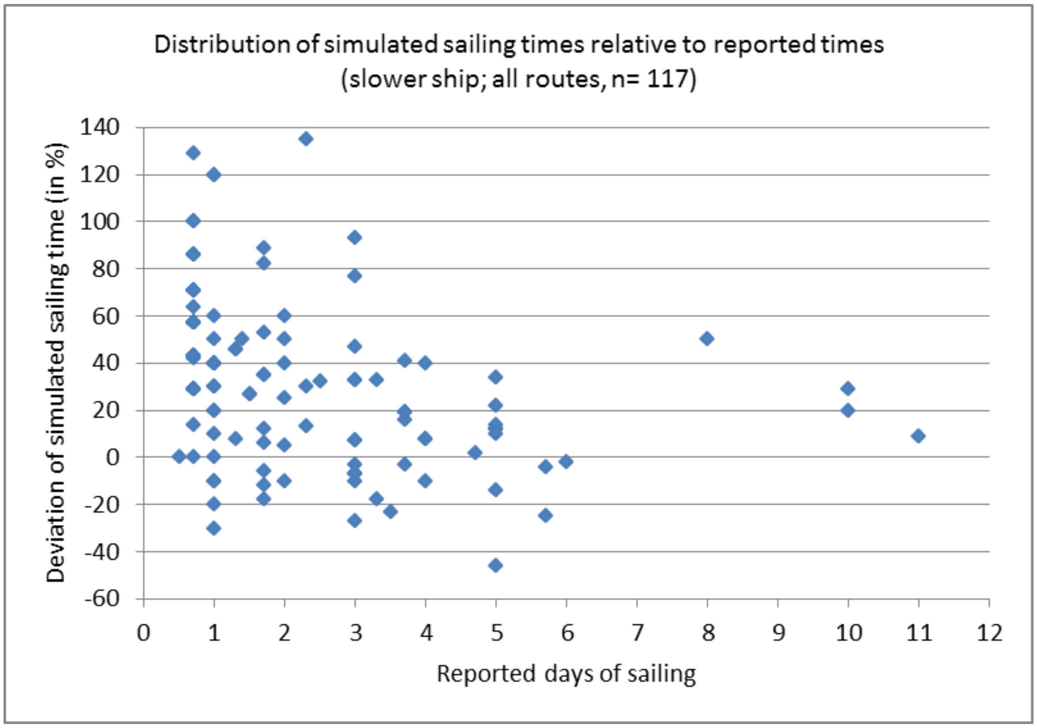
Simulated sailing times constitute mathematical averages that simulate the path and speed of a ship that experiences wind proportionate to the overall distribution of its strength and direction in a given month. They are not meant to reflect the actual experience of any given ship following a specific route but rather the cumulative experience of an infinite number of ships undertaking the same voyage, averaged across all individual outcomes. This approach emphasizes the structural properties of each route, which are of central importance to our understanding of the nature of the network as a whole.

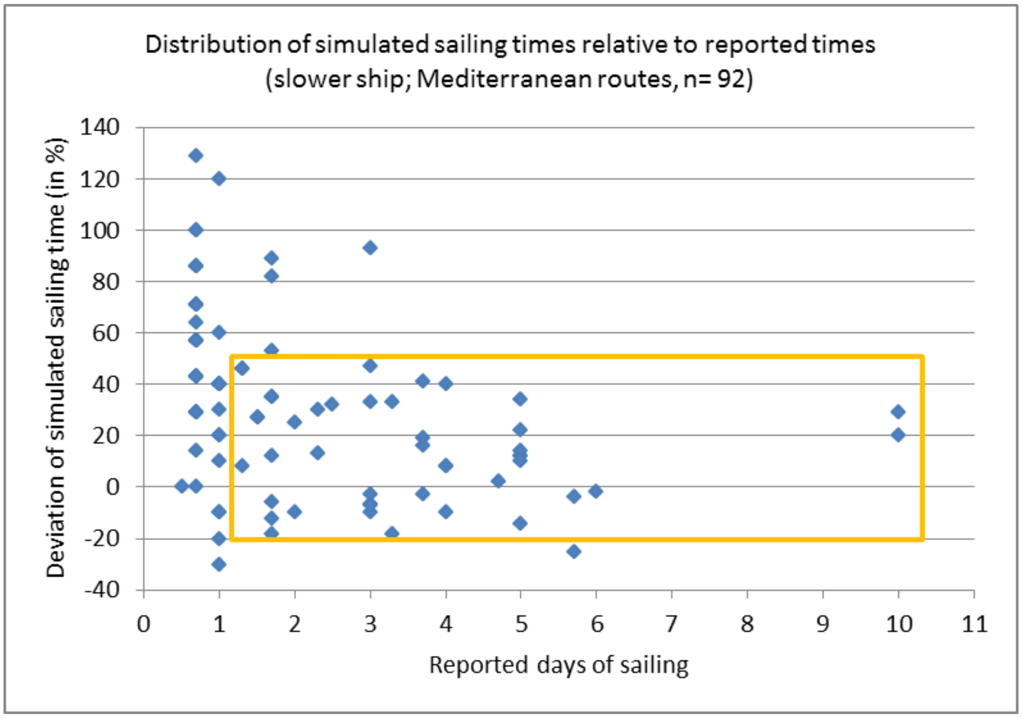
Simulations were checked against over 200 historically documented sailing times, not all of which were suitable for calibration purposes. Calibration relied on a reference sample of 117 sea routes for which putatively common sailing times or time proxies in the form of notional distances are recorded in ancient sources, and which were gathered from Arnaud 2005 and other resources. For the routes contained in this sample, mean simulated sailing speeds for the slower ship type are approximately one-sixth lower than for the faster one. This range not only underlines the approximate nature of the simulations but also reflects uncertainty about the most appropriate method of calibration. In statistical terms, the model's two sailing modes generate two significantly different outcomes. Applying the slightly faster sailing mode, simulated travel times in excess of 24 hours cluster around the values reported in the reference sample. (Among the Mediterranean routes, where the reference data are of somewhat superior quality, almost all simulated outcomes differ by less than plus or minus 30 percent from reported values, as indicated by the orange box.) Beyond trips of up to 24 hours, these deviations cumulatively cancel each other out, so that the average sailing time for all simulated voyages is virtually the same as the mean of all reported sailing times in the reference sample.





These findings suggest that the model's simulations are reliable in the aggregate if we proceed from the assumption that they should on average match reported travel times. While this may well be the most reasonable interpretation, concerns arise from the fact that in this scenario a large number of voyages are faster than expected. This is a problem because whereas actual travel times may frequently have exceeded expected values due to meteorological and navigational difficulties, they were less likely to fall short of them by a significant margin. Sailing speed cannot be expected to follow a normal distribution around a mean or median but is more heavily constrained on the high end than on the low end: ships are not normally capable of surpassing routine speeds by a wide margin but are always able to move much more slowly than usual. This raises concerns that a simulation that often over-performs relative to reported expectations might generate outcomes that are somewhat too optimistic overall. The slower sailing mode, by contrast, projects somewhat longer travel times for most routes, an outcome that might be preferable to the extent that reported expectations were slanted towards somewhat favorable conditions and therefore failed to approximate statistically average outcomes.


Distribution of simulated sailing times relative to reported times
(slower ship; all routes, n= 117)
Deviation of simulated sailing time (in %)
140
120
100
80
60
40
20
0
-20
-40
-60
0
1
2
3
4
5
6
7
8
9
10
11
12
Reported days of sailing


Distribution of simulated sailing times relative to reported times
(slower ship; Mediterranean routes, n= 92)
Deviation of simulated sailing time (in %)
140
120
100
80
60
40
20
0
-20
-40
0
1
2
3
4
5
6
7
8
9
10
11
Reported days of sailing

Both sets of simulations produce defensible outcomes. Instead of deciding between them, we prefer to present them as a range of outcomes that broadly match ancient expectations and therefore presumably circumscribe actual experience.

As is clear from the above charts, in both sailing modes very short simulated trips (of up to 24 hours) take much longer than reported. We consider this a strength rather than a flaw of the model. Trips that were expected to be completed between dusk and dawn or within 24 hours were governed by different choices than longer trips, in that meteorological conditions at the time of departure would have been of critical importance: trips were either undertaken under reasonably favorable circumstances or postponed. In this context, statistically average travel times would bear little relation to expected travel times, which cannot have been meant to include delays at the point of departure. Our simulations arguably improve on these reported expectations by factoring delays into overall outcomes: to give a simple example, a trip that would ordinarily take one day to complete but was on average only convenient on two days out of three would be assigned a mean duration of 1.5 days by our model. By coming closer to capturing the true cost of short-haul communications, the simulations are bound consistently to exceed reported expectations by a significant margin. This is borne out by the deviations charted in the above graphs, which show a clear discontinuity between day trips and longer voyages. This observation is consistent with comparative historical evidence of an inverse relationship between the length of voyages and the degree of variance in travel time (Braudel 1995: 364).

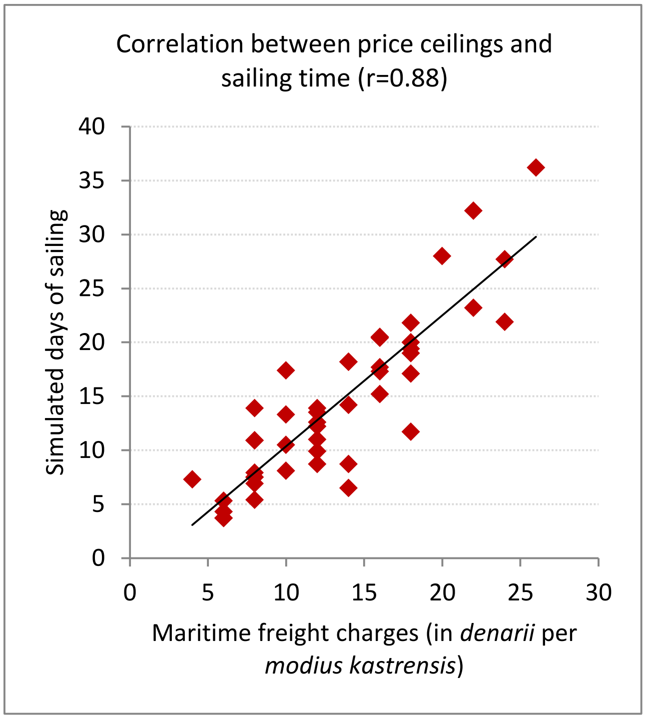
The model's simulations represent a radical departure from the conventional practice of estimating Roman sailing times from anecdotal references or attempts to derive average nautical speeds from relating documented durations to geographical distance. The statistically average character of the simulated outcomes requires them to exceed reported record times of particularly fast voyages, an expectation that is borne out by comparison between simulated and reported record speeds (e.g., Ramsay 1904: 379; Braudel 1995: 358-63; Casson 1995: 282-8; Arnaud 2005: 102). In practice, however, many actual voyages would have been slower than predicted by our simulations. For instance, even if they took place between the same start and end points without intermediate stops, they may have been marred by navigational shortcomings or costly constraints imposed by local preference, whereas the model simulations always select the optimal path for a given route, a degree of perfection that cannot readily be ascribed to real-life sailors. Vagaries of local geography, such as problems in entering or leaving ports under certain wind conditions, would have imposed costs that cannot be predicted by the model. More importantly, at least some of the historical sea voyages for which times are recorded may have been discontinuous, extended by undocumented layovers in ports or at anchorages. This makes it likely that simulated outcomes are faster than most recorded individual voyages, a prediction that is likewise consistent with preliminary tests.

As explained in "Understanding ORBIS," users need to be aware of the specific character of the model's simulations to appreciate their uses and limitations for historical study. The model allows users to adapt simulated outcomes to reflect different preferences. The option to disable open sea routes makes it possible to simulate, albeit very roughly, the practice of cabotage by constricting maritime movement to coastal routes and short-range movement between islands. This effect can be enhanced by restricting coastal sailing to daylight hours. Users who wish to add a further element of verisimilitude may simply choose to add a certain time cost to any port included in a voyage, a function that is not provided on this site but can easily be performed on an ad hoc basis. It is particularly advisable to allow for extra time in entering sea ports that are situated on rivers, a process that relied on tidal currents.

Expense

Maritime freight charges have been derived from the price ceilings stipulated by the tetrarchic price edict of 301 CE. This text records 51 prices for different routes, 49 of which are identifiable (Arnaud 2007: 336). Prices range from 4 to 26 *denarii communes* for the transport of 1 *modius kastrensis* (about 12.9 liters). Earlier attempts to employ these values in estimates of Roman shipping costs sought to relate them to direct geographical distance (e.g., Duncan-Jones 1982: 367-8; cf. Rougé 1966: 98-9). As Arnaud recently recognized, the problem with this approach lies in the fact that distances may not have been known or were in any case not particularly relevant per se; instead, travel time would have served as a critical determinant of monetary cost. Prior to the creation of the present model, it was not possible to test most of the edict's maritime freight rates against probable travel times. This is largely a function of the idiosyncratic character of the document, which centers on relations between the major political centers and secondary nodes and shows little overlap with records regarding well-established routes for which travel times or time proxies in the form of notional distances are reported in ancient geographical sources.[12]

The model follows Arnaud's intuition that the price ceilings recorded in the edict correspond to sailing times (Arnaud 2007: 330). The model's simulations based on the faster sailing ship support Arnaud's equation of 1 *denarius* with 1 day of travel (Scheidel in preparation b). Although the slower sailing mode would produce a somewhat different ratio, the model adopts this deliberately conservative equation to avoid exaggerating the price difference between cheap maritime travel and costlier modes of transport. Almost 80 percent of variance in price is explained by time cost. This finding indicates that the maritime price ceilings imposed by the price edict were far less vitiated by bureaucratic misapprehensions than has customarily been assumed.



In keeping with the proposed benchmark rate of 1 *denarius* per *modius kastrensis* per day, the model applies an expense of 0.1 *denarii* per 1 kilogram of wheat per day. The schematic conversion ratio (in section XXXVA.25-6 of the Aphrodisias copy of the price edict) that equates the cost of transporting a passenger by sea to the cost of shipping 25 *modii kastrenses* and yields a simulation rate of 25.2 *denarii* per passenger per day seems unduly low even for a passenger in steerage, given that the allowance of 323 liters (or one-third of a cubic meter) creates just about enough space for a person standing up straight. As already noted before (Duncan-Jones 1982: 386), the edict appears to understate the cost of passenger travel relative to that of goods.

There can be little doubt that even disregarding this last issue, the edict's figures provide at best a very rough sense of actual prices and price ratios, which must have depended on a variety of factors such as cargo type, ship size, season, tolls, and so forth. At the same time, the fact that Roman rule had created a relatively safe and predictable environment for maritime transport and traders would therefore have been less exposed to toll predation, piracy and other vagaries of commercial activity than in many other periods raises the possibility that variation in actual pricing might have been relatively muted (Scheidel 2011). In this context, even the crude representations of the price edict may be accepted as a serviceable index of shipping costs for the purpose of simulating the properties of the network as a whole. Future iterations of the model might seek to fine-tune these simulations by applying a sliding-scale discount function in order to accommodate trends in price/time ratios. Given the fairly crude character of the underlying data set, this cannot be expected to make a great difference overall. The main value of the expense simulation lies in highlighting the massive impact of cost differences between maritime and other forms of transport on the structure of the system. It also reinforces our understanding of the Mediterranean Sea as the essential core of the Roman imperial network, as illustrated in our distance cartograms. No plausible adjustment of the model parameters could alter this fundamental fact.

Road transport

Routes

The model contains 814 road segments that allow movement in both directions. The total length of the road network is 84,631 kilometers. While this matches conventional estimates of 80-100,000 kilometers for the principal Roman road network, the cumulative length of all the land routes depicted in Talbert 2000 must be considerably greater even than that. Our guiding principle in selecting road routes was to ensure adequate levels of connectivity throughout the Roman Empire. The model therefore seeks to include the most important roads as well as those required to reach all peripheral regions or maintain links between arterial roads. The model prioritizes radial arterial roads that connect center to periphery over orbital roads that link the former.[13] The selection process was informed by the paths of the routes listed in Roman itineraries, which were included as comprehensively as possible whenever they tracked major roads.[14]

The trajectories of most of the roads covered by the model follow the information given in Talbert 2000 (see "Building ORBIS: Geospatial technology: Roads") or are interpolated wherever the atlas does not offer a precise reconstruction. In a few cases, gaps in coverage were closed with the help of additional map resources for the southern Balkans (Koder et al. 1976; Soustal 1981), northern Mesopotamia (Stier et al. 1991), and the western Egyptian desert (Fakhry 1974).[15] In Upper Egypt, where the precise location of roads is notoriously unclear, the model assumes a single road along the Nile instead of separate ones on each river bank, a simplification that does not significantly affect overall cost outcomes. The model adopts another simplifying assumption by treating most roads as equivalent in terms of their physical condition and hence expected speed on level ground. An exception is made for caravan tracks in the Egyptian desert, which are considered unsuitable for certain types of travel (vehicles and horse relays).

Project contributor Eunsoo Lee has collected historical information on the names and construction dates of Roman roads in the network. Owing to uneven evidence, consistent coverage of either one of these attributes cannot be achieved. Pending a site upgrade, the existing information will be made available to users in response to queries in order to provide historical context. However, chronological differentiation within the network remains unfeasible except in very rough terms and would seem inadvisable given that an absence of Roman-built roads cannot be taken to imply an absence of preceding terrestrial transport routes. The model does not faithfully reflect conditions at any particular point in time but for practical reasons treats all Roman-era features documented in Talbert 2000 as effectively contemporaneous.

In keeping with the model's focus on large-scale connectivity, simulations of road routes work best over longer distances. Connections within regions may require detours that would have been made unnecessary by secondary roads that are not included in the model network, and most settlements that existed in the Roman period are not directly connected to the network at all. Enhanced articulation of the road network will require the addition of further sites and roads, which is planned for the future. The magnitude of this task is underscored by the fact that even excluding all bottom-tier settlements, Talbert 2000 shows more than 3,000 Roman-era sites, four times the number of sites in the model, not all of which are urban settlements.[16]

Road distances have been determined by measuring the routes derived from Talbert 2000 and other resources referenced in the previous section (see "Building ORBIS: Geospatial technology: Roads"). Due to the large scale of the maps that were utilized in generating the model's road network, road paths cannot be expected to match Roman roads with precision but are bound to be somewhat straighter and therefore somewhat shorter than in reality. Given Roman preference for straight roads, any such deviations are probably modest and unlikely to affect simulated cost outcomes in any significant way: the underlying time and expense parameters play a much greater role than distance in determining cost. Even so, we tested the hypothesis that measured road routes might be somewhat too short by comparing them to corresponding distances recorded in Roman itineraries. This hypothesis was not supported by the historical data (see Dan-el Padilla Peralta's summary in "Applying ORBIS").[17]

Time

Roman roads were used by a wide variety of pedestrians, animals and vehicles, and at an even wider variety of velocities. Time costs were determined not only by means of transport but by road quality, the spacing of suitable rest stops, grade, obstructions such as bodies of water, and seasonal constraints from spring floods to summer heat and winter ice and snow. The model captures only the most important types of time cost in what is inevitably a highly generalized fashion. Numerous studies were employed in establishing simulation parameters (key works include Ludwig 1897; Ramsay 1904; Riepl 1913; Renouard 1962; Vigneron 1968: 134-7, 171-6; Chevallier 1976: 191-8; Dubois 1986; Cotterell et al. 1990: 193-233; Laurence 1999: 78-94; Kolb 2000: 308-32; Matthews 2000; McCormick 2001: 474-81; further on antiquity, see also Hunter 1913; Ramsay 1925; Yeo 1946; Eliot 1955; Forbes 1955: 131-92; Burford 1960; Engels 1978: 15-6; Röring 1983; Sippel 1987; Hyland 1990; Polfer 1991; Stoffel 1994: 161-5; Erdkamp 1998: 72-3; Roth 1999: 205-13; Raepsaet 2002, 2008; Adams 2007; and for further comparanda, e.g., Leonard 1894; Renouard 1961: 110-17; Goitein 1967: 290; Clark and Haswell 1970: 202; Leighton 1972: 48-124; Brühl 1986: 66, 163; Ohler 1989: 97-101; Castelnuovo 1996; Silverstein 2007: 191-3). The considerable amount of relevant scholarship – much more substantial than for sea and river transport costs – makes it impossible to provide even a short review of the complexities of the material (for which see Scheidel in preparation c).

Mean daily travel distances have been set at 12 kilometers per day for ox carts, 20km/day for porters or heavily loaded mules, 30km/day for foot travelers including armies on the march, pack animals with moderate loads, mule carts, and camel caravans,[18] 36km/day for routine private vehicular travel with convenient rest stops, 50km/day for accelerated private vehicular travel, 56km/day for routine travel on horseback, 60km/day for rapid short-term military marches without baggage, 67km/day for fast carriages (state post or private couriers), and 250km/day for continuous horse relays (Scheidel in preparation c). Except for the final option, which is primarily meant to provide an absolute speed ceiling for multi-day terrestrial information transfer, these transport options are predicated on movement during daytime. Adjustment for night travel would produce higher rates but would usually be feasible only in the short term.

The model seeks to generate values that would, on average, have been sustainable for days or weeks. Just as in the case of sea and river routes, the objective is to approximate the statistically average experience of a large number of travelers, an approach that necessitates critical engagement with individually reported performance times (Scheidel in preparation c). In the absence of experimental data, the question of how the generally high quality of Roman surfaces affected travel speed compared to the experience of later periods of premodern history is difficult to address. Roman carriage design (e.g., Röring 1983) and harnessing systems (e.g., Raepsaet 2002, 2008), both of which continue to be subject to debate, were vital determinants of actual performance that complicate any attempt at comparison. To name just one example, comparative data suggest that even though by the late eighteenth century, improvements in roads and equipment sometimes enabled French fast carriages to cover considerably larger daily distances than in previous centuries, even then speeds that exceed corresponding values applied to our model simulations were confined to a few privileged routes (e.g., Renouard 1961: 116; Vigneron 1968: 171-2). We cannot therefore presuppose Roman travel speeds that were consistently far superior to those encountered in other premodern communication systems. Most Roman evidence is consistent with this conservative approach (e.g., Kolb 2000: 321-32 and Scheidel in preparation c *contra* Laurence 1999: 81-2).

Uncertainty about the impact of grade on travel speed is perhaps the most important concern about simulations of time costs, especially for routes in mountainous terrain. Initial plans to model speed constraints as a function of road grade proved impracticable owing to a number of factors such as the imprecision of the road trajectories shown in Talbert 2000, lack of consistent information on road contours, and most importantly the paucity of relevant comparative historical evidence. Review of data for Alpine travel in the Middle Ages, when road conditions were inferior to those of the Roman imperial period, suggests that at least as far as individual travelers on horseback or in light carriages are concerned, grade did not represent a very serious impediment and did not systematically increase travel times except in extreme circumstances, notably at high-altitude mountain passes (e.g., Ludwig 1897: 108-9, 121, 126-7; Renouard 1961: 113; Castelnuovo 1996). Even winter conditions did not normally impose severe time costs on Alpine crossings (e.g., Ludwig 1897: 118-9; Renouard 1962; but cf. Castelnuovo 1996: 227). Increased travelers' efforts to minimize time spent in the mountains may have helped maintain routine travel speeds, but this conjecture is not fully compatible with the observation that rest stops before and after mountain crossings are only rarely recorded. More importantly, time costs of heavy transport may well have been more significantly affected by grade. Relevant comparative data are badly needed to address this open question.

For the time being, speed adjustments for variation in altitude have only cautiously been applied to the model by adding three degrees of time cost (0.5, 1 and 1.5 extra days for routine vehicular travel and proportionate amounts for other means of transport; cf. Renouard 1962) to mountain roads depending on the scale of ascent and route length. These schematic constraints operate in the Pyrenees, Apennines and Alps and in mountain ranges in the Balkans, Anatolia, and the Maghreb. Seasonal constraints have been kept to a minimum by disallowing particular means of transport such as ox carts and fast carriages in certain winter months in the Pyrenees, Alps, and Taurus.[19] Due to this conservative approach, the model may understate the time cost of moving goods across difficult terrain, especially under unfavorable weather conditions. More generally, in all terrains, the model is less adept at taking account of seasonal speed variation for land routes than for sea routes, which are simulated based on concrete monthly data. Users therefore have to bear in mind that in as much as terrestrial winter travel was undertaken at all (e.g., Ramsay 1904: 377), it might very well have been somewhat costlier than projected by the model.

Expense

Freight charges have been set in accordance with the tetrarchic price edict of 301 CE that imposes ceilings on specific transportation costs. The relevant amounts are 2 *denarii communes* per Roman mile (*c.*1,478 meters) for a passenger in a carriage, 4 *denarii* for a donkey load per mile, 8 *denarii* for a camel load of 600 Roman pounds (194 kilograms) per mile, and 20 *denarii* for a wagon carrying 1,200 Roman pounds per mile (XVII.1-5). Although the weight of the donkey load is not specified, the model puts it at 300 pounds based on reported donkey and camel loads of wood of 200 and 400 pounds, respectively, elsewhere in the edict (XIV.9, 11), a value that is also consistent with comparative evidence (Vigneron 1968: 135; Cotterell et al. 1990: 194; Roth 1999: 205). These loads translate to expenses of 1.35 *denarii* per kilometer for a passenger, 0.028 *denarii* per kilogram of wheat carried by donkey or camel, and 0.035 *denarii* per kilogram of wheat per kilometer transported on a wagon. These three options are matched to three particular time cost options to allow the simultaneous computation of time and expense costs: the speed of transport by wagon is equated to that of a (mule) cart covering 30 kilometers per day, the donkey and camel are considered moderately loaded pack animals moving at the same speed,[20] and the passenger is conjectured to move in the mode of accelerated private vehicular travel at 50 kilometers per day.

The implied ratio of the maximum freight charges for road and river transport is compatible with some later historical evidence (Dubois 1986: 290). Additional comparative data are required to put them in perspective. The simulated costs rates are best understood as quantitative illustrations of the overall scale of terrestrial transport costs, which were high compared to aquatic options. As a consequence, “fastest” and “cheapest” outcomes greatly differ in the model’s simulations: whereas road travel was often faster than sailing, depending on the route and means of transportation, it was invariably more expensive even if it offered the most direct connections. Just as Roman travelers and merchants, users of the model have to choose between speed and price in plotting their paths.

River transport

Routes

River transport in the Roman period still awaits comprehensive study (relevant work includes Johnson 1936; Le Gall 1953; Rougé 1965; Sasel 1973; Eckoldt 1980; Deman 1987; de Izarra 1993; Jung et al. 1999; Laurence 1999: ch.8; Konen 2000; Bremer 2001; Salway 2004; Jones 2009; Cooper 2011). Campbell 2012 (esp. ch.6) is a welcome overview but far from exhaustive with regard to transportation issues. Detailed explorations of local or regional conditions (such as Eckoldt 1980 and Bremer 2001 for Roman Germany) show just how much would need to be done to appreciate the complexities of fluvial transport in the Roman period.

For the purposes of this model, we have confined coverage to major rivers and select tributaries which are known or likely to have been navigable all or most of the time. The crucial issue of navigability raises serious questions: some rivers that are navigable today reached this state only thanks to modern improvements while others that are not currently considered navigable may well have been negotiated by rafts and shallow vessels in the more distant past, at least for part of the year (e.g., Brewster 1832; http://www.european-waterways.eu/; and miscellaneous internet resources). These shifting experiences make it extremely difficult to determine the accessibility of many ancient rivers. Even some of the major rivers included in our network, such as Rhone, Garonne and Seine (e.g., Brewster 1832; Denel 1970: 290; de Izarra 1993: 77), used to be subject to significant seasonal constraints. Only the lower reaches of the Tiber were navigable throughout the year (Pliny, *Letters* 5.6), and even the massive river Nile was continuously navigable only for boats up to 6 tons, and only half of the time for much larger vessels (Cooper 2011: 196). There are open questions about the navigability of the Orontes (K. Butcher, pers. comm.). Only segments of the major rivers of the Iberian peninsula or the Medjerda in the Maghreb would have been navigable and are therefore largely bracketed out. The status of rivers in the southern Balkans and Anatolia is likewise uncertain. It is also unclear whether canals made the Iron Gate area of the Danube passable for some river craft (Sasel 1973); the model conservatively assumes transport discontinuity at that location. During the Roman Warm Period, the focal point of our model, the freezing of rivers was probably only a moderate concern even in northern latitudes (cf. Ohler 1989: 13) although accounts of historical events on the frozen Danube and Rhine suggest that ice would at least on occasion have interrupted communications.

Very few canals have been included in the model. The *fossae Marianae*, for instance, are subsumed within the riverine sea port of Arelate, the canal linking the Nile to the Red Sea has been considered too transient to become a permanent element of the model, and the trajectory of the canal from Ravenna to Altinum and Aquileia is not provided by our main map source. The Tomis (Bahr Yusuf) canal has been amalgamated with the river Nile. Lakes, which played a role for transport in Alpine settings, have generally been excluded from our model, with no significant effect on cost.

The model's focus on major and reasonably reliable waterways is consistent with its overall emphasis on large-scale connectivity. We anticipate that further refinements will be undertaken as additional evidence is being reviewed, especially for the Iberian peninsula, the Maghreb and the Levant. It may seem as though frequently conservative assumptions about the navigability of major rivers and the exclusion of many minor rivers causes the model to underestimate the importance of river transport. However, any such concerns are put in context by questions about the role of this medium in the Roman world relative to other periods. It has been observed that the subsequent decline of the Roman road network precipitated a fluvialization of land transport in much of the Middle Ages, a trend that was reversed by renewed investment in higher-quality roads in more recent centuries (Lopez 1956). This suggests that in terms of overall importance, river routes may well have been overshadowed by the massive Roman network, which remained unparalleled until well into the late premodern period. The anti-cyclical character of river transport was another feature that might more generally have diminished its usefulness: outside Egypt, falling water levels rendered fluvial communications more difficult during the summer, at precisely the time when conditions on roads and the sea were most conducive to travel (e.g., Leighton 1972: 127; Ohler 1989: 33). These complexities call for a much more sophisticated approach to river transport than has so far been observed among Roman historians.

Time

The time cost of river transport is generally very poorly documented in ancient sources: with the exception of one reference to the Po the scarce data all pertain to the Nile (Scheidel in preparation c). The model therefore relies primarily on comparative evidence from the medieval and early modern periods, which is likewise relatively rare but sufficient to establish a rough outline of plausible speed values (e.g., Brewster 1832; Thomas et al. 1880; Ludwig 1897: 184-5; Mollat 1952; Goitein 1967: 295-301; Denel 1970; Ellmers 1972; Leighton 1972: 126-8; Fasoli 1978; Lebecq 1988; Ohler 1989: 32-7). Historical records have been checked against more recent data on the velocity of river currents, which are a principal determinant of speed for vessels that are not towed or rowed (e.g., Prati et al. 1971; Hesselink et al. 2002, 2006; Saad 2002; Abdel-Fattah et al. 2004; van Gils 2004; Liska et al. 2008; and miscellaneous internet resources).

The application of contemporary information about river currents is problematic to the extent to which rivers have been transformed by modern improvements. This is a particular concern in parts of Europe where the straightening and shortening of rivers has increased their velocity. An extreme example is provided by the Rhine, which has been shortened by 105 kilometers or one-eighth of its length and for the most part has come to resemble a canal (Cioc 2005). In Egypt, by contrast, the construction of successive Aswan dams had the opposite effect by eliminating the strong currents historically associated with the Nile inundation. Historical flow data are occasionally available to address this problem (Hesselink et al. 2002, 2006; Cooper 2011).

The model reflects these various difficulties by keeping riverine speed variation to a minimum, allowing for rough adjustments only for major segments of some of the longest rivers in the network. The Nile is the only inland waterway for which the simulations recognize seasonal variation, which resulted from the interplay of flood and strong winds (Cooper 2011). Travel speed on many rivers is being simulated based on a review of historical data on travel times and current velocity, and generic default conditions apply in those cases where no specific information has been found.

The “civilian” mode of river travel supposes use of cargo vessels that mainly relied on currents for propulsion downriver, assisted by occasional sailing (which may only have been feasible on the widest rivers), and on towing for upriver movement. The “military” option envisions travel by fast oar-propelled vessels that may also have been equipped with sails (Konen 2000: 51-3; Himmler et al. 2009, with Bockius 2011).

In the “civilian” mode, the most common downriver speed is 65 kilometers per day (Tiber, Po, Arno, Rhine, Mosel, Rhone, Tyne, Ouse, Witham, Upper Seine, Upper Loire, Upper Garonne, Guadalquivir, Guadiana, Tagus, Upper Danube, Inn, Drava, Sava, Nisava, Middle Euphrates, Orontes, Khabur), with occasional rough adjustments to 75km (Upper Euphrates), 60km (Lower Loire and Garonne), 55km (Middle Danube), 50km (Lower Seine), and 45km (Lower Danube). Daily upriver speeds are set at 15km for all of these rivers except the Lower Tiber, the Rhone and the Euphrates (10km), the Lower Loire and Garonne and the Middle Danube (20km), the Lower Danube (25km), and the Lower Seine (30km). Conditions on the Nile were of considerable complexity but are rendered here in a highly simplified format to capture merely the main trends: downriver speeds in Lower Egypt are set at 90km from July to October and at 35km in other months, and at 100km from July to October and 50km in other months in Upper Egypt. The upriver values are 90km in Lower Egypt from July to October and 30km in other months, and 65km from July to October and 35km in other months in Upper Egypt. Canals are assigned a daily default rate of 15km in both directions that conservatively presupposes towing. The “military” mode is constant at 120km per day downriver and 50km upriver, which approximates the probable performance of oar-driven vessels.[21]

With the notable exception of Egypt, where northerly winds dominated, and with the partial exception of some rivers in Gaul that experienced Atlantic westerlies, upriver travel was a very slow and costly affair. Historical data have been employed in establishing the above speed rates but any simulation is called into question by uncertainty about the feasibility of towing by animals or people, which relies on accessible river banks (e.g., Bremer 2001: 87-90). The maintenance requirements inherent in this system of propulsion may further justify the model’s focus on the main waterways, where adequate provisions were perhaps more likely to be available.

The simulations restrict travel to daylight hours, which is a conservative assumption given that at least during the summer boats may have navigated rivers at night (cf. also Horace, *Satires* 5). Certain very fast attested voyages imply continuous movement. This restriction stems from concerns that the provision of a continuous travel option might generate values that are too high to serve as plausible averages even in favorable conditions. The notional daytime values applied by the simulations are best seen as a hybrid between the outcome of genuine daylight travel and continuous travel, in that the projected daylight rates likely overstate actual daily averages, which would routinely have been affected by various kinds of interruptions and obstacles. The model thus compensates for the absence of a continuous travel option by projecting relatively high average values for daytime travel.

Expense

Apart from a handful of freight charges reported in papyri from Roman Egypt (Johnson 1936: 407-8), the monetary cost of river travel is only attested in the tetrarchic price edict of 301 CE. Section XXXVA.31-33 of the Aphrodisias copy stipulates a maximum price of 1 *denarius communis* per *modius* (*kastrensis*?) for every 20 miles of downriver travel and of 2 *denarii* plus an unspecified food allowance per *modius* for every 20 miles going upriver.[22] Expressed in wheat equivalent, the edict’s price ceiling for downriver travel resembles actual short-haul charges in Roman Egypt (Scheidel in preparation c). By contrast, the envisaged somewhat more than doubling of the cost for upriver travel seems overly conservative given the very considerable speed and energy advantages of downriver movement. However, in the absence of viable alternatives, the model adopts these rates for cargo, projecting a price of 0.0034 *denarii* per kilogram of wheat and kilometer of downriver travel and of 0.0068 per kilogram and kilometer upriver. In order to allow the movement of people across the whole network, the model simulates the cost of river travel for a passenger by applying the edict’s maritime cost conversion formula of 1 person = 25 *modii kastrenses* (XXXVA.26), resulting in charges of 0.86 (downriver) and 1.72 *denarii* (upriver) per passenger per kilometer.

It is worth noting that the price edict allows a discount for one particular longer voyage, an adjustment that can also be observed in relevant freight charges from Roman Egypt.[23] While our simulations do not currently adjust cost in relation to distance, this may be factored into a future iteration of the model. Comparative historical data may also have a role to play in this process (e.g., Hopkins 1980; Duncan-Jones 1982; Dubois 1986: 290; Langdon 1993; Masschaele 1993).

Geospatial technology

Multi-modal network model

The model that drives ORBIS consists of several datasets and the interrelation between those datasets as defined algorithmically by various functions. The data was developed through several mechanisms, the most familiar being the creation of GIS features through transcription and derivation. The data that underlies the model is explained below, and all of the functions which process this data in PostGIS will be released with annotation at a later point.

Sites

Figure 5 - Sites displayed in ORBIS, sized by rank

There are technically 751 sites in ORBIS. However, many of them are not displayed due to their being considered outside the scope of the model or redundant, or because they are considered a hidden "crossroads" node that is only taken into account during pathfinding. (see figures below) Sites have been ranked by Scheidel into five categories that determine the size of the icons representing them as well as whether or not their label is displayed on the map at particular resolutions.

Figure 6 - Undisplayed sites (blue) in ORBIS

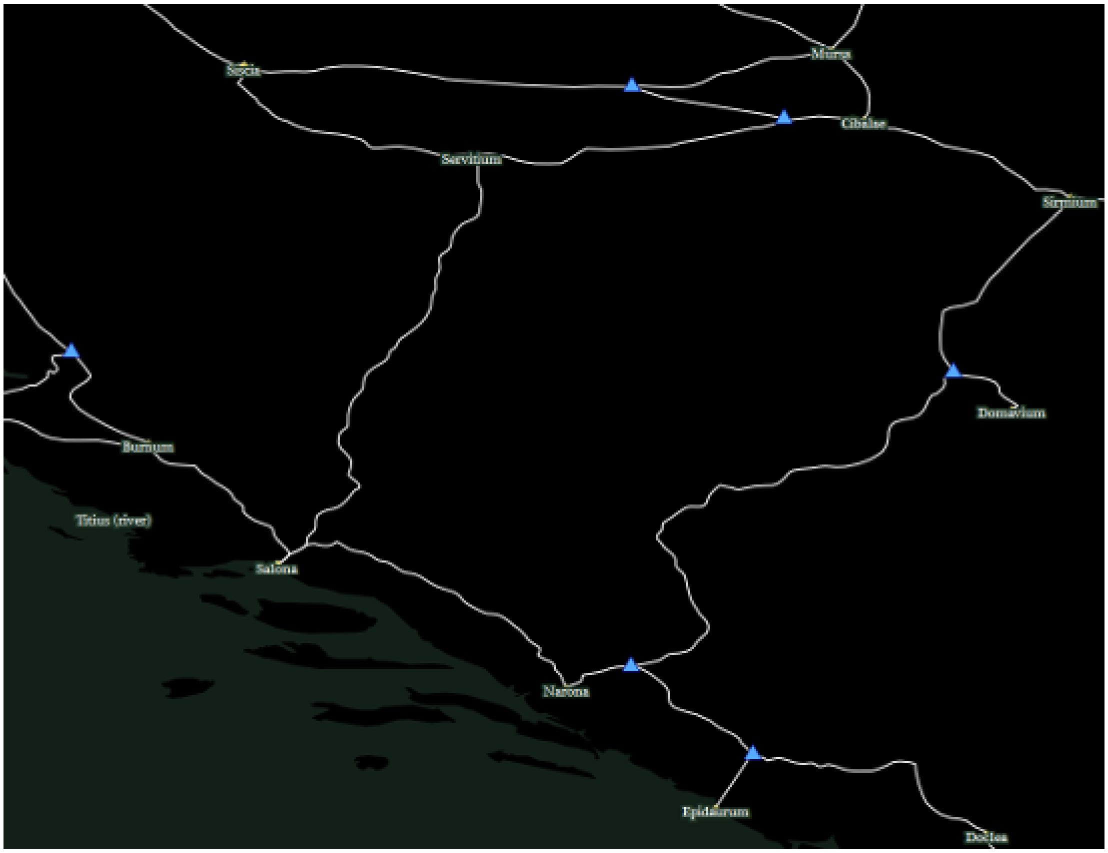


Figure 7 -Crossroads sites (blue triangles) are treated as nodes by the underlying pathfinding algorithm.

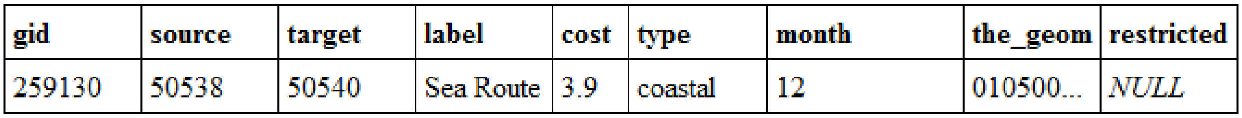
The Routing Table

Routes in ORBIS are determined by finding the Dijkstra distance through a table of segments derived from three models representing the road, river and sea routes, as well as five special ferry routes. Segments are represented as edges between two nodes, referred to in ORBIS as sites, which are stored in a separate table with additional data such as the site's name and administrative ranking. Dijkstra's pathfinding algorithm determines the shortest path through a network based on arbitrary costs for movement from one node to another. In the case of the ORBIS network, this cost is either the expense of shipping grain or passengers; the duration of travel along the route by a particular transportation method; or the raw distance of the routes themselves. In the web interface as well as later explanations, these three methods are referred to as, respectively, the cheapest, fastest or shortest routes. While the obvious differences in priority between the cheapest and fastest routes will be most interesting to scholars, we included the shortest route possibility as well so as to highlight the fact that the shortest distance between two points is rarely the least cost distance between them, regardless of whether that cost is in time or money.

The ORBIS model takes into account a time variable (at monthly resolution) in the determination of a least cost path through the system, but it does not take into account the time taken by the actual path. As such, any route that takes longer than 30 days is not aware of a change in the state of the model during travel time. This was explored during the early stages of building the model but set aside due to complexity. Higher resolution temporal data, as well as dynamic routes temporally through the system, would be an improvement for a future model.

More advanced pathfinding with heuristics was tested (primarily the A* algorithm implemented in pgRouting) but given the relatively small dataset (only 12,000 or so individual segments in the network), there was no improvement in speed as far as typical pathfinding queries, for which computing costs are primarily those necessary to divide and sort the network based on its multimodal and temporal characteristics.

The routing table itself has a simple format:



gid	source	target	label	cost	type	month	the_geom	restricted
259130	50538	50540	Sea Route	3.9	coastal	12	010500...	*NULL*

This is the entry for the coastal route from Euesperides (ORBIS ID 50538) to Zacynthus (ORBIS ID 50540). The cost value indicates the amount of time, in days, it would take to travel this route during December as derived from the sea model below. In the case of river and road routes, the amount of time is derived from the length of the polyline representing the route and the speed of the transportation method selected or the speed of the river, respectively.

The Ferry Routes

Ferry routes exist across the Strait of Gibraltar (Tingi to Gades), the Bosporus (Constantinopolis to Chalcedon), the Strait of Messina (Regium to Messana), the Dardanelles (Kallipolis to Lampsacus) and the Strait of Dover (Rutupiae to Gesoriacum). These ferry routes cannot be disabled in the web interface and are designed to serve two purposes. First, they allow a user to explore purely land travel without restricting such travel to contiguous areas. Second, they ensure year-round access to Britain, which was historically true but--for a single month--runs afoul of the wave-height restrictions used in the sea model (explained in detail below). The ferry routes are hard-coded to take 1 day in either direction, except in the Dardanelles and the Strait of Gibralter, which take the modeled amount of time.

The Road Model

Figure 8 - Road Routes in ORBIS

Roads within this system are represented as polyline segments connecting two sites. Generally, the directionality of these lines is not taken into account, as the entire table of road segments is duplicated and mirrored to build the routing table mentioned above. There is one exception to directionality, and that is in relation to cost modifiers that simulate the effects of traveling on steep grade. This condition is obviously amenable to a sophisticated solution. Given that the entire ORBIS database exists in a PostGIS2 database and is therefore natively capable of 3D spatial data, there were some early experiments with deriving z-values of the road network from 30m ASTER digital elevation models (DEMs).

During the course of this project we were made aware of higher resolution route data in Spain (González 2011) and Turkey, which might prove suitable for integration into the ORBIS network but would require mechanisms to account for the uneven resolution in contrast with the rest of the network.

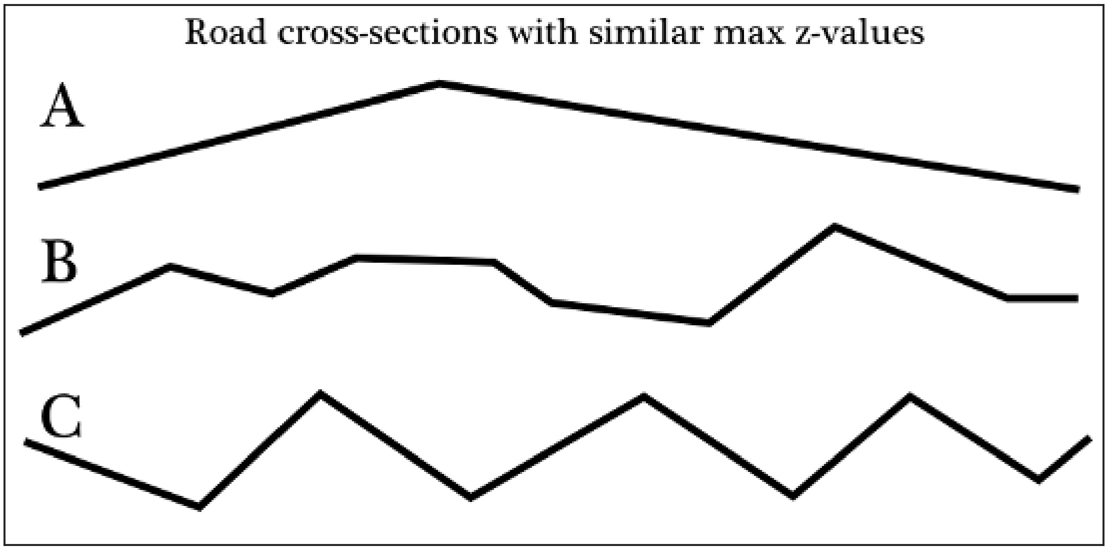


Figure 9 - Representative elevation changes in roads as cross-sections

By sampling the polyline segments using available raster elevation data, we could provide more than just the net change in altitude from the start of the route to the end of the route (a value that would fail to account for the difference between any of the above routes) as well as provide more meaningful route cost data than the maximum altitude of the route (which would work well for routes like A in Figure 5, but only poorly account for the cost of those like B and miss entirely the cost of a route like C).

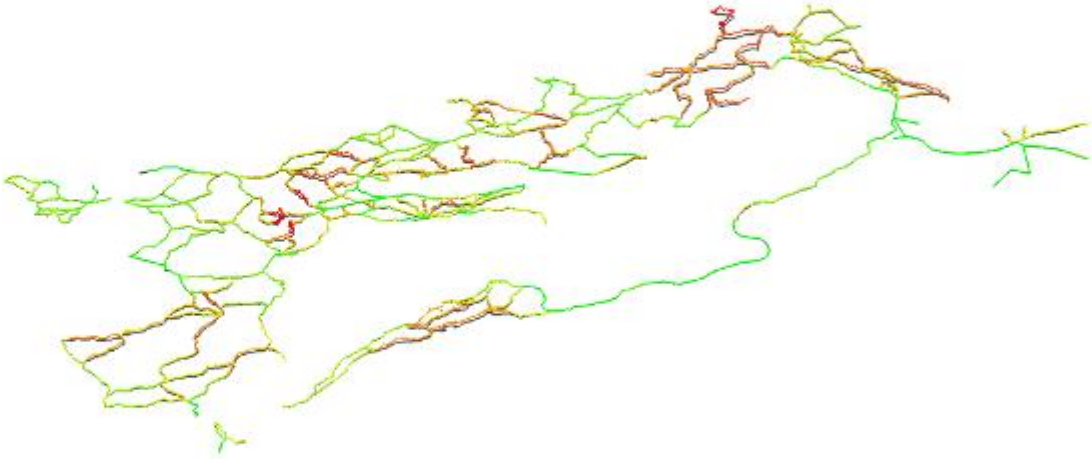


Figure 10 - ORBIS Land Routes with Z-level Data

In Figure 6 is displayed a draft scene of the early ORBIS network with the altitude of the road routes derived from DEM data. Road segments are colored by maximum elevation though a proper implementation would focus on total slope or some type of vector ruggedness measure.

With 3D roads, ORBIS would be able to determine cost modifiers based on direction on-the-fly and take into account not only overall change in elevation but aggregate change in elevation over the course of the entire segment. Unfortunately, the low resolution and uncertainty of certain road segments resulted in erroneous z-values. This is one of the most achievable improvements to the ORBIS model but would require significant investment to improve the resolution of the described road segments followed by a study of the historical record to correlate cost modifiers based on change in altitude.

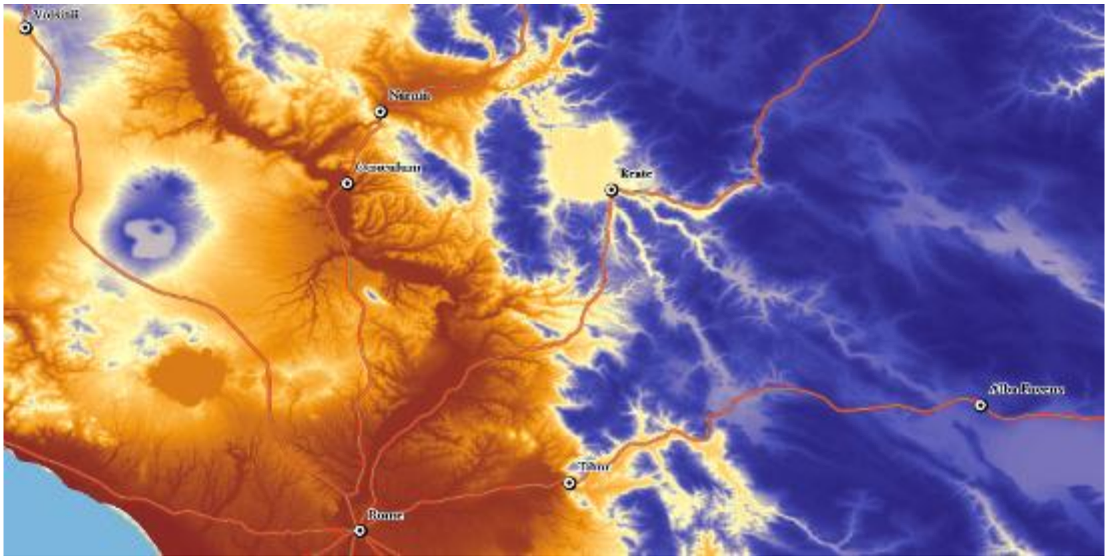


Figure 11 - Elevation data around Rome from 30m SRTM data

Note especially the path of the road from Tibur to Alba Fucens in Figure 7, which if sampled directly would indicate several major grades rather than more intuitive paths that avoid major shifts in elevation. While it would be seductive to simply "fix" these routes based on putative least cost paths using slope or vector ruggedness derived from DEMs, a set of historically accurate paths would require a focused scholarly effort.

As a result of issues involving integration of 3D data, the road model currently handles altitude-based modifiers and restrictions purely categorically. Certain routes have additional cost applied to travel upon them (either in one direction or both directions) and some of these routes are further restricted in the transportation methods that can utilize them during set months of the year.

The road model factors in altitude constraints using two methods. The first is to increase the amount of time necessary to travel along certain routes. This can be in either direction (represented on the figure as routes with circles) or in one direction (represented with triangles). The second method is to make certain routes unavailable to certain transportation methods during particular months. In the figures below, these routes are highlighted in green.

Figure 12 - Restricted Route Segments. Category 1 route segments in light orange, category 2 in medium orange and category 3 segments in red. Monthly restricted routes are further highlighted in green.

The three levels of movement modifier categorization (including directionality) as well as the restrictions in transportation method are stored in fields in the roads table and affect the transformation of the road data into directed edges in the network when pulled into the routing table.

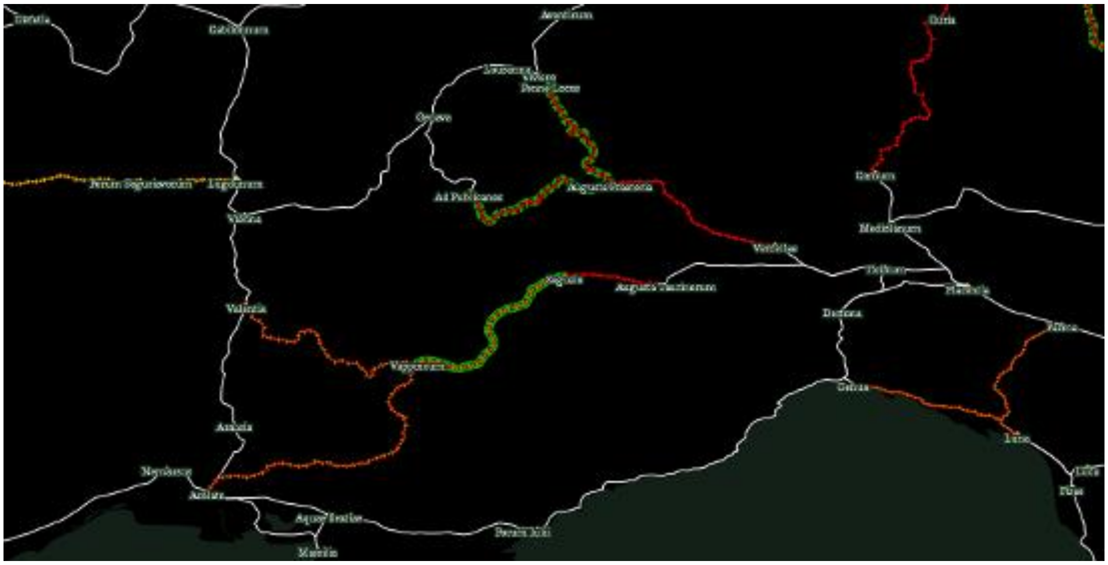


Figure 13 - Detail of Restricted Land Routes

Note that the route from Segusio to Augusta Taurinorum shows the arrows pointed toward A. Taurinorum when the route restriction actually applies to travel from A. Taurinorum to Segusio. This is because when the route was originally drawn, the polyline itself (a spatial data object) was drawn left to right and so technically points in that direction. The ORBIS model, however, does not take this direction into account, but only looks at the accompanying source and target entries for the polyline, which are properly labeled in the other direction.

For instance, the road from Vappincum to Segusio is considered a Category 2b road with restrictions. Category 2 roads are treated as being 36km longer than the actual length of the road, and the 'b' designation indicates that this is bidirectional, so this modifier is accounted for in trips from Vappincum to Segusio as well as trips from Segusio to Vappincum. If this was a Category 2d (or directed) road, then the modifier would only apply for trips from Vappincum to Segusio. Further, this road is restricted in transportation modes such that oxcarts and carriages cannot use it from January to March.

The River Model

Figure 14 - River Routes in ORBIS

Rivers, in contrast to roads, are always directed edges. The data model stores rivers with their direction of flow downstream, as well as the variable upstream and downstream speed as determined per river (and in the case of the Nile, per month) by Scheidel. When processed into the routing table, the rivers table is first brought in as downstream edges and then brought in a second time, flipped, as upstream edges. River courses are based on modern tracks.

The Sea Model

Figure 15 - Coastal routes in green and overseas routes in blue.

The sea model is based on a mesh of polylines (referred to as the sea mesh) that connect ~40,000 points (referred to as nodes in the sea mesh), each separated by .1 degree, that overlap on the water areas corresponding with the Mediterranean, Black Sea and the small part of the Atlantic within the study area. There are 8 connections between each node, and these connections are referred to as edges and have the cardinal or ordinal direction of the edge coded in the table that stores them. So, we have a node at every .1 degree interval with eight edges to its neighboring nodes (if there is an immediate neighbor node) labeled "N", "NE", "E", "SE", "S", "SW", "W", "NW".

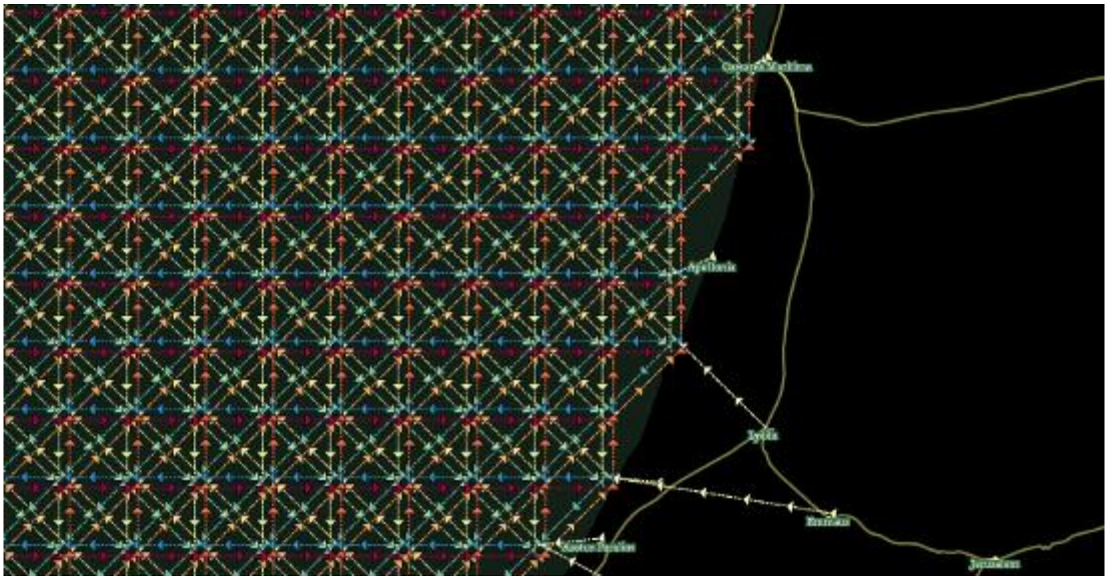


Figure 16 - The mesh off the coast of the Levant, including port routes connecting possible ports with the mesh

The data for wind force and frequency is drawn from two sources: a pilot chart that gives wind roses at 2 degree intervals for the Atlantic and Mediterranean regions and a table of similar but more detailed data at 1 degree intervals for the Black Sea. This data provides wind frequency by cardinal or ordinal direction as a percentage over the course of a month, as well as wind force using the Beaufort scale from that direction during the month. Currently, due to the manner in which the Black Sea data is stored, wind force for all Black Sea data is treated as Beaufort 3.

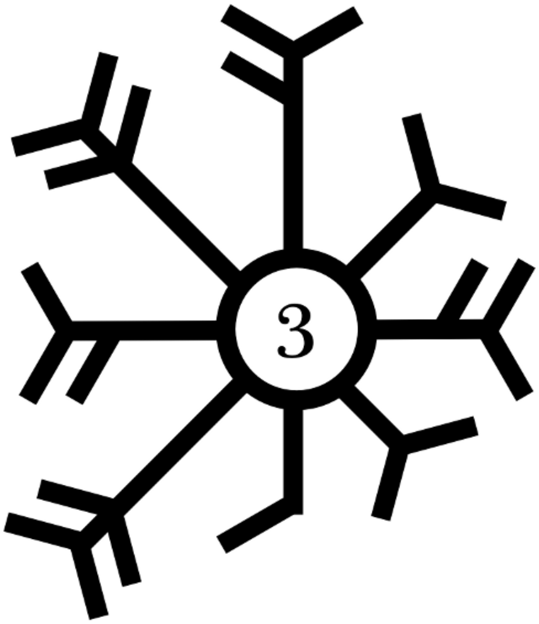


Figure 17 - A typical wind rose

There are several formats for storing wind data in environmental science datasets, whether on-line or traditional. The most suitable and approachable for our model is in the form of wind roses, like those above. The wind rose describes average force and frequency during a period (such as a month) by direction denoting the former with ticks on and the latter with length of the line corresponding to the ordinal or cardinal direction of the wind.

The model derives a cost, in time, to travel along one edge in the direction of the edge based off the length of the edge times the speed in knots of a ship assumed to be subject to the average frequency and force of winds for that region. We have used several ship models, which react differently in their effectiveness of dealing with headwinds and also have different top speeds. This gives each edge a different cost value in time depending on the direction of travel from node to node.

With these values assigned to the sea mesh, we run directed Dijkstra least cost paths through the network to find hypothetical sea route paths as well as cost in time for an entire route. Regions defined by pilot charts as having greater than 10% occurrence of 3m+ waves during the month of the route are considered impassable and are removed from the sea mesh before any paths are run.

So far, our two ship models based on the performance of Dutch Cogs (deemed Slower and Faster due to slight variations in the way the model handles wind strength resulting in slightly slower and faster ships) have had the closest results to historically attested routes for the region and the months in question.

Initial test runs of the sea model used the ArcGIS package's ArcPy scripting tool to provide raster interpolation of the wind data over the study area. Inverse Distance Weighting, Kriging and splines were explored to determine the most appropriate method to interpolate wind frequency and strength. This raster data was then sampled by the mesh using zonal statistics. These methods were set aside to use Theissen interpolation (also known as "nearest neighbor") to foreground the necessity for more work in this area and avoid increasing the appearance of sophistication of the model without adequately being able to assure it was increasing its accuracy. Additionally, a search for higher resolution wind data in wind rose format yielded poor results. Given these factors and the low number of sensor points available for the wind data, it was decided that any method of interpolation of values beyond assigning the wind value for each mesh point from the nearest sensor point should be explored in later iterations of this model.

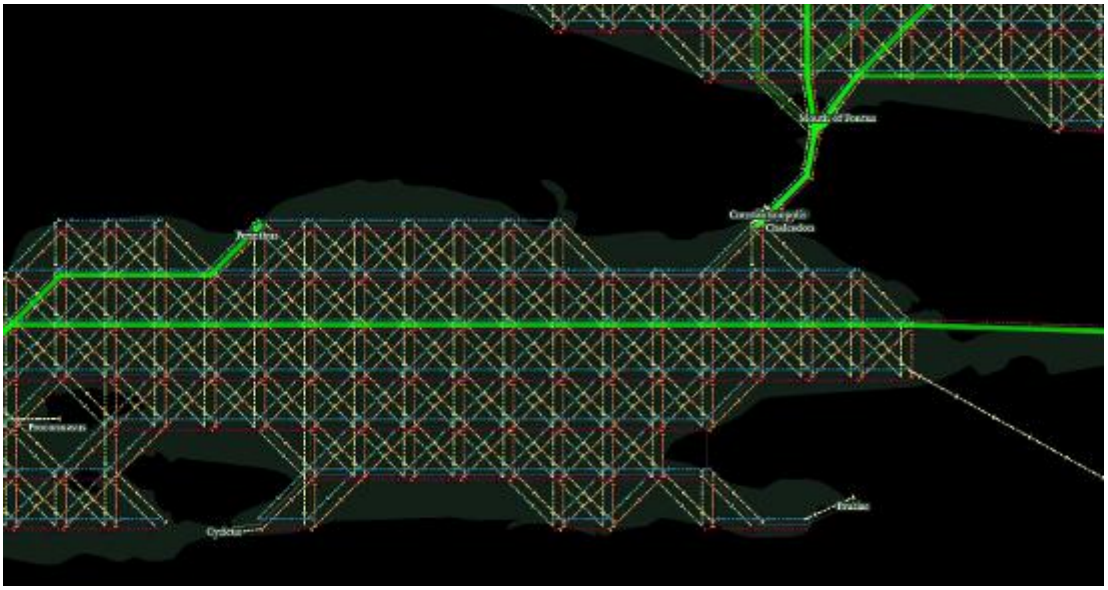


Figure 18 - Derived routes (in green) through the mesh.

Dijsktra distance through this mesh results in different paths to and from each site. While we wanted to run all routes for all months for all sea ports and then trim these routes based on certain parameters, this proved to be unfeasible given the amount of processing time necessary to run ~1 million shortest path queries on the 160,000 entry mesh table. Instead, the coastal and sea routes that have been run were drawn from a list created by Scheidel.

Sea routes are grouped into two categories, coastal and overseas based on designation by Scheidel. These definitions are based solely on whether a route connects nearby sites that share the same coastline, and do not operate with any relation to the coastlines (for instance, through a buffer or a viewshed). As such, some coastal routes will follow least cost paths beyond the visible range of coastlines and some overseas routes may hug coastlines for much of their path. The ability to turn coastal and overseas travel off and on is available to ORBIS users in order to facilitate simulation of different types of participants.

Figure 19 - Restricted sea zones based on wave height

Along with wind speed and direction, the pilot charts we examined showed regions of 3m+ waves with more than 10% frequency during the month reported. We designated these regions to be impassable during those months, affecting the sea routes by forcing the model to go around these restricted zones. Wave height-based restrictions affect the Atlantic primarily, but also create a shifting barrier between Sardenia/Corsica and the coast of France from November to March. As with other elements of this model, a more accurate reflection of the constraints posed by high seas or other navigational restrictions will have to wait until sufficient data and applicable models have been developed.

Roads

The ORBIS road network is made up of 751 vector line segments digitized from a number of georeferenced maps using the common GIS applications ESRI ArcGIS and Quantum GIS. In a technical sense, especially compared with how the sea route network was derived, the digitizing of roads is relatively straightforward. The basic data set to which the roads would be introduced was a vector polygon outline of the countries surrounding the Mediterranean and a vector point file representing the ancient sites included in the ORBIS network. Our goal was to create land-based routes between all these points. The roads were selected according to research criteria outlined elsewhere on this website, and drafted according to their depiction in georeferenced raster map images (either TIFFS or JPGS). The principal source of information on roads was The Barrington Atlas of the Greek and Roman World (Talbert 2000), already made available in a georeferenced format by the Cambridge University Press in association with Talbert 2011. Greece, Egypt, and northern Mesopotamia were the only areas of our network where Talbert 2000 did not include details of the Roman road system. For these regions, suitable alternative maps were scanned and introduced as TIFF files to ArcGIS (Fakhry 1974; Koder and et al.

1976; Soustal 1981; Stier 1991). These scanned maps were then georeferenced based on the ancient cities point file and national outlines polygon.

All roads in the ORBIS network were in a single line vector file created in an equidistant projection. Each of these roads begins and ends either at a point representing a site, or connect directly with the other road lines, so that the network roads either reach a destination or merge with another road. For this process, the ESRI ArcMAP snapping function was utilized so that the road segments began and ended precisely at the site points or at alternate roads. Each line was assigned a name and code number which acted as a primary key for the large attribute table associated with the vector lines. For example a road between city "A" and city "B" would be named "A to B" and given a number assigned sequentially such as "1010". This coding was useful as a handle for those building the network, as each route has a significant amount of information associated with it. The attribute table keyed by the name and code number contained information such as the list of possible means of transport for each road and the time cost of each travel mode for each of the road segments. Also included in the attribute table was information from more traditional research such as references, dates, and primary sources. The length of each route was automatically generated and included in this table by the geodatabase format typical of these GIS platforms.

Because the sea routes and river routes of the ORBIS network are also line vector data connected using the city point file, the road network easily integrates with the other forms of travel to create the greater ORBIS network.

Web site

The ORBIS web site is a work in progress. Like many web mapping applications, it experiments with several open-source technologies. The software stack includes: (i) PostgreSQL 9.0 database with PostGIS 2.0SVN and pgRouting 1.05 spatial extensions; (ii) OpenLayers 2.11; (iii) Geoserver 2.1.3; (iv) GeoExt JavaScript library; (v) the d3 v2 JavaScript visualization library; (vi) Gephi v0.8.1 graph visualization and (vii) the ExtJS 3.4 Javascript framework.

The site is not simply a web map of course, but a scholarly publication. The text in this article appears verbatim in the "Introducing," Understanding," and "Building" sections of the site, and is made available as a downloadable PDF file at http://orbis.stanford.edu/version1.pdf.

Although the article and interactive web mapping application could each stand alone, they are more effectively published together as an entirely integrated *digital scholarly work*. In this sense, the ORBIS project seeks to extend that broad, still nascent genre in novel ways.

Using ORBIS: Examples

The following sample simulations illustrate specific features of the route simulation tool in Mapping ORBIS. Further examples may be added later in response to user feedback.

Time, price, and distance

A long-range route simulation from Carthago (in present-day Tunisia) to Londinium (London) highlights difference in outcomes depending on priority, mode, and season.

In the month of July, generally a favorable time of the year for travel, the fastest connection utilizing all four modes (road travel by pack animal, river travel by civilian boat, open sea and coastal sea travel on the faster sailing ship) is represented by the purple line that crosses the western Mediterranean in a northwesterly direction, cuts across southwestern Gaul (France) in part by using the river Garonne and subsequently follows the Atlantic coast to the final destination. Travel time is 27.2 days over a distance of 3,099km (or 114km/day), at a cost of 7.8 denarii per kilogram using a donkey for land transport. Disabling the open sea function diverts the fastest route to track the coast of Sicily and Italy, a change that increases travel time by 40 percent to 37.4 days and distance by the same rate to 4,384km (or 117km/day), while the price rises by no more than one-eighth to 8.8 denarii thanks to the continuing predominance of cheap maritime travel. The low price cost of sailing also accounts for the fact that the cheapest route overall for the original four modes and settings (displayed in green) takes a very different path, relying as it does as much as possible on the sea and therefore completing virtually the entire voyage by sea ship, a choice that results in a comparable travel time of 37 days over a longer distance of 5,097km (or 138km/day) but halves the price to merely 3.7 denarii/kg.

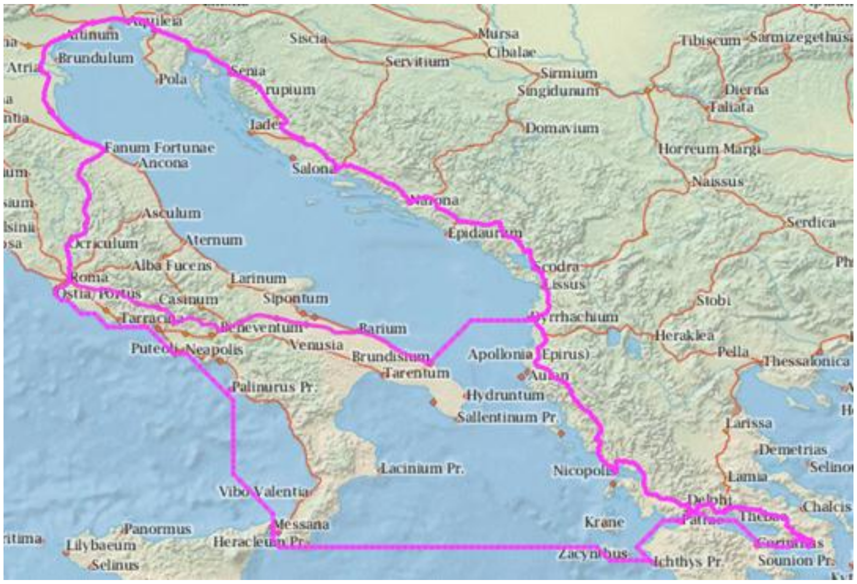
This route depends on access to Atlantic shipping: an easy way of excluding this particular option is by selecting the same configuration of modes and settings for the month of January, when heavy winds curtailed sailing in the Atlantic Ocean. This creates a dramatically different path, represented by the green line that initially curves across the western Mediterranean in order to avoid the area of rough winter weather west of Sardinia and later relies as much as possible on river transport, first up the Rhone and then down the Rhine, before sailing to the mouth of the Thames. In this scenario, travel time increases massively to 93.2 days over 3,361km (or 36km/day) while the price rises fourfold to 15.7 denarii/kg. The yellow route (for the original modes and settings, in July), partly obscured by (purple) the sea route from Carthago to Narbo (Narbonne), shows the physically shortest route, which at 2,403km is almost a quarter shorter than the fastest route but, at 36.2 denarii/kg, also far more expensive than any of the others because it does not shy away from expensive road travel.

This particular simulation also serves to illustrate the consequences of discontinuity in the Roman road network. Although most sites in our network are accessible by road, except for those on smaller islands, along the northern Black Sea coast, promontories and a few other isolated coastal sites, the gap in the Roman road system on what is now the northeastern coast of Morocco (along the Rif mountain massif) forces non-maritime travel from Carthago to Londinium on an absurdly circuitous route around the entire Mediterranean basin that would have taken almost nine months of travel on foot or by pack animal.

Composite routes

This deliberately counterfactual example shows that composite routes may sometimes be necessary to achieve historically plausible outcomes: the longer a given route, the more often a single configuration of modes and options will generate implausible simulations. In such cases, routes need to be spliced by selecting modes and means of travel that are appropriate to particular segments of the overall route.

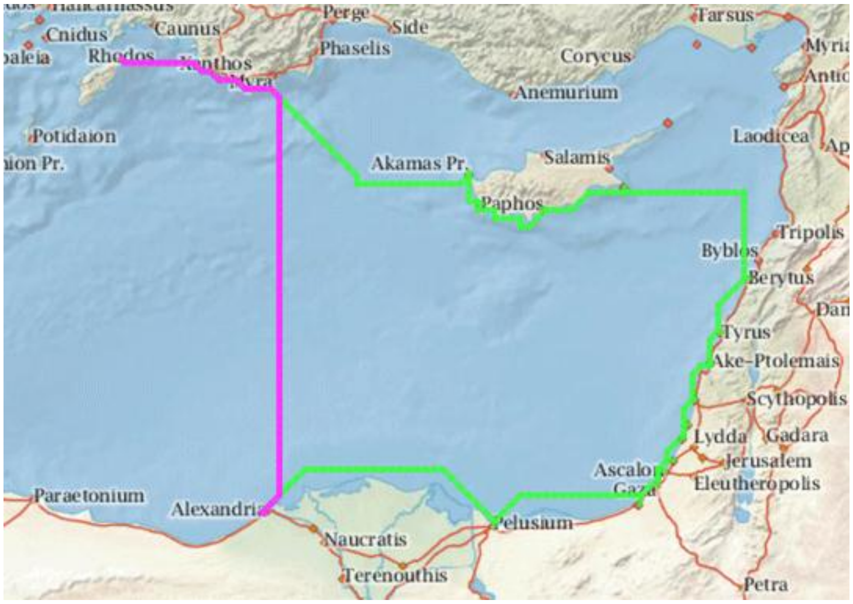
In the above-mentioned case, if the objective is to reach Londinium from Carthago by prioritizing road travel but without going to the extremes of a nine-month trip around the entire Mediterranean basin, the most economical approach involves road travel from Carthago to Rusaddir (Melilla) followed by a short sea crossing to Gades (Cadiz) and more road travel all the way to the English Channel. This hybrid route cuts travel time by half, from nine to four-and-a half months.



A further example of the characteristics of composite routes is provided by simulation of travel from Roma (Rome) to Athenae (Athens). By faster sea ship and using a fast carriage for the very short land legs of this almost entirely maritime voyage, the route that runs south to the Strait of Messina and east to the Isthmus of Corinth and on to Athens requires 10.2 days of travel in July. Undertaken wholly by land, in a fast carriage, the same trip (around the entire Adriatic) would take much longer, 33.4 days, whereas a 24-hour horse relay narrowly beats the sailing option by 0.7 days. The fastest route overall, however, is a hybrid, using a horse relay from Rome across Italy to Brundisium (Brindisi), crossing the Strait of Otranto to Dyrrhachium (Durres) by ship, and continuing to Athens again by horse relay, for a total travel time of 6.4 days. If a fast carriage is used on the land segments of this spliced route, travel time increases to 20.6 days, twice as long as the sailing option and only 40 percent faster than the land-only option by fast carriage.

What does this kind of thought experiment mean for historians? The model projects average travel times, but mean outcomes might have been easier to ensure on land than by sea: while a sea trip of 10.2 days seems faster than a hybrid trip of 20.6 days involving a fast carriage, the latter option might well have been more reliable. Moreover, it would probably have been easier to send a carriage of the state post across Italy and the southern Balkans than to find a ship that was to sail directly from Rome to central Greece. Horse relays would have sped things up but must also have been very costly and as far as we can tell were very rarely employed even on urgent state business. Particular simulations are not meant to tell us what would have happened: they are primarily meant to provide food for thought, to give us a better sense of a range of possible outcomes that in practice would have been determined by context and highly contingent priorities.

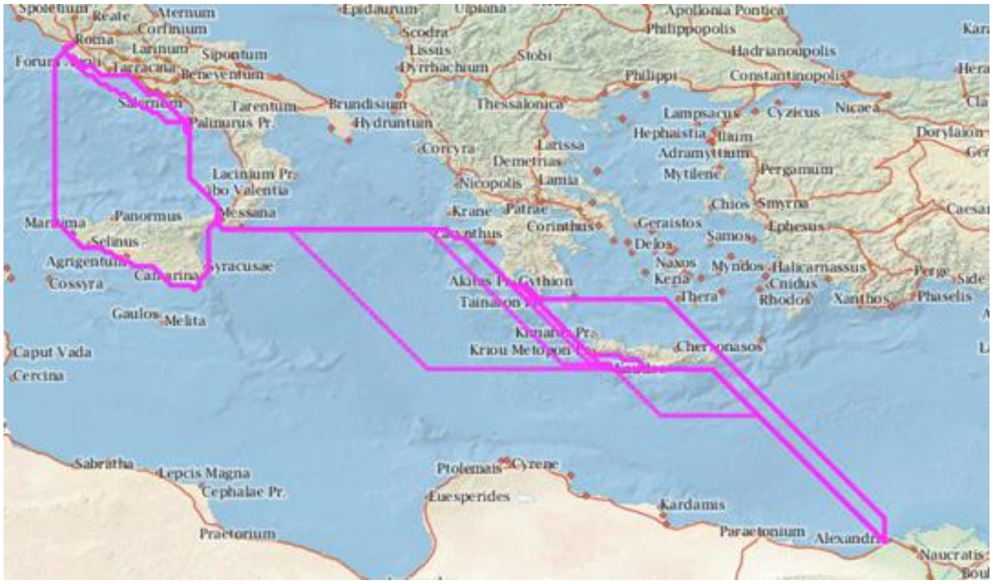
Open sea and coastal sea routes



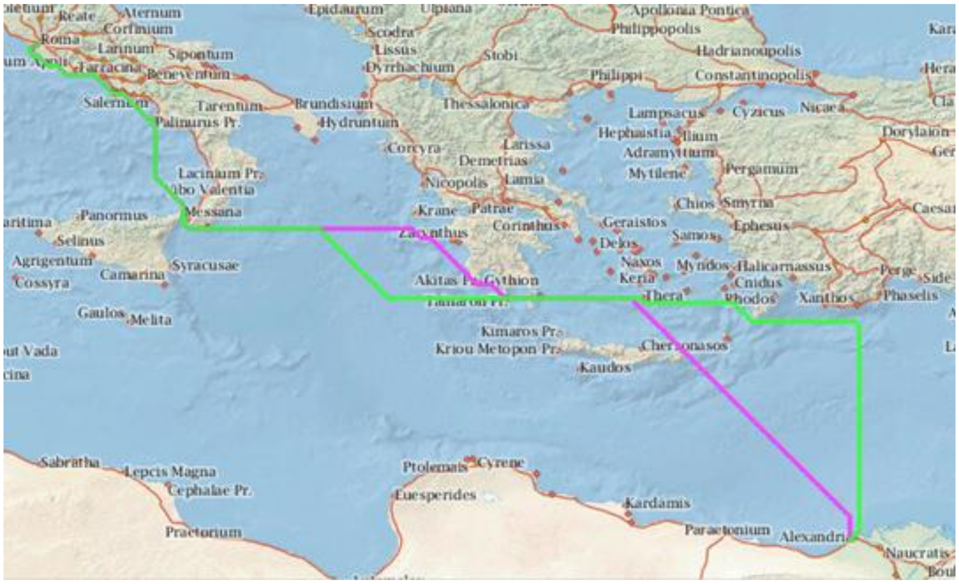
Open sea routes were the backbone of long-range connectivity in the Roman empire. Their critical importance is underscored by the consequences of their absence. For example, in July a faster sea ship was capable of reaching Rhodos (Rhodes) from Alexandria in Egypt in five days and six nights (along the purple route) but would have taken two weeks to complete the same trip via the Levantine coast and Cyprus (along the green route).

Seasonal and directional variation

Seasonal variation is captured by the different paths of the fastest/cheapest sailing route from Rome to Alexandria.



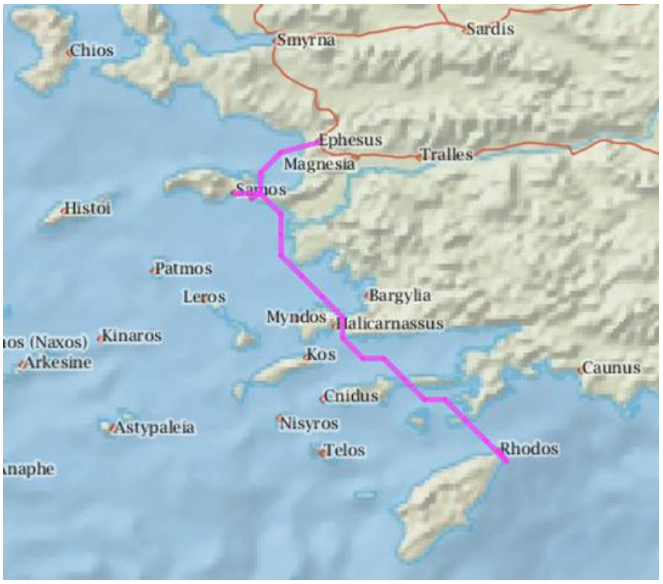
The most conspicuous change occurs in the winter, when the Strait of Messina became more hazardous and therefore, in terms of our model, more costly. This projected detour should not be taken to suggest that ships actually chose the longer route around Sicily: it merely signals the fact that this particular option would on average have been less costly than delays awaiting safe passage between Sicily and Italy. Lesser monthly deviations, caused by variation in wind conditions, are visible along much of the route.



The impact of wind on the path of the optimal sailing route, in July, from Rome to Alexandria (in purple) and from Alexandria to Rome (in green) illustrates directional variation, tracking the documented open sea route between eastern Crete and Alexandria as well as the alternative route via Lycia and/or Rhodes (cf. Arnaud 2005: 212).

Optimization

For a few maritime route simulations, the principle that the model always searches for the optimal route (in terms of the selected priority of speed or price) results in slight detours. This is because it may sometimes be faster or cheaper to take a longer route that bypasses intermediate sites but overshoots the destination and subsequently turns back to reach it than to approach the target via a series of adjacent ports. Substantial distortions caused by this process have been eliminated by reconfiguring certain routes, and its remaining impact is minor and now largely confined to the highly articulated Aegean coastline.



The modest significance of this phenomenon can be illustrated by simulating a maritime trip from Rhodos to Samos, which first goes to Ephesus, to which Rhodos is linked by a direct sea route, and then back to Samos, a detour that adds only a fraction of a day to the duration of the voyage.

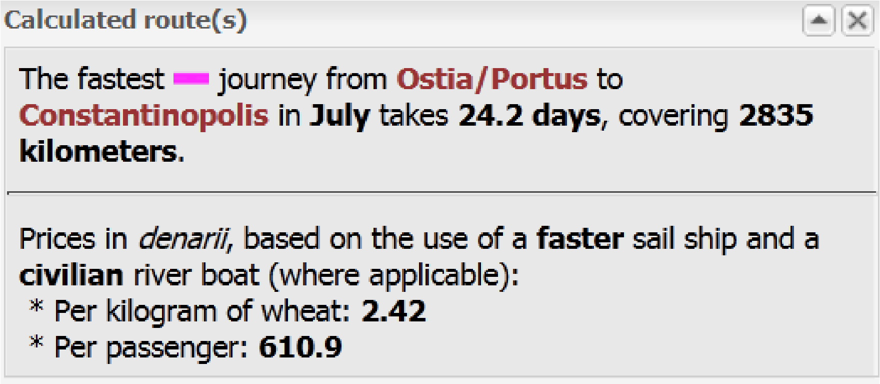
Small-scale connectivity

As explained in Understanding ORBIS, selective coverage of existing Roman routes may at times make short-range connections appear costlier than they would have been in practice.

For instance, the shortest available land route from Londinium (London) to Lindum (Lincoln) in the network runs through Verulamium (St Albans) and Venonis (High Cross, Leics.) despite the fact that a roughly parallel but more direct road connection existed between London and Lincoln (Talbert 2000: 8). In this particular case, inclusion of every element of the unusually well-documented Roman road system in Britain would have introduced imbalances into our network and not added much of significance to its overall degree of connectivity. The available route was selected in the first instance because of its presence in two major Roman itineraries, the Antonine Itinerary and the Peutinger Table, which points to its general importance.

In Egypt, widespread uncertainty about the precise location of Roman roads accounts for the fact that certain sites that (in Mapping ORBIS) are not visibly connected to the road or river networks may nevertheless be part of them. Thus, it is possible to travel by road and canal/river from Krokodilopolis (Faiyum) to Oxyrhynchus (el-Bahnasa) on the Bahr Yusuf canal even though the latter site is not visibly connected either to the road (which is a simplified rendition of more complex infrastructure) or the Nile (which in our model subsumes the Bahr Yusuf). (For further discussion, see Building ORBIS.)

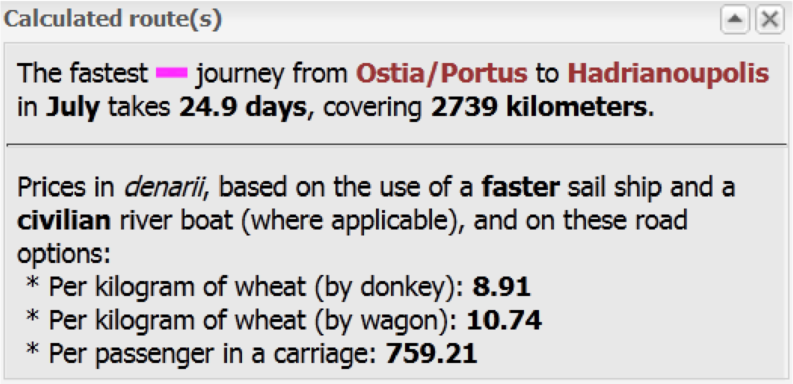
Price results



The fastest ▬ journey from **Ostia/Portus** to **Constantinopolis** in **July** takes **24.2 days**, covering **2835 kilometers**.

Prices in *denarii*, based on the use of a **faster** sail ship and a **civilian** river boat (where applicable):
* Per kilogram of wheat: **2.42**
* Per passenger: **610.9**

As mentioned in the Overview section of Using ORBIS, price results are displayed in two ways. For trips that do not involve land travel, prices are based on the selected sea ship speed and on use of a civilian river boat, where applicable: in the shown example, the entire trip is undertaken by sea ship, hence the qualification "where applicable." Prices refer to the two types of cargo modeled for aquatic travel, 1 kilogram of wheat and a passenger.

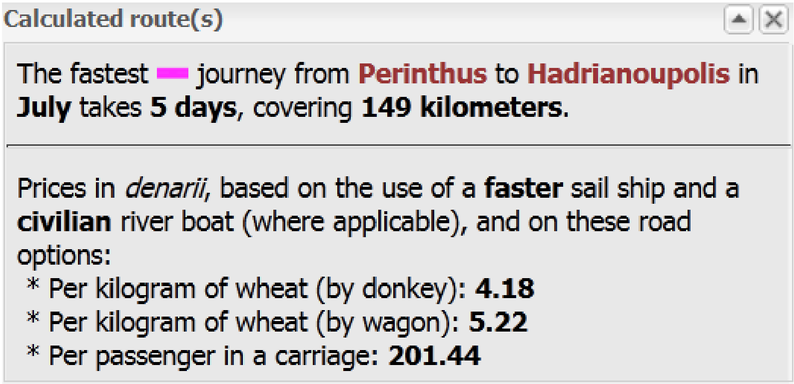


Calculated route(s)

The fastest ▬ journey from **Ostia/Portus** to **Hadrianoupolis** in **July** takes **24.9 days**, covering **2739 kilometers**.

Prices in *denarii*, based on the use of a **faster** sail ship and a **civilian** river boat (where applicable), and on these road options:
* Per kilogram of wheat (by donkey): **8.91**
* Per kilogram of wheat (by wagon): **10.74**
* Per passenger in a carriage: **759.21**

By contrast, the fastest route from Ostia/Portus to Hadrianoupolis (Edirne, in the hinterland of Constantinopolis) involves two short segments of road travel, across the Isthmus of Corinth and from Perinthus on the Sea of Marmara to the final destination. In a case like this, the price results also include outcomes for the three types of road cargo that can be modeled: 1 kilogram of wheat carried by a donkey or camel, the same item conveyed by a wagon, and a passenger in a carriage.



Calculated route(s)

The fastest ▬ journey from **Perinthus** to **Hadrianoupolis** in **July** takes **5 days**, covering **149 kilometers**.

Prices in *denarii*, based on the use of a **faster** sail ship and a **civilian** river boat (where applicable), and on these road options:
* Per kilogram of wheat (by donkey): **4.18**
* Per kilogram of wheat (by wagon): **5.22**
* Per passenger in a carriage: **201.44**

As shown in the final example, sea and river options are mentioned even if a trip takes place entirely by road, as in the route from Perinthus to Hadrianoupolis. This does not mean that any pricing based on aquatic transport is actually included in these price results: hence, again, the qualification "where applicable."

The future of the project

This site represents merely the opening phase of our project. Future expansion may take various directions.

One option is intensification. The existing network may be augmented and fine-tuned by adding roads, rivers and sea ports as well as more detailed information on winds and currents and adjustments for grade. As noted in the section on "Understanding ORBIS," such additions would not change the broad picture but make the model more amenable to simulations on a micro-regional scale. We hope to explore this option by undertaking one or more regional case studies.[24] More comprehensive coverage of the road network would allow us to conduct an exhaustive test of the distances reported in Roman itineraries (cf. "Applying ORBIS").

More importantly, this kind of intensification would open up new avenues for systematic analysis of the network properties of the entire system, an approach that is currently called into question by the possibility that the deliberately selective nature of our coverage might distort the findings.[25]

Intensification beyond the introduction of additional sites and routes might entail the provision of layers that contextualize our routes by visually portraying Roman landscapes as depicted in the *Barrington Atlas of the Greek and Roman World* (Talbert 2000),[26] or the application of a more flexible and realistic model of expense rates that transcend the overly schematic nature of the late Roman data used in the current simulations.

Spatial extension of the network is another option. Inclusion of the maritime routes of the Red Sea and the Indian Ocean would allow us to model the seasonal regime of the monsoon winds and to simulate Roman trade with South Arabia, West Africa, and India. Ancient documentation such as the *Periplus of the Erythraean Sea* would facilitate this endeavor. Eastward extension of maritime connections could be complemented by the addition of caravan routes in the Arabian peninsula and the inclusion of southern Mesopotamia.

It is worth noting that our model of sea routes might in principle be extended over the entire planet. Data on winds and currents are available in a standardized format for most of the world's oceans. Once a continuous global cost surface has been established, relatively minor adjustments of navigational capabilities based on specific historical evidence would suffice to enable the simulation of the voyages of the Norse, the Ming treasure fleets, or later European East or West Indiamen. We hope that colleagues specializing in other periods of history will seize this opportunity.

A third option is to transition from simulation of average outcomes to consideration of probabilities. The existing model offers a ready-made infrastructure for agent-based modeling that would allow the introduction of probabilistic simulations and evolutionary developments in response to environmental and other constraints. This approach promises an enhanced understanding of the structural properties of the network.

In addition to these options, our project has the potential to benefit from and contribute to existing databases of spatial information from the ancient world. Links to data-rich assemblages such as Pleiades (http://pleiades.stoa.org/) and the Digital Atlas of Ancient and Medieval Civilizations (http://darmc.harvard.edu/icb/icb.do) or emerging applications such as Google Ancient Places (http://googleancientplaces.wordpress.com/) and Pelagios (http://pelagios-project.blogspot.com/) would not only enrich our own model environment by providing historical context but also compensate for the built-in limitations of these resources: whereas conventional initiatives tend to focus on the accumulation of ever larger amounts of static factual information, our model prioritizes the dynamic elements of simulation and analysis.[27] Our ultimate goal is the creation of an interface that enables seamless integration of local data and dynamic processes. We are confident that other scholars will come to share this aspiration.

Notes

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[1] Forthcoming studies include a survey of the model with illustrations of its applicability to broader historical questions, a separate analysis of the maritime cost data in the tetrarchic price edict of 301 CE, and a detailed review of Roman travel speeds currently prepared by Scheidel (Scheidel in preparation a, b, c), a formal presentation of the projection of sailing speed developed by Arcenas, and an assessment of the value of Roman itinerary records by Padilla Peralta and Weiland. Meeks has discussed aspects of his work at https://dhs.stanford.edu/author/emeeks/.

[2] In Talbert 2000, cities in peninsular Italy and the Balkans tend to be more highly ranked than substantively similar cities in other parts of the Roman Empire.

[3] For the Black Sea, see also Clavijo 1859; Majeska 1984; and assorted sources in the *Geographi Graeci Minores*.

[4] Accounts such as Avienus' *Ora Maritima* are of little value here. For recent scholarship, see Carreras et al. 2010. It appears to be unknown whether Roman ships were able to by-pass the entire Bay of Biscayne by sailing directly between Galicia and Brittany or the English Channel.

[5] We did not have access to comparable data for the Black Sea.

[6] The Sea of Azov is the only possible exception, but even there the sea stopped freezing in recent decades as temperatures have come to resemble those of the Roman Warm Period.

[7] For the correspondence between ancient and modern winds, see Murray 1987.

[8] On the Bosporus and Dardanelles, see Taitbout de Marigny 1947; Labaree 1957; National Geospatial-Intelligence Agency 2011a; and miscellaneous internet resources; on Gibraltar, see National Geospatial-Intelligence Agency 2011d. The effective time cost of these local currents is the result of complex interactions between wind and water and can only be approximated in an extremely crude fashion. From April to September, the model adds 7 and 5 days to south-north passages through the Bosporus and Dardanelles, respectively, and 3 and 4 days for the other months. The added cost for leaving the Mediterranean through the Strait of Gibraltar is 1 day. For discussion, see Scheidel in preparation c.

[9] See National Geospatial-Intelligence Agency 2011d. The model adds 4 days from December to March to account for the probability of storms.

[10] See National Geospatial-Intelligence Agency 2010a, 2011d. Strong currents in the Strait of Bonifacio are only caused by certain winds that primarily obstruct westward travel. Currents in the Strait of Kerch are too peripheral to our network to be included.

[11] For wind-driven temporary increases in current strength, see, e.g., National Geospatial-Intelligence Agency 2011a, on the Levant. Pryor's 1988: 13 intimation of powerful currents throughout the Mediterranean is not supported by the official hydrographic data at our disposal.

[12] Cf. the paucity and often anecdotal nature of the relevant comparanda gathered by Arnaud 2007: 330-1.

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[13] For the same reason, no roads on islands are included. Islands are included into the larger network by means of maritime routes.

[14] See "Applying ORBIS". Tracking of itinerary routes was greatly facilitated by the multiple map layers provided at http://peutinger.atlantides.org/maps-c-f/.

[15] Peloponnesian roads may be added later, drawing on Sanders and Whitbread 1990.

[16] We owe this information to Carlos Norena's "Mapping Urbanization in the Roman Empire" project, which has already geo-referenced all these sites. Even so, incorporating them into the network as functional nodes would require considerable effort.

[17] Owing to the poor quality of many of the distances records in the Peutinger Table, http://omnesviae.org cannot readily be used as a resource for reconstructing Roman travel.

[18] For the last one, see note 20.

[19] For the complexities of Roman travel in the Alps, see Hyde 1935; Bergier 1975; Walser 1984, 1986, 1994; Hunt 1998.

[20] According to project contributor Hans Wietzke's survey of historical camel speed, loaded camels can be expected to have covered a slightly larger daily distance of 36 kilometers. The model assimilates their performance to that of donkeys to permit the application of uniform cost rates for pack animals across the entire network. The difference is effectively modest.

[21] For discussion of the evidence, see Scheidel in preparation c.

[22] Roueché 1989: 307-8. Although the text reads merely "mo." instead of "ke.mo.", we may assume that the intended unit of measurement was the *modius kastrensis* just as elsewhere in the edict, most notably in XXXVA.33 (see the following note). The fact that a food allowance (*victus*) is only provided for upriver transport (Roueché 1989: 308, which qualifies the needless conjecture in XXXV.56 on p.305) makes sense if it is interpreted as support for a towing crew. However, assuming a boat with several tons of cargo and applying the edict's own stipulations concerning daily wages for unskilled labor, even employment of a dozen crew members would not have made a palpable difference to unit costs, and the cost of the food allowance is therefore disregarded in the model.

[23] In XXXVA.33, it cost 7,500 *denarii* to ship 1,000 *modii kastrenses* from Ravenna to Aquileia, presumably along a 200 mile-long network of lagoons and canal that tracked the Adriatic coast: Roueché 1989: 308; Laurence 1999: 118), 25 percent less than implied by the standard price ratio for downriver transport. For discounts in Egypt, see Johnson 1936: 407-8.

[24] The *Stadiasmus Patarensis* provides detailed terrestrial routes for Roman Lycia (see forthcoming work to be posted in "Applying ORBIS), and Wietzke has identified a dense network of caravan routes in and around Egypt.

[25] Selective coverage is a problem for any network analysis that equates the extent to which networks are documented with the scope of the networks as such: cf., e.g., Graham 2006.

[26] Most of the maps in Talbert 2000 are available online at http://peutinger.atlantides.org/maps-c-f/. Attempts to obtain permission from Princeton University Press to use these files as a background layer for our network have so far been unsuccessful.

[27] Carlos Norena's *Mapping Urbanization in the Roman Empire* project (2009-), which references over 3,000 urban sites drawn from Talbert 2000, belongs in the same category.

References

S. Abdel-Fattah, A. Amin and L. C. van Rijn 2004. “Sand transport in Nile river, Egypt.” *Journal of Hydraulic Engineering* 13 (doi: 10.1061/(ASCE)0733-9429(2004)130:6(488)).

C. E. P. Adams 2007. *Land transport in Roman Egypt: a study of economics and administration in a Roman province*. Oxford.

C. Adams and R. Laurence (eds.) 2001. *Travel and geography in the Roman empire*. London.

P. Arnaud 1992. “Les relations maritimes dans le Pont-Euxin d’après les données numériques des géographes anciens (pseudo-Skylax, Strabon, Pomponius Mela, Pline, Arrien, Anonyme de 500, Marcien d’Héraclée).” *Revue des Etudes Anciennes* 94: 57-77.

P. Arnaud 1998. “La navigation hauturière en Méditerranée antique d’après les données des géographes anciens: quelques exemples.” In E. Rieth (ed.), *Méditerranée antique: pêche, navigation, commerce*. Paris: 75-87.

P. Arnaud 2005. *Les routes de la navigation antique: itinéraires en Méditerranée.* Paris.

P. Arnaud 2007. “Diocletian’s prices edict: the prices of seaborne transport and the average duration of maritime travel.” *Journal of Roman Archaeology* 20: 321-336.

A. Babeu 2011. *“Rome wasn’t digitized in a day:” building a cyberinfrastructure for digital Classics*. Washington DC.

M. Balard 1987. “Le film des navigations orientales de Gênes au XIIIe siècle.” in H. Dubois et al. (eds.), *Horizons marins, itinéraires sprirituels (Ve-XVIIIe siècles)*. Vol. 2. Nancy: 99-122.

N. Beardmore 1872. *Manual of hydrology*. London.

J. F. Bergier 1975. “Le trafic à travers les Alpes et les liaisons transalpines du haut Moyen Âge aux XVIIe siècle.” In *Le Alpi et l’Europe*. Vol. 3. Bari: 1-72.

V. Borghesi 1986. “Rotte e tempi di percorrenza nel Mediterraneo tra XV e XVI secolo.” in Marx (ed.) 1986: 245-250,

F. Braemer 1989. “La coordination de la voie d’eau et de la route terrestre dans l’antiquité romaine: villes de transbordement.” in *La ville et le fleuve*. Paris: 109-121.

F. Braemer 1998. “Eléments naturels (vents, courants, avantages, inconvénients, risques) et itinéraires maritimes.” In E. Rieth (ed.), *Méditerranée antique: pêche, navigation, commerce*. Paris: 61-74.

F. Braudel 1995. *The Mediterranean and the Mediterranean world in the age of Philipp II*. Berkeley.

E. Bremer 2001. *Die Nutzung des Wasserweges zur Versorgung der römischen Militärlager an der Lippe*. Münster.

D. Brewster 1832. “Inland navigation.” In *The Edinburgh Encyclopaedia*. Vol. 14. Philadelphia: 249-447.

P. Briant and R. Descat 1998. “Un registre douanier de la satrapie d’Egypte à l’époque achéménide.” In N. Grimal and B. Menu (eds.), *Le commerce en Egypte ancienne*. Cairo: 59-104.

C. Brühl 1986. *Fodrum, gistum, servitium regis*. Cologne.

A. Burford 1960. “Heavy transport in classical Greece.” *Economic History Review* 13: 1-18.

G. C. Calcagno 1986. “Rotte e tempi di percorrenza nel Mediterraneo occidentale nel secolo XVII.” In Marx (ed.) 1986: 251-256.

M. Calzolari 1997. “Ricerche sugli itinerary romani: L’Itinerarium Burdigalense.” In *Studi in onore di Nereo Alfieri. Atti dell’Accademia delle Scienze di Ferrara* 74 Supplemento: 127-89.

B. Campbell 2012. *Rivers and the power of ancient Rome*. Chapel Hill (in press).

C. Carreras and R. Morais (eds.) 2010. *The Western Roman Atlantic façade: a study of the economy and trade in the Mar Exterior from the Republic to the Principate*. Oxford.

L. Casson 1951. “Speed under sail of ancient ships.” *Transactions of the American Philological Association* 82: 136-48.

L. Casson 1995. *Ships and seamanship in the ancient world*. 2nd ed. Baltimore.

G. Castelnuovo 1996. “Tempi, distanze e percorsi in montagna nel basso medioevo.” In *Spazi, tempi, misure e percorsi nell’Europa del bassomedioevo. Atti del XXXII convegno storico internazionale, Todi, 8-11 ottobre 1995*. Spoleto: 211-236.

R. Chevallier 1976. *Roman roads*, London.

M. Cioc 2005. *The Rhine: an eco-biography, 1815-2000*. Seattle.

C. Clark and M. Haswell 1970. *The economics of subsistence agriculture*. London.

D. Claude 1985. *Der Handel im westlichen Mittelmeer während des Frühmittelalters*. Göttingen.

R. J. de Clavijo 1859. *Narrative of the embassy of Ruy Gonzalez de Clavijo to the court of Timour, of Samarcand, A.D. 1403-6*. Translated by C. R. Markham. London.

J. P. Cooper 2011. “No easy option: Nile *versus* Red Sea in ancient and mediaeval north-south navigation.” In Harris and Iara (eds.) 2011: 189-210.

C. Corsi 2000. *Le strutture di servizio del cursus publicus in Italia : ricerche topografiche ed evidenze archeologiche*. Oxford.

B. Cotterell and J. Kamminga 1990. *Mechanics of pre-industrial technology*. Cambridge.

F. De Izarra 1993. *Hommes et fleuves en Gaule romaine*. Paris.

A. Deman 1987. “Réflexions sur la navigation fluviale dans l'Antiquité.” In T. Hackens and P. Marchetti (eds.), *Histoire économique de l'Antiquité. Bilans et contributions de savants belges présentés dans une réunion interuniversitaire à Anvers/Antwerpen, Universitaire Fakulteiten Sint-Ignatius.* Louvain-la-Neuve: 79-106.

F. Denel 1970. “La navigation sur le Rhone au XVe siècle d’après les registres de péage de Baix.” *Annales du Midi* 82: 287-299.

E. de St Denis 1981. “Le Rhône vu par les Grecs et les Latins de l’antiquité.” *Latomus* 40: 545-70.

H. Dubois 1986. “Techniques et couts des transports terrestres en France aux XIVe et XVe siècles.” In Marx (ed.) 1986: 279-291.

R. Duncan-Jones 1982. *The economy of the Roman empire: quantitative studies*. 2nd ed. Cambridge.

R. Duncan-Jones 1990. *Structure and scale in the Roman economy*. Cambridge.

M. Eckoldt 1980. *Schiffahrt auf kleinen Flüssen Mitteleuropas in Römerzeit und Mittelalter*. Oldenburg.

C. W. J. Eliot 1955. “New evidence for the speed of the Roman imperial post.” *Phoenix* 9: 76-80.

D. Ellmers 1972. *Frühmittelalterliche Handelsschiffahrt in Mittel- und Nordeuropa*. Neumünster: 248-254.

R. Elze 1980. “Über die Leistungsfähigkeit von Gesandtschaften und Boten im 11. Jahrhundert.” In W. Paravicini and K. F. Werner (eds.), *Histoire comparée de l’administration (IVe-XVIIIe siècles)*, Munich: 3-10.

D. W. Engels 1978. *Alexander the Great and the logistics of the Macedonian army*. Berkeley.

P. Erdkamp 1998. *Hunger and the sword: warfare and food supply in Roman Republican wars (264-30 B.C.)*. Amsterdam.

http://www.european-waterways.eu/

A. Fakhri 1974. *The oases of Egypt, II: Bahriyah and Farafra oases*. Cairo.

G. Fasoli 1978. “Navigazione fluviale – porti e navi sul Po.” In *Navigazione* 1978: 565-620.

R. J. Forbes 1955. “Land transport and road building.” In R. J. Forbes, *Studies in ancient technology*. 2nd ed. Vol. 2. Leiden: 131-192.

J. van Gils 2004. “Danube WQ model: analysis of available data.”

S. D. Goitein 1967. *A Mediterranean society: the Jewish communities of the world as portrayed in the documents of the Cairo Geniza, I: Economic foundations*, Berkeley.

J. L. V. González 2011. “GIS and Roman ways research in Hispania.” ESRI European User Conference 2011, Madrid (Spain), October 26-28, 2011.

S. Graham 2006. “Networks, agent-based models and the Antonine itineraries: implications for Roman archaeology.” *Journal of Mediterranean Archaeology* 19: 45-64.

S. Graham 2009. “The space between: the geography of social networks in the Tiber valley.” In F. Coarelli and H. Patterson (eds.), Mercator Placidissimus*: the Tiber valley in antiquity. New research in the upper and middle river valley*. Rome: 671-686.

Great Britain, Meteorological Office 1963. *Weather in the Black Sea*. London.

K. Greene 1986. *The archaeology of the Roman economy*, London.

J. F. Haldon (ed.) 2006. *General issues in the study of medieval logistics*, Leiden.

W. V. Harris and K. Iara (eds.) 2011. *Maritime technology in the ancient economy: ship-design and navigation*. Portsmouth RI.

P. Heilporn 2000. “77. Registre de navires marchands.” In H. Melaerts (ed.), *Papyri in honorem Johannis Bingen*. Leuven: 339-359.

P. Herrmann 2007. *Itinéraires des voies romaines de l’antiquité au Moyen Age*. Paris.

A. W. Hesselink and M. G. Kleinhans 2002. “Flow characteristics of the Rhine distributaries, The Netherlands, calculated from historic flow measurements.” *Proceedings NCR-days*: 38-40.

A. W. Hesselink, M. G. Kleinhans and G. L. Boreel 2006. “Historic discharge measurements in three Rhine branches.” *Journal of Hydraulic Engineering* 132 (doi:10.1061/(ASCE)0733-9429(2006)132:2(140)).

F. Himmler, H. Konen, and J. Löffl 2009. *Exploratio Danubiae: ein rekonstruiertes spätantikes Flusskriegsschiff auf den Spuren Kaiser Julian Apostatas*. Berlin.

O. Höckmann 1985. *Antike Seefahrt*. Munich.

K. Hopkins 1980. “Models, ships and staples.” In P. Garnsey and C. R. Whittaker (eds.), *Trade and famine in classical antiquity*. Cambridge: 84-109.

P. Horden and N. Purcell 2000. *The corrupting sea: a study of Mediterranean history*. Oxford and Malden MA.

G. W. Houston 1988. “Ports in perspective: some comparative materials on Roman merchant ships and ports.” *American Journal of Archaeology* 92: 553-564.

P. Hunt 1998. “*Summus Poeninus* on the Grand St Bernard Pass.” *Journal of Roman Archaeology* 11: 265-74.

L. W. Hunter 1913. “Cicero’s journey to his province of Cilicia in 51 B.C.” *Journal of Roman Studies* 3: 73-97.

W. W. Hyde 1935. *Roman Alpine routes*. Philadelphia.

A. Hyland 1990. *Equus: the horse in the Roman world*. London.

G. Jehel 1993. *Les Génois en Méditerranée occidentale (fin XI-début du XIV siècle)*. Paris.

A. C. Johnson 1936. *Roman Egypt to the reign of Diocletian. An Economic Survey of Ancient Rome.* Vol. 2. Baltimore.

J. E. Jones 2009. *The maritime and riverine landscape of the west of Roman Britain: water transport on the Atlantic coasts and rivers of Britannia*. Oxford.

C. Jung and T. Odiot 1999. “La moyenne vallée du Rhône, de l’Isère à l’Ardèche.” *Gallia* 56: 81-90.

J. Koder and F. Hild 1976. *Hellas und Thessalien: Tabula Imperii Byzantini 1*. Vienna.

A. Kolb 2000. *Transport und Nachrichtentransfer im römischen Reich*. Berlin

H. C. Konen 2000. *Classis Germanica: Die römische Rheinflotte im 1.-3. Jahrhundert n. Chr.* St. Katharinen.

B. W. Labaree 1957. “How the Greeks sailed into the Black Sea.” *American Journal of Archaeology* 26: 29-33.

La navigazione mediterranea nell’alto medioevo 1978. 2 vols. Spoleto.

J. Langdon 1986. *Horses, oxen, and technological innovation: the use of draft animals in English farming, 1066-1500*. Cambridge.

J. Langdon 1993. “Inland water transport in medieval England.” *Journal of Historical Geography* 19: 1-11.

R. Latouche 1961. *The birth of western economy*. London.

R. Laurence 1998. “Land transportation in Roman Italy: cost, practice, and the economy.” In H. Parkins and C. Smith *(eds.), Trade, traders, and the ancient city*. London: 129-48.

R. Laurence 1999. *The roads of Roman Italy: mobility and cultural change*. London and New York.

S. Lebecq 1988. “En barque sur le Rhin’: pour une étude des conditions matérielles de la circulation dans le bassin du Rhin au cours du premier moyen âge.” *Publications de la Section historique de l’Institut grand-ducal de Luxembourg* 104: 33-59.

J. Le Gall 1953. *Le Tibre, fleuve de Rome, dans l’antiquité*. Paris.

J. Leidwanger 2011. “Maritime archaeology as economic history: long-term trends of Roman commerce in the Northeast Mediterranean,” Ph.D. thesis University of Pennsylvania.

A. C. Leighton 1972. *Transport and communication in early medieval Europe AD 500-1100.* Newton Abbot.

A. G. Leonard 1894. *The camel*. London.

I. Liska, F. Wagner and J. Slobodník (eds.) 2008. *Joint Danube survey 2: final scientific report*. Vienna.

M. A. Littauer and J. Crouwel 1979. *Wheeled vehicles and ridden animals in the ancient Near East*. Leiden.

B. Löhberg 2010. *Das “Itinerarium provinciarum Antonini Augusti:” ein kaiserzeitliches Straßenverzeichnis des Römischen Reiches. Überlieferung, Strecken, Kommentare, Karten*. 2nd ed. Berlin.

R. S. Lopez 1956. “The evolution of land transport in the Middle Ages.” *Past and Present* 9: 17-29.

F. Ludwig 1897. *Untersuchungen über die Reise- und Marschgeschwindigkeit im XII. und XIII. Jahrhundert*. Berlin.

R. Lugand 1926. “Note sur l’itinéraire maritime de Rome à Arles.” *Mélanges de l’École française de Rome: Antiquité* 43: 124-139.

G. P. Majeska 1984. *Russian travelers to Constantinople in the fourteenth and fifteenth centuries*. Washington DC.

E. Malamut 1988. *Les îles de l’empire byzantin: VIIIe-XIIe siècles*. Paris.

A. V. Marx (ed.) 1986. *Trasporti e sviluppo economico. Secoli XIII-XVIII*. Florence.

J. Masschaele 1993. “Transport costs in medieval England.” *Economic History Review* 46: 266-279.

J. Matthews 2000. *The journey of Theophanes: travel, business, and daily life in the Roman East*. New Haven.

M. McCormick 2001. *Origins of the European economy: communications and commerce, A.D. 300-900*. Cambridge.

F. J. Meijer 1983. “Mare clausum aut mare apertum: een beschouwing over zeevart in de winter.” *Hermeneus* 55: 2-20.

M. Mollat 1952. *Le commerce maritime normand á la fin du Moyen Age: etude d'histoire éocnomique et sociale*. Paris.

J. Morton 2001. *The role of the physical environment in ancient Greek seafaring*. Leiden.

E. Müller-Mertens 1978. *Die Reichsstruktur im Spiegel der Herrschaftspraxis Ottos des Grossen*. Berlin.

W. M. Murray 1987. "Do modern winds equal ancient winds?" *Mediterranean Historical Review* 2: 139-167.

National Geospatial-Intelligence Agency 2010a. *Sailing directions (enroute): English Channel*. 16th ed. no place.

National Geospatial-Intelligence Agency 2010b. *Sailing directions (enroute): North Sea*. 13th ed. no place.

National Geospatial-Intelligence Agency 2011a. *Sailing directions (enroute): Eastern Mediterranean*. 13th ed. no place.

National Geospatial-Intelligence Agency 2011b. *Sailing directions (enroute): Ireland and the West Coast of England*. 12th ed. no place.

National Geospatial-Intelligence Agency 2011c. *Sailing directions (enroute): West Coast of Europe and Northwest Africa*. 13th ed. no place.

National Geospatial-Intelligence Agency 2011d. *Sailing directions (enroute): Western Mediterranean*. 15th ed. no place.

National Imagery and Mapping Agency 2002. *Atlas of pilot charts: North Atlantic Ocean*. no place.

N. Ohler 1989. *The medieval traveler*. Woodbridge.

J. Oleson (ed.) 2008. *The Oxford handbook of engineering and technology in the classical world*. New York.

G. Petti-Balbi 1996. "Distanze e programmi di viaggi sul mare." In *Spazi, tempi, misure e percorsi nell'Europa del bassomedioevo. Atti del XXXII convegno storico internazionale, Todi, 8-11 ottobre 1995*. Spoleto.

M. Polfer 1991. "Der Transport über den Landweg – ein Hemmschuh für die Wirtschaft der römischen Kaiserzeit?," *Helinium* 31: 273-295.

B. Porten and A. Yardeni 1993. *Textbook of Aramaic documents from ancient Egypt.* Vol. 3. Jerusalem.

N. J. G. Pounds 1974. *An economic history of medieval Europe*. London

L. Prati and Q. B. Richardson 1971. "Water pollution and self-purification study on the Po river below Ferrara." *Water Research* 5: 203-212.

J. H. Pryor 1989. "The voyage of Rutilius Namatianus: from Rome to Gaul in 417 C.E." *Mediterranean Historical Review* 4: 271-280.

J. H. Pryor 1992. *Geography, technology and war: studies in maritime history of the Mediterranean 649-1571*. 2nd ed. Cambridge.

L. Quilici 2008. "Land transport, Part 1: roads and bridges." In Oleson (ed.) 2008: 551-579.

G. Radke 1971. *Viae publicae romanae* (= RE Suppl. 13). Stuttgart 1971.

G. Raepsaet 2002. *Attelages et techniques de transport dans le monde gréco-romain*. Brussels.

G. Raepsaet 2008. "Land transport, Part 2: riding, harnesses, and vehicles." In Oleson (ed.) 2008: 580-605.

A. M. Ramsay 1925. "The speed of the Roman imperial post." *Journal of Roman Studies* 15: 60-74.

W. M. Ramsay 1904. "Roads and travel." In J. Hastings (ed.), *A dictionary of the Bible*. Extra volume. New York: 375-402.

M. Rathmann 2003. *Untersuchungen zu den Reichsstrassen in den westlichen Provinzen des Imperium Romanum*. Mainz.

M. Redde 1986. *Mare nostrum: les infrastructures, le dispositif, et l'histoire de la marine militaire sous l'empire romain*. Paris.

Y. Renouard 1961. "Information et transmission des nouvelles." In C. Samaran (ed.), *L'histoire et ses methods*. Paris: 95-142.

Y. Renouard 1962. "Routes, étapes et vitesses de marche de France à Rome au XIIIe et au XIVe siècles d'après les itinéraires d'Eudes Rigaud (1254) et de Barthélemy Bonis (1350)." In *Studi in onore di Amintore Fanfani. III: Medioevo*. Milan: 403-428.

W. Riepl 1913. *Das Nachrichtenwesen des Altertums*. Leipzig (repr. Hildesheim 1972).

S. Rippon 2008. "Coastal trade in Roman Britain: the investigation of Crandon Bridge, Somerset, a Romano-British transshipment port beside the Severn estuary." *Britannia* 39: 85-144.

C. Röring 1983. *Untersuchungen zu römischen Reisewagen*. Koblenz.

J. P. Roth 1999. *The logistics of the Roman army at war (264 BC – AD 235)*. Leiden.

C. Roueché 1989. *Aphrodisias in late antiquity: the late Roman and Byzantine inscriptions including texts from the excavations at Aphrodisias conducted by Kenan T. Erim*. London.

J. Rougé 1952. "La navigation hivernale sous l'empire romain." *Revue des études anciennes* 54: 316-325.

J. Rougé 1965. "Les relations de Lyon et de la mer: a propos de CIL XIII, 1942." In *Actes du 89e Congrès national des sociétés savantes. Section d'archéologie: Lyon 1964.* Paris: 136-152.

J. Rougé 1966. *Recherches sur l'organisation du commerce maritime en Méditerranée sous l'empire romain*. Paris.

M. B. A. Saad 2002. "Nile river morphology changes due to the construction of the high Aswan dam in Egypt."

B. Salway 2004. "Sea and river travel in the Roman itinerary literature." In R. J. A. Talbert and K. Brodersen (eds.), *Space in the Roman world: its perception and presentation*. Münster: 43-96.

G. D. R. Sanders and I. K. Whitbread 1990. "Central places and major roads in the Peloponnese." *Annual of the British School at Athens* 85: 333-361.

P. Sardella 1948. *Nouvelles et spéculations à Venise au début du XVIe siècle*. Paris.

J. Sasel 1973. "Trajan's canal at the Iron Gate." *Journal of Roman Studies* 63: 80-85.

A. Schaube 1906. *Handelsgeschichte der romanischen Völker des Mittelmeergebiets bis zum Ende der Kreuzzüge*. Munich.

W. Scheidel 2011. "A comparative perspective on the determinants of the scale and productivity of Roman maritime trade in the Mediterranean." In Harris and Iara (eds.) 2011: 21-37.

W. Scheidel in preparation a. "The shape of the Roman world."

W. Scheidel in preparation b. "A new explanation of the maritime freight charges in Diocletian's Price Edict."

W. Scheidel in preparation c. "The speed of travel in the Roman world."

P. Sillières 1990. *Les voies de communication de l'Hispanie méridionale*. Paris.

A. J. Silverstein 2007. *Postal systems in the pre-modern Islamic world*. Cambridge.

D. V. Sippel 1987. "Some observations on the means and cost of the transport of bulk commodities in the late Republic and early empire." *Ancient World* 16: 35-45.

S. Smith 1876. *The Edinburgh Review* 144/145.

P. Soustal 1981. *Nikopolis und Kephallenia: Tabula Imperii Byzantini 3*. Vienna.

M. Stefan and G. Romanescu n.d. "Problems of seagoing navigation in Bosphorus strait."

H.-E. Stier et al. (eds.) 1991. *Grosser Atlas zur Weltgeschichte*. Munich.

P. Stoffel 1994. *Über die Staatspost, die Ochsengespanne und die requirierten Ochsengespanne*. Bern.

E. Taitbout de Marigny 1847. *New sailing directions of the Dardanalles, Marmara Sea, Bosphorus, Black Sea, and the Sea of Azov*. London.

R. J. A. Talbert (ed.) 2000. *Barrington atlas of the Greek and Roman world*. Princeton.

R. J. A. Talbert 2007. “Author, audience, and the Roman empire in the Antonine Itinerary.” In R. Haensch and J. Heinrichs (eds.), *Herrschen und Verwalten: Der Alltag der römischen Administration in der hohen Kaiserzeit*. Cologne: 256-70.

R. J. A. Talbert 2010. *Rome’s world: the Peutinger Map reconsidered*. Cambridge.

R. J. A. Talbert, J. Bodel and S. Alcock (eds.) forthcoming. *Highways, byways and road systems in the pre-modern world*.

M. Tangheroni 1992. “Economia e navigazione nel Mediterraneo occidentale tra XI e XII secolo.” *Medioevo: Saggi e Rassegne* 16: 10-24.

M. Tangheroni 1993. “Trasporti navali e commercio marittimo nell’Italia del Quattrocento.” In T. Fanfani (ed.), *La penisola italiana e il mare: costruzioni navali, trasporti e commercio tra XV e XX secolo*. Naples: 31-56.

J. Thomas and J. Baldwin (eds.) 1880. *Lippincott’s gazetteer of the world: a complete pronouncing gazetteer, or, geographical dictionary of the world*. Vol. 1. New ed. Philadelphia.

Trasporti e sviluppo economico, secc. XIII-XVIII. Atti della 5 settimana di studio dell’Istituto F. Datini di Prato 1986. Florence.

A. L. Udovitch 1978. “Time, the sea and society: duration of commercial voyages on the southern shores of the Mediterranean during the High Middle Ages.” In *La navigazione* 1978. Vol. 2: 503-563.

U.S.A. National Imaging and Mapping Agency 1967-. *Distances between ports* (internet resource).

U.S. Navy, Hydrographic Office 1943. *Table of distances between ports via the shortest navigable routes*. Washington DC.

P. Vigneron 1968. Le cheval dans l’antiquité gréco-romaine. Nancy.

G. Walser 1984. Summus poeninus : Beiträge zur Geschichte des Grossen St. Bernhard-Passes in römischer Zeit. Wiesbaden.

G. Walser 1986. Via per Alpes Graias : Beiträge zur Geschichte des Kleinen St. Bernhard-Passes in römischer Zeit. Stuttgart.

G. Walser 1994. *Studien zur Alpengeschichte in antiker Zeit*. Stuttgart.

C. A. Yeo 1946. “Land and sea transportation in imperial Italy.” *Transactions of the American Philological Association* 77: 221-244.

Presentations and publications

Elijah Meeks, "ORBIS: A Geospatial Network Model of the Roman World." 3rd Leonardo satellite symposium on Arts, Humanities, and Complex Networks at NetSci2012, Evanston, Illinois, June 19, 2012

Walter Scheidel, “Orbis: The Stanford Geospatial Network Model of the Roman World.” University of Pennsylvania, Philadelphia, PA, March 28, 2012.

------, “Orbis: The Stanford Geospatial Network Model of the Roman World.” Jokouwsky Institute for Archaeology and the Ancient World, Brown University, Providence, RI, April 16, 2012.

------, “The shape of the Roman world.” Annual Meeting of the Association of Ancient Historians, University of North Carolina, Chapel Hill, NC, May 4, 2012.

Jonathan Weiland, “The Stanford ORBIS project: the shape of the Roman empire.” 2012 Computer Applications in Archaeology Conference, Southampton, UK, March 29, 2012.