The roadblock effect:
War shocks, modal shifts, and population changes

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ABSTRACT: This paper investigates a novel "roadblock effect," whereby temporary forced route changes catalyse the adoption of a new transport technology. The Taiping rebellion in 19th-century China ravaged many cities, but also blocked key land routes, triggering investments facilitating steamship trade. Combining a trade model featuring modal and route choice, shipping records, and a new method to estimate historical trade costs, I show that the post-rebellion spatial variation in steamship trade was driven by blocked land routes and the feasibility of sea alternatives. This permanently moved many trade routes to sea and shifted population towards port cities.

Key words: city populations, path dependence, modal choice, Taiping rebellion
JEL classification: F12, J61, N95, R12, R40

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1. Introduction

I use the Taiping rebellion in 19th-century China to study the evolution of city populations when shocks hit them, not only directly, through deaths and displacement, but also indirectly, by promoting some trade routes and modes over others. This highlights the complex interplay between large population shocks, shifting natural advantage, the persistence of agglomerations, and substantial changes in trade costs through technology and investment.

City locations and sizes reflect a combination of natural advantage and agglomeration economies. Natural endowments and technology differ across space, making some potential city locations much more suitable than others. At the same time, localised increasing returns also make locations that already have many firms and people more attractive to other firms and people. Such increasing returns can then reinforce or counteract comparative advantage.[1] Reinforcement happens when a location with advantageous underlying conditions sees them amplified by agglomeration economies. However, if conditions change, concentration in a location can remain very persistent even if it is no longer superior, whether because of coordination problems or sunk infrastructure costs (e.g. Bleakley and Lin, 2012; Michaels and Rauch, 2017).

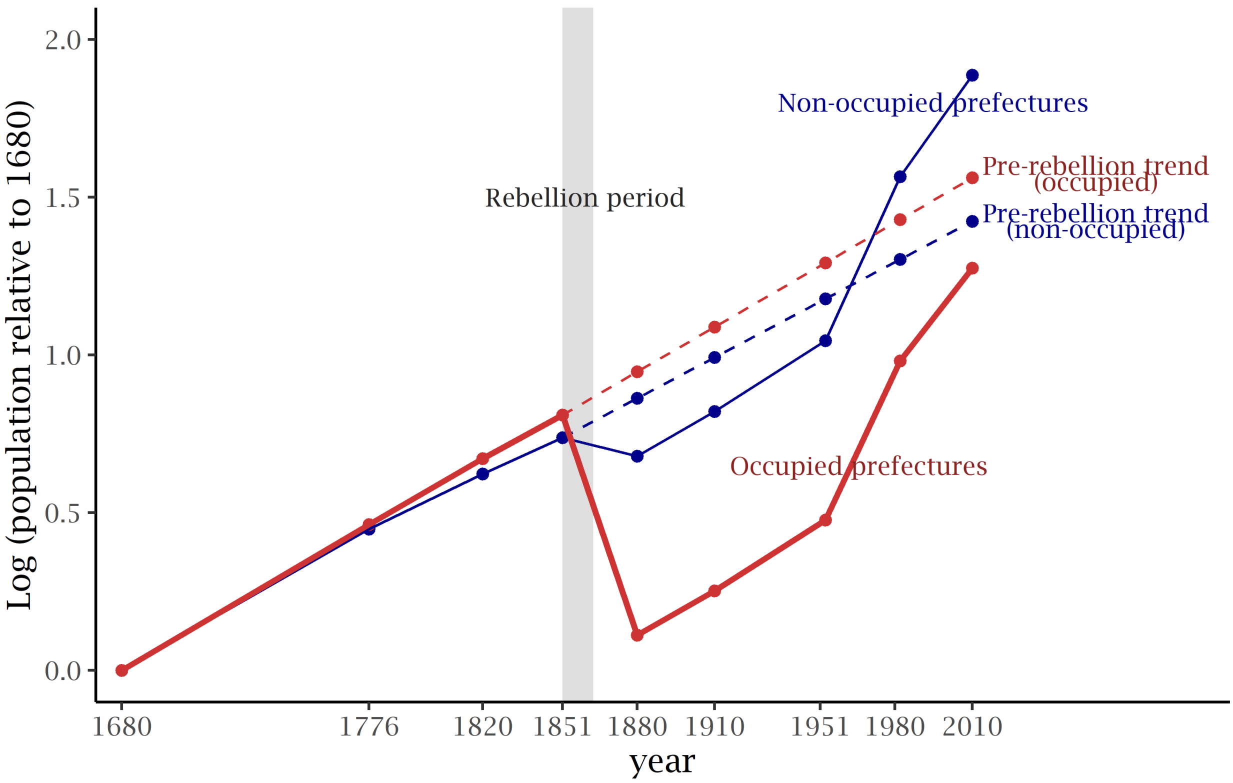
Trade costs complicate the analysis of relative city sizes further because, in addition to underlying conditions ("first nature") and the current concentration at each location ("second nature"), we have to consider the access each of them has to a larger market (Krugman, 1993). Moreover, trade costs can change over time. Normally they change because of new transport infrastructure, and there is a large literature that examines its consequences (e.g. Faber, 2014; Donaldson, 2018). However, trade costs can also change because of new transport technologies (e.g. Tsivanidis, 2018; Heblich, Redding and Sturm, 2020). A common difficulty in investigating the effects of changing trade costs is that they are often endogenous. Here, I exploit the heterogeneous incentives to adopt steamship transport through the route and modal changes induced by shocks of civil conflict elsewhere.

The Taiping rebellion was the largest peasant revolt in the history of China. The civil war between the rebels and the Qing government led to the death of one out of every four Chinese people (Ge, Hou and Zhang, 1999). This shock was unevenly distributed, and places heavily ravaged by war, concentrated in rebellion occupied region, lost up to 80% of their population (Cao and Li, 2000). Figure 1 compares the long-term evolution of population across occupied and non-occupied prefectures. The thin blue continuous line corresponds to prefectures that were not occupied by the rebellion, while the thick red continuous line corresponds to prefectures that were occupied.[2] We see that the occupied prefectures had a slightly higher population growth rate than the non-occupied prefectures before the rebellion, but they experienced a much larger population drop during the rebellion. Afterwards, population in both groups grew in a parallel manner. Thus, the population in occupied prefectures did not catch up but instead suffered a permanent loss, the consequences of which are still evident a century and a half later.

[1]Models examining different aspects of this trade-off include Venables, 1999; Forslid and Wooton, 2003; Amiti, 2005; Pflüger and Tabuchi, 2019.

[2]Population is expressed as the natural logarithm of population in each data year (1680, 1776, 1820, 1880, 1910, 1953, 1982 and 2010) relative to 1680 population. Thus, initial population is normalised to 0. The dashed lines plot the pre-rebellion trends for each of the two prefecture groups, based on the average growth rate between 1680 and 1851. The shaded grey rectangle marks the rebellion period, 1851-1864.

Figure 1: Evolution of population in occupied/non-occupied prefectures

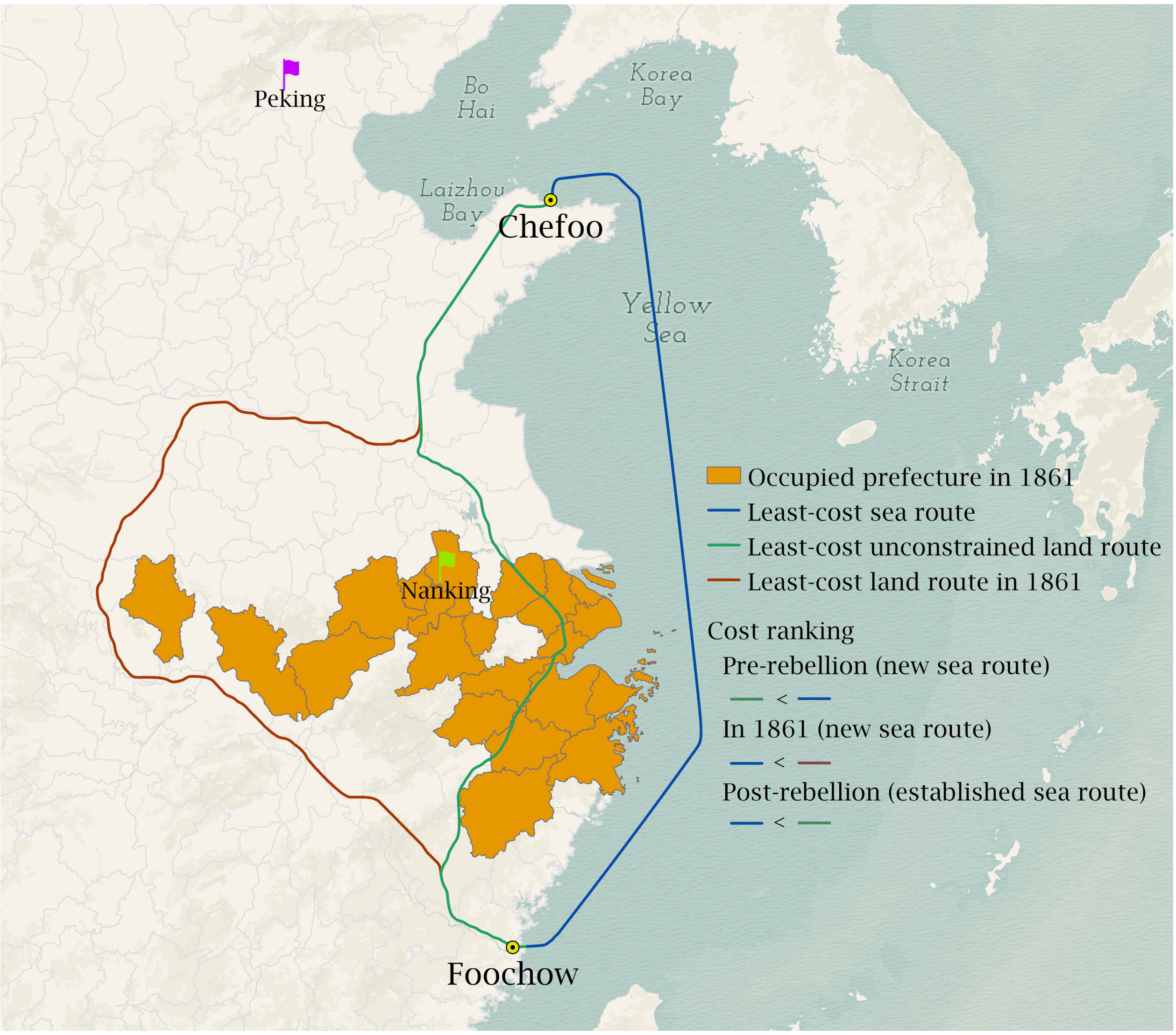


Notes: Based on the 2018 update of the prefecture population data in Cao (2000), 1982 China county census, and 2010 China township census. The pre-rebellion trends project forward the average annual growth rate of population for each group of prefectures (those that were occupied by the Taiping rebellion and those that were not) between 1680 and 1851.

There is debate about the extent to which large shocks can alter the equilibrium distribution of population across cities. Based on the Allied bombing of Japanese cities during World War II, Davis and Weinstein (2002) find that the long-run distribution of relative city sizes can be highly persistent even after large temporary shocks. Japanese cities experiencing more intense bombings quickly reverted to their pre-war relative sizes. Instead, I find strong permanent effects of war shocks. I argue this is because much of the medium-term impact on the distribution of population across Chinese cities operates through an indirect channel.

Despite a large potential for sea trade, trade activities and population in China remained largely inland before the rebellion. When the rebellion blocked some of the main land trade routes in China, this forced a search for alternatives. It triggered substantial investments to facilitate sea trade, notably using steamships, which until then had a slow take-up. After the rebellion, with sunk investment already incurred for establishing sea lanes, many trade routes permanently shifted to sea transport. This in turn catalysed a shift of population towards port cities. An example of this can be seen in Figure 2. The figure shows in green the least-cost land route connecting Chefoo (located in today's Yantai) and Foochow (Fuzhou) before the rebellion. These two coastal cities could also have been connected by sea, but my estimates show that the cost savings compared with

Figure 2: An example of the "roadblock effect"



Notes: Least-cost land and sea routes between Chefoo (today's Yantai) and Foochow (Fuzhou) based on travel costs in *Panel A* of Table 2. Land routes can combine courier and non-courier land routes with different levels of terrain ruggedness as well as river transport. The cost ranking takes into account the cost of using each mode, the cost of inter-modal transfer, and the cost of developing a new land or sea route, as estimated in *Panel B* of Table 2.

the usual land route was not large enough to incur the sunk costs associated with establishing such a route. These sunk costs include learning about the current and tides along the sea lane, being warned of dangerous spots, having staging-posts ready and ensuring safe anchorage on arrival. The rebellion occupied many of the prefectures traversed by the usual land route between Chefoo and Foochow. The dark shaded area in the map shows the rebellion-occupied prefectures in 1861. To transport goods between Chefoo and Foochow one would have had to take the large detour marked in red. According to my estimates presented below, the additional cost this detour entailed was large enough to instead incur the sunk cost of establishing a steamship route between these two cities. Although the unconstrained regular land route became once again usable after the rebellion, with the sea route already in operation, steamship trade remained a less costly option. Indeed the data show that there was active steamship trade between the two ports immediately after the rebellion. In contrast, regular land routes between other city pairs (e.g. Amoy and Canton) were not blocked by the rebellion and steamship trade between them did not become established. I next explain how I examine this process systematically through my analysis.

I start by providing some historical background in Section 2, then describing the data in Section 3, and characterising the impact of the rebellion on population in Section 4. After controlling for pre-existing trends and other differences across prefectures, I find that being occupied during the rebellion was associated with a permanent population loss of 55%, whereas being located on the coast was associated with a 32% population increase. This increase was even greater in coastal cities that saw a surge in steamship trade.

To separate the direct effect of the rebellion on population from the indirect effect operating through the shift from land to sea trade, I exploit regional variations in incentives to take up steamship trade. The key for my identification strategy is that, depending on their location along the regular land trade network, locations would have had their trade flows more or less affected. Maritime trade could boom broadly when the general technology of sea transport advanced. At the same time, land trade could be directly hit in areas occupied by the rebellion, since an explicit aim was to cut off supplies from this area to the capital of the Qing government in Peking. However, regions not directly hit by the rebellion may nevertheless have been substantively affected if a regular land trade route became unusable when the rebellion hits some intermediate point on this connection. Bilateral trade flows by land to and from unoccupied locations were affected indirectly and differently depending on roadblocks on the corresponding routes and the feasibility of sea trade alternatives. Thus, in Section 5, I proceed to show that the probability of sea trade after the rebellion is persistently higher for locality pairs where the regular land trade route connecting them became unusable because of the conflict.

To implement this strategy, I combine new data on bilateral historical trade flows with a trade model featuring modal and route choice. I collect a new data set of bilateral maritime trade in 19th-century China by digitising archives of trade reports from the China Maritime Customs Service.[3] Given that only steamship trade is observed in the data, some additional theoretical structure needs to be given to the analysis to characterise the indirect effect of the rebellion through trade. Trade models typically do not incorporate a modal choice, since trade data is generally not differentiated by which transport method was used to carry the cargoes. Instead, I add modal choice (by land, by steamship, and by sailing ship) to an otherwise standard trade model. Steamships required fixed investments, and this likely held them back until blockage of land routes made such investments a necessity. Thus, I also incorporate sunk investment costs into the model.

The model features a "roadblock effect," by which a temporary increase in land trade costs can trigger sunk investments for steamship trade, thus having permanent effects on modal choices. Across location pairs, the heterogeneous increase in land trade costs during the rebellion can be linked to the increase in the probability of steamship trade immediately after the rebellion, mediated by the incentives to make sunk investments in steamship trade.

[3] The China Maritime Customs Service was a bureaucratic agency set up in 1853 by foreign consuls in Shanghai to collect tariffs that went unpaid when the Qing government was overwhelmed by the Taiping Rebellion.

The model yields a probability of steamship trade for each location pair, which we observe in the data, given relative transport costs via each possible mode. The relative cost of using different land trade routes and their sea alternatives is a key driver of the differential take-up of steamships in different geographical areas. The literature on transport costs usually infers them from freight rates, so the lack of data on freight rates in 19th-century China imposes a challenge.

In the second part of Section 5, I develop a new method to estimate travel costs by different transportation modes using China's 1903 postal map. The map contains the locations of postal district headquarters and the assignment of prefectures to these. Under the assumption that the assignment was made to minimise transport costs to the postal district headquarters, a rich transport cost function can be paramterised, which includes the typical speed of different transport modes, variations in speed due to road types and the terrain, and the fixed costs associated with transitions between modes (which can be unavailable even in modern times).

Despite the limitations imposed by being able to observe steamship trade only immediately after the rebellion, with the estimated transport cost before, during, and after the rebellion, the elasticity of trade costs and sunk infrastructure costs can be pinned down jointly.

The predictions of the model closely match observed modal choices. In particular, the model predicts an average probability of steamship trade between "roadblocked" location pairs of 0.72 compared with 0.42 for "non-roadblocked" location pairs. The respective probabilities in the data are 0.71 and 0.37. The model also suggests that the "roadblock effect" was very important in practice. Under a counterfactual scenario that eliminates roadblocks between roadblocked location pairs, the model estimates that the probability of steamship trade between them would have been much lower, 0.44 instead of 0.72.[4]

Within the literature on the effect of temporary shocks on relative city sizes already mentioned above, some other papers also incorporate changing comparative advantage. Bleakley and Lin (2012) document the continuing importance of historical portage sites as city locations in the United States even though their original advantages have long since become obsolete. Michaels and Rauch (2017) also consider an episode where natural advantages shift over time, but in their case such a shift is combined with a larger population shock in one country than in another. In particular, they compare the diverging experiences of British and French cities following the collapse of the Western Roman Empire. In Britain, subject to a more intense shock, the urban network was displaced towards emerging navigable waterways. In France, where the ensuing destruction and deurbanisation was more limited, medieval towns instead re-emerged more often on their Roman-era locations. I also consider a historical episode where shifting natural advantage (due to the introduction of steamships) was combined with large but heterogeneous population shocks (due to the Taiping rebellion). A key contribution of my framework is that, in addition to the direct channel operating through temporary population shocks, I highlight an indirect channel operating through temporary roadblocks and the incentives they provide to invest in new transport technologies.

[4]The model also delivers a gravity equation of trade. Using the trade costs that I am able to construct using the method introduced in Part B of Section 5, in AppendixF I estimate the elasticities of trade and migration with respect to transport costs in historical China. Reassuringly, these elasticities are similar to those estimated with modern data and for other parts of the world.

In this respect, the paper also connects to the literature on the importance of trade costs and market access in determining the distribution of population across cities (e.g. Redding and Venables, 2004; Faber, 2014; Donaldson, 2018) and within cities (e.g. Baum-Snow, Brandt, Henderson, Turner and Zhang, 2017; Tsivanidis, 2018; Heblich et al., 2020). An important challenge when trying to evaluate the consequences of transport improvements is the endogeneity of infrastructure investments. An advantage of the setting in this paper is that the Taiping rebellion creates exogenous variation in the incentives to invest in sea transport technology.

The paper also adds to the literature on the effect of wars and conflicts on urban development (e.g. Glaeser and Shapiro, 2002; Voigtländer and Voth, 2012; Dincecco and Onorato, 2016). While the previous papers have focused on local impacts of war, this paper shows that the indirect effect on other regions via trade disruption and the ensuing incentives to adopt new technologies can be just as important.

A debate related to the persistence of city locations also pertains to the slow adoption of new technologies even when they are obviously superior to old ones. This could be due to the trade-off between the sunk costs of developing and adopting new technologies and the accumulated learning by doing of incumbent technologies (Brezis and Krugman, 1997). In fact, the introduction of a new technology sometimes revitalises innovation of an incumbent technology. Ward (1967) coined the term "sailing ship effect" for this phenomenon, following the analysis by Gilfillan (1935) of advances made in sailing ships in the second half of the 19th century in response to the introduction of steamships. According to Ward, such advances led to greater improvements in sailing ships than those made in the previous three centuries.

The "roadblock effect" I document and investigate in this paper works in precisely the opposite direction: the temporary blockage of land trade routes during the Taiping rebellion triggered substantial investments to facilitate the use of steamships instead. This had long-term consequences for the distribution of population across Chinese cities in addition to the direct shocks of the rebellion.

2. Historical background

A *The Taiping rebellion*

The Taiping rebellion (1851-1864) was the largest peasant revolt in the history of China and one of the deadliest civil wars in human history. About one out of every four people in China died during the rebellion (Ge et al., 1999). It started as a guerrilla warfare at Kweiping, Guangxi, in southwestern China. Peasants rose up against the Qing government, which levied ever-increasing taxes after a series of natural disasters and an economic crisis following its defeat in the First Opium War. The uprising escalated into a civil war with the Qing government. The rebels swiftly moved northeast to occupy Nanking and established around it "the Taiping Heavenly Kingdom" in the mid and lower Yangtze region (Figure 3). When the rebels' attempt to besiege the imperial capital Peking was defeated, wars between the two forces receded to the area occupied by the rebellion, causing great damage and civilian deaths.[5] Some prefectures in the occupied region lost up to 80% of their population and many places were razed to ground (Cao and Li, 2000).

Before the rebellion, the area around the Yangtze river, especially its lower section, had become the most prosperous part of China, contributing to half of the nation's wealth. The Qing government had relied on the Grand Canal to transport tax-in-kind from this region to the imperial capital.[6] The rebels strategically seized this area as a base to overthrow the Qing dynasty. They occupied prefectures sitting on the Grand Canal to strangle the flow of goods from the lower Yangtze to the imperial capital. With their supplies through the regular routes combining land and canal transport cut off, the Qing government was forced to switch to sea transport to ship tribute grain via Shanghai and Tientsin.

This paper will show that this modal change was not unique to the transport of tribute grain nor to trade between Shanghai and Tientsin, but instead affected a much broader exchange of goods across the whole country. The military confrontation between the rebellion and the Qing government severely curtailed land transport (including canals) that previously used trade routes traversing through the rebellion-occupied region. Depending on the roadblock of their usual land routes and the feasibility of sea trade alternatives, bilateral trade flows between unoccupied locations were affected differently, triggering investments facilitating steamship trade on some routes but not others.

B *The failure to adopt sea trade before the Taiping rebellion*

Since I will argue that the Taiping rebellion acted as a catalyst for sea trade, using steamships in particular, it is important to also understand the status of sea trade before the rebellion.

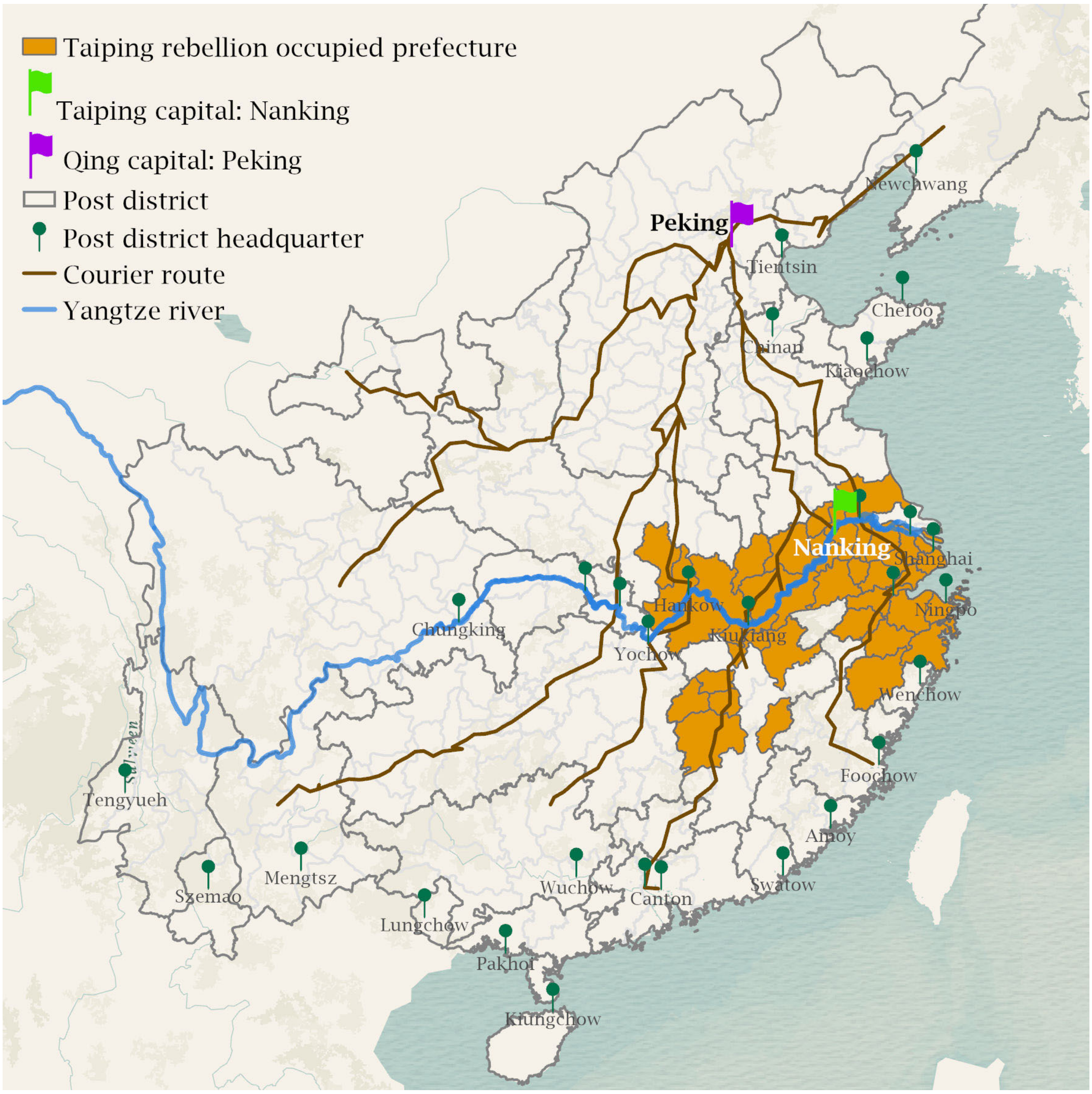
One reason for the weakness of sea trade prior to the Taping rebellion was the concentration of population away from coastal areas. Early during its rule, the Qing government, which ruled China from 1644 to 1912, implemented a sea ban on the mainland. The purpose was to cut off supplies to the Zheng regime in Taiwan, which was founded by loyalists of the previous Ming dynasty. As a part of the policy, coastal residents in the mainland were evacuated to areas 16-26 kilometres inland. When the Zheng family surrendered in 1683, the ban was lifted and former coastal residents were allowed to return. Thereafter, except for a short sea ban placed between 1717 and 1727, maritime trade with foreign countries was acquiesced. [7] Nevertheless, it did not recover to its full blossom in the previous dynasties and population in coastal regions continued to decline.

[5]The rebellion indirectly spurred conflicts in other regions during this period. As Qing troops from all parts of China were transferred to fight against the Taiping soldiers, the military vacuum spurred a series of uprisings in the periphery areas of China, including Yunnan, Shensi, Kansu, Szechuan and Kueichow provinces.

[6]The Grand Canal connects Peking, the capital, to Hangchow in the lower Yangzte region, passing from the north to the south through Tientsin, Hopeh, Shantung, Kiangsu and Chekiang. It formed the inland navigation network of China connecting the Yellow River and the Yangtze River.

[7]In 1758, the Qing government established the Canton system, restricting all trade with western countries to only one port in the South, Canton. Seen by some scholars as a closed-door policy, the restriction was not strictly carried out. Foreign ship arrivals in other ports were documented. Their numbers and trade value were not restricted (e.g. merchant ships arrivals in Canton between 1757 and 1838 increased by 16 times over the previous 72 years and all ports combined). Trade with non-western countries was not subject to the Canton rule.

Figure 3: The Taiping rebellion and Imperial postal districts



Notes: Author's map based on the 1903 postal working map from the China Maritime Customs Postal Series and the China W dataset. Prefectures delimited in light grey and coloured if occupied by the Taiping rebellion. China's historical postal districts delimited in black with the district headquarters marked by a green pin.

Traditionally, domestic trade used a combination of land transport and inland navigation.[8] By the beginning of the 19th century, canal shipping had become increasingly costly, yet flows of goods between different regions continued to rely heavily on the Grand Canal. At the time, the canal was constantly flooded by the Yellow River, which called for regular and costly maintenance by damming up the river and dredging the canal. The problem became so severe that in 1826 the emperor Daoguang launched an initiative to transport tax-in-kind by sea from the lower Yangtze region to the imperial capital. The trial was promising. Sea transport appeared to be one-third as costly and much faster than canal shipping.[9] Yet the initiative met strong political opposition and was quickly abandoned.

In 1842, after the defeat in the First Opium War, China was forced to further integrate into the global market by opening up treaty ports, in addition to Canton, to trade with western countries. Foreign steamships started to appear in large numbers on the Chinese coast.[10] They were faster and less reliant on wind and currents than sailing ships. Despite these new changes, trade routes remained persistent. Foochow was one of four ports signed to open, but its celebrated black tea continued to take a lengthy detour overland to Canton for export, which took ten times as long as a direct export from Foochow. It was not until the outbreak of the Taiping rebellion, when the regular land route to Canton became blocked, that the first batch of tea shipped directly from Foochow.

The inertia in the use of established land and river routes could be due to a large sunk cost usually associated with establishing new trade routes. Especially for sea trade, mariners need to harness the current and tides along the way, be warned of dangerous spots, have supplies when needed and find safe anchorage on arrival. The large investment needed for safe voyage became evident when concerted efforts were made by the China Maritime Custom Service in the late 19th century, drawing on expertise of mechanics, engineers, surveyors and constructors from home and abroad to build a chain of lighthouses and a system of navigation aids to safeguard trips along the Chinese coast and the Yangtze River.[11] The scope of the investment was something that no individual merchant before the 20th century could undertake without generous support from the state. While collectively, merchants could benefit from investment to facilitate sea trade, in the absence of coordinated efforts, the gain from engaging in sea trade for any individual merchant would not be large enough to compensate it for the large investment upfront, which resulted in inefficient modal choice.

3. Data

This paper intends to identify the "roadblock effect," whereby blocked land routes during the Taiping rebellion catalyse adoption of sea trade and relocation of populations to the coast. This

[8]Domestic sea trade was used for some specific commodities (e.g. export of soy bean from the northeast to Shanghai), but it was never the major transport method. It also varied substantially from year to year: there could be 85 ship arrivals in one year and only 2 in the next (Liao, 2010). Being unpredictable and marginal, there was barely any infrastructure developed for sea trade.

[9]It took sea transport ten to twenty days to transport tribute grain compared to two months by canal (Wei, 1826).

[10]Steamships first appeared in China sea as early as in late 1820s and early 1830s.

[11]These efforts include surveys by British Royal Navy since 1842, a series of updates on *Notice to Mariners* and construction of lighthouses, beacons and buoys (Bickers, 2013).

requires data on trade, historical transport costs, population and measures of roadblocks due to the rebellion. I describe each one of them in more detail in the following.

I collected a new data set of bilateral domestic maritime trade between treaty ports by digitising archival reports of *Returns of Trade at Treaty Ports* published by China Maritime Customs Service (Henceforth CMCS). CMCS was a bureaucratic agency established in 1853 by foreign consuls in Shanghai to collect tariffs that went unpaid when the Qing government became overwhelmed by the Taiping rebellion.[12] CMCS supervised tariff collection of foreign exports and imports, as well as domestic maritime trade that went through treaty ports. Its statistics department published trade reports following strict statistics standards that are consistent across ports and over time. The trade data from CMCS is believed to be "the only reliable and systematic material" to use in studying China's historical trade (Cheng, 1956). Keller, Li and Shiue (2012) made a thorough introduction of the trade data from CMCS.

The earliest data on bilateral domestic trade flow is available for 1867, when more accurate and consistent accounting practice was established, which is 3 years after the Taiping rebellion ended. In addition, I digitised bilateral domestic trade for 1873, 1882, 1887, 1892 and 1897 to look at the long-term effects of the rebellion.[13] A useful feature of the CMCS data is that it differentiates between exporting and re-exporting. I use direct export to measure trade between treaty ports. The limitation of the CMCS data is that it only includes domestic maritime trade between treaty ports, which were ports opened to trade with western countries, and only the part of maritime trade carried by steamship. Maritime trade by traditional sailing ships in China (i.e. junks) went missing for most years and ports.

To deal with this data limitation, I built a trade model featuring modal and route choice, which helps to infer the missing trade by other transportation methods. Estimation of the model requires some intermediate inputs, which are the trade costs of using different transport methods in 19th-century China.

While in the literature transport costs are usually derived from freight rates or travel speed, this information is not available in historical China. In Part B of Section 5, I develop a novel method to estimate transport costs in history based on the index to the postal working map in 1903, which lists each prefecture in China under a postal district. Postal districts were regional divisions of the Imperial post office that were established by CMCS in 1896 to provide mail delivery service to the general public. The service expanded from postal district headquarters, usually a treaty port, to inland area through its extensive delivery network (See Figure 3 for postal districts and their

[12] CMCS was a Qing government agency, but its staff was a mix of Chinese, usually in lower rank positions, and foreigners performing managerial roles. Set up to assess taxes of foreign imports and exports, over time its role extended to the collection of domestic tariffs, the maintenance of harbours and lighthouses, weather inspection, the payment of foreign loans and the establishment of the modern postal system in China.

[13] Trade was recorded in Customs Taels, a silver based monetary unit uniform across all ports and for all years except for 1867. In 1867, the southern ports reported their trade value in Mexican dollars and I converted these to the Customs Taels using the conversion rate at the time. In 1901, CMCS took over native customs within 25 kilometres of the treaty port, at which point trade data may begin to include trade by sailing ship that went through native customs. Therefore, I used domestic trade data up to 1897.

headquarters.[14]).[15]

The Imperial postal office developed a system of transliterating Chinese places names, referred to as postal romanisation. In this paper, I use postal romanised place names as they appear in trade reports to indicate reference to historical places. The mapping from the postal place names to their current locations can be found in Table A.1.

The transport cost by land is modelled to vary with road types (i.e. courier routes and navigable rivers) and terrain. I obtained the locations of the Qing courier route (1800-1900) from China W dataset, locations of rivers from the CHGIS V4 dataset of coded river in 1820 and terrain ruggedness from Nunn and Puga (2012).[16]

Transport by sea could be by either steamship or junk sailing ship. The relative unit transport costs of the two is taken from Pascali (2017), which covers the same period. To get the transition cost from land to steamship, I digitised CMCS *Returns of Trade at Treaty Ports* in 1904, which has information about the usage of steamships and sailing ships at two treaty ports, Newchwang and Kiaochow, in their interregional trade with locations over various distances.

To look at whether roadblocks induced population changes when trade routes shifted to sea, I used the 2018 update of historical prefecture population data from Cao (2000).[17] The data was constructed based on government-administered census, and cross-checked with literary accounts, notes and more than 3000 local gazettes. Prefectures are the second level administrative divisions in China. They are subdivisions of provinces, followed by counties and towns. Historical prefecture population is available for the pre-rebellion period in 1680, 1776, 1820, 1851 and post-rebellion period in 1880, 1910 and 1953. I supplemented with population data from the 1982 county census and from the 2010 township census and mapped modern population data to the historical prefecture boundaries in 1820 taken from the China Historical Geographic Information System (CHGIS V4) constructed by the Harvard Yenching Institute and Fudan Center for Historical Geography.

I obtained the information on prefectures occupied by the rebellion on a monthly basis from Guo (1989) and Hua (1991). To measure roadblocks, I constructed a measure of yearly occupation by the rebellion from 1853 to 1864 by aggregating occupied prefectures within one year.[18]

[14]The headquarters of each postal district was usually a treaty port with the custom commissioner as the postmaster, with the exception of the Peking and Chinan districts.

[15]There were no major changes in land transportation technology in 19th-century China. Railway was a nascent technology and its wider application in China was not implemented until the 20th century. In 1903, only regional railways operated in the northern part of China surrounding the capital. They were rail lines connecting Chengting to Peking and Peking to Tientsin and Chinchow. Therefore, the planning of postal districts that could be affected by the railway network are dropped from the estimation (i.e. Peking, Tientsin and Newchwang districts). The Yellow River changed its course in 1855 and could potentially affect the part of the courier routes where the new river intersected. The postal district in charge of this region was Chinan and is also excluded from the estimation.

[16]The Qing courier route was a transportation network of roads, canals and smaller rivers. The rivers are coded with values between 1 to 6. I used rivers of order greater than 4, which corresponds to navigable rivers.

[17]The previous version of the data was used by Jia (2014) to study the long-run effect of treaty ports on population and economic development in China.

[18]Although the earliest uprising took place in Kweiping, Kuangsi in 1851, the rebels advanced to the middle and lower Yangtze region and occupied the first prefecture, Chinkiang, in January, 1853. The last occupied prefectures fell to the Qing government in August, 1864.

4. The evolution of population

I begin my analysis in this section by examining the long-term evolution of the population of Chinese prefectures (cities and their immediate surroundings). This shows that prefectures directly occupied by the rebellion suffered a huge shock from which they never recovered. In addition, the population shifted towards coastal areas, in particular those in which trade took off. Then, in the next section, I will show that the rapid but heterogeneous adoption of sea trade using steamships was also an effect of the rebellion, through the "roadblock effect" that is the focus of this paper.

As a motivation, I estimate the following reduced-form relationship between population, timing relative to the rebellion, occupation during the rebellion, coastal location and sea trade:

$$\log \text{pop}_{it} = \phi + \psi_i + \sum_{p=prov} I_i^p \lambda_p t + \alpha \text{post}_t + \beta(\text{post}_t \times X_i) + \sum_{j=1910}^{2010} I_t^j \kappa_j + \sum_{j=1910}^{2010} I_t^j \gamma_j \times X_i + \epsilon_{it} \ , \quad (1)$$

where pop_{it} denotes the population of prefecture i in year t, ϕ is a constant, ψ_i is a prefecture fixed effect, I_i^p is an indicator for province p (taking value 1 if prefecture i belongs to province p and 0 otherwise), $\lambda_p t$ is a province specific time trend, post_t is an indicator variable denoting whether year t is after the 1851–1864 Taiping rebellion, I_t^j is an indicator for post-rebellion year j (taking value 1 if $j = t$ and 0 otherwise), X_i is a vector of prefecture characteristics, including whether the prefecture was occupied during the rebellion, whether it is located on the coast, and a number of controls, and ϵ_{it} is an error term. Each observation is one of the 179 prefectures from 13 provinces in the core region of 19th-century China in each data year.[19]

The results are presented in Table 1. Standard errors are clustered at the province level to adjust for heteroskedasticity and within-province correlation over time. Column (1) looks at the different evolution of populations in those prefectures that were occupied by the rebellion and those that were not, parametrising the changes that were already evident in Figure 1. The prefecture fixed effects make the population evolution measured relative to the initial level in each prefecture. Provincial time trends can capture differential trends in population evolution across occupied and non-occupied provinces. The post-rebellion indicator captures the 26% average drop in population in non-occupied prefectures during the rebellion. The post-rebellion $\times$ occupied interaction then captures the additional drop in occupied prefectures, an extra 60% on average. The two combined gives the overall population drop in occupied prefectures, which is about 86%.

To look at population evolution in later periods, I include year fixed effects for post-rebellion years, except for immediately after the rebellion in 1880, whose effect is captured by the post dummy. Year fixed effects give us the change in population levels for later periods with respect to the pre-rebellion trends after incorporating the drop immediately after the rebellion. The results show that the levels of population in 1910 and 1953 did not change, while there was an increase in the levels of population in 1982 and 2010. More importantly, we are interested to know whether population evolution in occupied and non-occupied prefectures was different in later years, which

[19]The Taiping rebellion spurred uprisings in Yunan, Shensi, Kansu, Szechuen and Kueichow at the same time. These were periphery regions inhabited also by non-Han minority groups, so they are dropped from the analysis. Nomadic regions of the Qing Dynasty such as the Northeast provinces (Kirin, Heilungchiang and Shengching), Outer Mongolia, Inner Mongolia, Xinjiang, and Tibet are also excluded. The panel is balanced except for Taiping prefecture, whose population in 1982 is missing. Despite sharing the same name, this prefecture is not related to the rebellion.

is given by the post-rebellion year dummy $\times$ occupied interactions. The result shows slow catch-up of the level of population in occupied prefectures even after a century and a half (17% additional increase in the level of population in occupied prefectures in 2010 rendering 43% relative loss in 2010). This is in sharp contrast to Davis and Weinstein (2002), which shows swift recovery of Japanese cities to their relative sizes after the Allied bombings.

In addition to the direct impact of the rebellion on war-torn areas, I hypothesise that it could affect relative attractiveness of locations through diverting trade routes to sea. Locations that stood to benefit from sea trade would be coastal prefectures, and I investigate this possibility in column (2). The post-rebellion $\times$ coastal interaction shows that the population of coastal prefectures increased by 29% after the rebellion, after controlling for the direct effect of the rebellion on the occupied region. I further include post-rebellion year dummy $\times$ coastal interactions. They show that the relative population of coastal prefectures decreased in 1910, 1953 and 1982, in contrast to the sizeable increase immediately following the rebellion.

Population growth in coastal regions immediately after the rebellion could be driven by other characteristics of coastal areas. While prefecture fixed effects account for the population differences across prefectures in levels, those characteristics may have a differential impact on population growth after a large shock to population sizes. For instance, coastal areas may have better agricultural productivity, which may have attracted migration after the rebellion. Therefore, in column (3), I include a variety of locational traits interacted with the post dummy. These are the initial level of human capital and a set of geographic controls including terrain ruggedness, agricultural suitability for major crops in historical China (i.e. rice, foxtail millet and sweet potato) and whether the Grand Canal went through the prefecture. The positive coefficient estimate of the interaction on post-rebellion and coastal dummies is robust to inclusion of differential impacts of these locational characteristics on populations after the rebellion, showing a 32% increase in the level of population in coastal prefectures after the rebellion.

To provide suggestive evidence that populations relocated because trade activities were diverted to the coast as the rebellion blocked regular inland trade routes, in column (4), in addition to the post-rebellion $\times$ coastal interaction, I further interact them with the natural logarithm of the value of domestic trade by steamship relative to its average in 1867 to see whether port cities with more sea trade had a greater increase in population after the rebellion. Since trade data is only available in treaty ports, which were large ports that had trade with western countries, the number of observations drops. For this subset of large ports, the post-rebellion $\times$ coastal interaction indicates that their post-rebellion population increase was about 44% on average. The post-rebellion$\times$coastal$\times$trade value triple interaction indicates that an increase in sea trade by 1% was associated with a 0.2% increase in coastal population after the rebellion.[20]

[20] While both the volume of trade and population growth could be greater in larger cities, using the value of trade per capita gives very similar results.

Table 1: Prefecture population evolution 1680–2010

	Dep. var.: Log (population)				
	(1)	(2)	(3)	(4)	(5)
Post-rebellion	-0.263**	-0.323***	-0.104	-0.319**	-0.0443
	(0.0938)	(0.103)	(0.219)	(0.105)	(0.255)
Post-rebellion ×	-0.594***	-0.575***	-0.546***	-0.576***	-0.559***
	(0.0932)	(0.0915)	(0.105)	(0.108)	(0.129)
Post-reb. × coastal		0.286***	0.315***	0.441***	0.593***
		(0.0844)	(0.0938)	(0.0658)	(0.118)
Post-reb. × coastal × trade val.				0.201***	0.162**
				(0.0372)	(0.0595)
Post-reb. × initial human capital			-0.0442		-0.0640*
			(0.0256)		(0.0327)
1910	0.0244	0.0379	0.0203	0.0354	0.0178
	(0.0325)	(0.0372)	(0.0234)	(0.0383)	(0.0240)
1953	0.0329	0.0458	0.0281	0.0417	0.0247
	(0.0625)	(0.0721)	(0.0620)	(0.0748)	(0.0644)
1982	0.462***	0.481***	0.445***	0.483***	0.448***
	(0.0712)	(0.0795)	(0.0740)	(0.0825)	(0.0766)
2010	0.566***	0.551***	0.523***	0.559***	0.532***
	(0.0798)	(0.0936)	(0.0814)	(0.0959)	(0.0835)
1910 × occupied	0.0556	0.0548	0.0677	0.0714	0.0845*
	(0.0519)	(0.0483)	(0.0422)	(0.0537)	(0.0474)
1953 × occupied	0.119	0.121	0.131	0.152	0.160
	(0.0783)	(0.0767)	(0.0737)	(0.0923)	(0.0928)
1982 × occupied	0.120	0.122	0.146*	0.127	0.148*
	(0.0867)	(0.0783)	(0.0737)	(0.0877)	(0.0821)
2010 × occupied	0.167	0.179	0.194*	0.167	0.176*
	(0.0962)	(0.102)	(0.0976)	(0.101)	(0.0963)
1910 × coastal		-0.0682	-0.0523	-0.0726	-0.0579
		(0.0399)	(0.0331)	(0.0509)	(0.0475)
1953 × coastal		-0.0680	-0.0507	0.0295	0.0454
		(0.0708)	(0.0707)	(0.115)	(0.120)
1982 × coastal		-0.0948	-0.0606	-0.0751	-0.0444
		(0.0750)	(0.0747)	(0.0789)	(0.0786)
2010 × coastal		0.0646	0.0927	0.328**	0.354**
		(0.120)	(0.111)	(0.139)	(0.132)
Constant	-1.129**	-1.129**	-1.043**	-1.198**	-1.099**
	(0.469)	(0.459)	(0.452)	(0.483)	(0.480)
Post-reb. × geographic controls			Yes		Yes
Prefecture fixed effects	Yes	Yes	Yes	Yes	Yes
Provincial time trend	Yes	Yes	Yes	Yes	Yes
Observations	1,610	1,610	1,565	1,368	1,323
R-squared	0.832	0.839	0.867	0.832	0.866
Number of prefectures	179	179	174	152	147
Number of coastal prefectures	35	35	35	8	8

Notes: In columns (4) and (5), trade val. is the natural logarithm of domestic trade value by steamship relative to the average in 1867, which is only available for 8 out of 35 treaty port prefectures (and is 0 for all 144 non-coastal prefectures). In columns (3) and (5), initial human capital is proxied by the natural logarithm number of graduates from the Imperial Exam in the 1840s, which is not available for 5 prefectures. The geographic controls are an indicator for whether the Grand Canal passes through, terrain ruggedness, and categorical variables for agricultural suitability for major crops in historical China. Robust standard errors clustered by province are reported in parentheses. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

On the basis of column (4), column (5) further controls for locational characteristics interacted with the post-rebellion dummy. The general picture remains the same, indicating that the positive association between population and trade was not confounded by locational characteristics that could at the same time affect sea trade.

The evidence of an greater increase in coastal population with a surge in steamship trade is based on a small sample of ports and thus needs to be taken with a grain a salt. Luckily, trade data comes in more details (e.g. information about who trades with whom by steamship). Exploiting the regional variation in incentives to use sea trade depending on whether their regular inland routes were affected by the rebellion will allow us to identify the "roadblock effect", which could explain population relocation to coastal regions with more steamship trade after the rebellion. For this closer look at the effect of rebellion on trade routes and transport modes, I combine a trade model, shipping records and a new method to estimate historical transport costs, which is described in the section that follows.

5. The roadblock effect

In this section, I identify the "roadblock effect" by exploiting the heterogeneous incentives for locations to adopt steamship trade depending on whether the rebellion blocked their regular inland trade routes. Given only trade by steamship after the rebellion is observed in the data, the analysis needs some additional theoretical structure. Therefore I build a trade model with modal and route choice in Part A. An essential input of the model is the relative transport cost of using different inland routes and their sea alternatives. As we lack information about the transport cost in 19th-century China, in Part B I develop a novel method to estimate historical transport costs. Part C shows the estimation and prediction of the model.

A *Model set-up*

We consider a country with J cities (prefectures in historical China), indexed by $j = 1,2....J$. A continuum of symmetric firms in each city and each firm produces a distinct product, which can be consumed locally as well as in other locations subject to iceberg trade costs.[21] If we assume that consumers have constant elasticity of substitution utility and firms face monopolistic competition, we can write the firm profit function for exporting merchandise from location j to i at time t:

$$\pi_{ijt} = (1-\alpha)(\frac{\tau_{ijt}^{m} c_{jt}}{\alpha P_{it}})^{1-\epsilon} Y_{it} - c_{jt} f. \tag{2}$$

The elasticity of substitution is denoted as α, which falls between 0 and 1. To keep the notation concise, I introduce $\epsilon = 1/(1-\alpha)$. As standard in trade models, the profit increases with income Y_{it} and Dixit-Stiglitz price index P_{it} in the destination $(1-\epsilon < 1)$ and decreases with the cost of production c_{jt}, which is common to all firms in origin j. There is a fixed cost of entry f , which can be thought of as the number of workers needed to build the firm.

[21]Recent trade models have incorporated heterogeneous firms (e.g. Helpman, Melitz and Rubinstein, 2008; Tintelnot, 2017), but since only aggregate but not firm level trade data is available in 19th-century China, there is no gain from modelling heterogeneous firms here.

Departing from the standard setting, I allow the iceberg trade cost τ^m_{ijt} to vary with transport mode m. There were three prevailing transport modes: by land (including inland navigation), by steamship and by junk (Chinese sailing ships), which I denote l, st, jk respectively. In addition to making the trade cost a function of the transport cost D^m_{ijt} that takes into account optimal route choice within each mode, I incorporate intertemporal investment for establishing new trade routes for sea transport, I^s_t, and land transport, I^l_t. The mode-dependent iceberg trade costs are:

$$(\tau^l_{ijt})^{1-\epsilon} = (D^l_{ijt} I^l_t))^{-\gamma} e^{\eta_{l,ijt}}, \quad (\tau^{st}_{ijt})^{1-\epsilon} = (D^{st}_{ijt} I^s_t)^{-\gamma} e^{\eta_{s,ijt}}, \quad (\tau^{jk}_{ijt})^{1-\epsilon} = (D^{jk}_{ijt} I^s_t)^{-\gamma} e^{\eta_{s,ijt}} e^{\eta_{j,ijt}} \tag{3}$$

for land, steamship and junk respectively. The investment cost is modelled here as a multiplier to the transport cost, so that we can interpret it as the cost ratio of establishing a new route over using an existing route.[22] The benefit and cost of investment in establishing new sea routes are shared by sail and steam ships. Their investment cost I^s depends on whether a sea route has already been established in the previous period. Define C_{ijt} as indicator for whether sea trade happens in the previous period $t-1$. We have:

$$I^s_t = \begin{cases} I^s, & \text{if } C_{ijt-1} = 0; \\ 1, & \text{if } C_{ijt-1} = 1. \end{cases} \tag{4}$$

If sea route was established in the previous period, there is no extra cost of using sea trade in addition to the transport cost. If, instead, sea trade was not used previously, firms need to incur the sunk investment cost for establishing a new sea route in order to use sea transport. The investment cost for new land routes I^l_t is defined analogously.

Trade costs are also subject to shocks. There are three types of shocks in the model. The shocks to land and sea transport $\eta_{l,ijt}$ and $\eta_{s,ijt}$ are modelled to be realised annually, and could be thought of as medium-term shocks to transport costs (e.g. road damage, port maintenance). In addition to common shocks to sea transport for both sail and steam ships, sailing ships are subject to an additional shock $\eta_{j,ijt}$. As sailing ships are vulnerable to changes in current and wind, they are susceptible to weather shocks that are more short-lived (e.g. storms). Therefore, I assume their shocks to be realised for T times within a year.[23] All shocks are assumed to be log normal and independent:

$$\eta_{l,ijt} \sim \mathcal{N}(0,\sigma^2_l), \quad \eta_{s,ijt} \sim \mathcal{N}(0,\sigma^2_s), \quad \eta_{j,ijt} \sim \mathcal{N}(0,\sigma^2_j). \tag{5}$$

The timing of the events is the following: at the beginning of each year, firms observe origin-destination specific shocks to land and sea transport and choose either land or sea transport for that year; afterwards, shocks to sailing ships are realised for multiple times within the year. After each realisation, firms that chose sea transport in the first stage choose between steamships and junks.

From the model set-up, we can write the probability of sea trade in any given year. As sea transport was generally not available before the rebellion and sunk investment cost had not been

[22] The implicit assumption here is that sunk investment is proportional to the transport cost. This is a reasonable assumption given establishing a new sea route involves acquainting with tides, current, dangerous spots and installing staging posts along the way. These costs all increase with distance.

[23] The discrete number of shocks is modelled because of observed zero trade by sailing ship in the data.

incurred, we can ignore the pre-rebellion period, as it does not affect decisions on adopting sea trade after the rebellion. The period during the rebellion matters. When land transport was curtailed by the rebellion, it forced some locations to look for alternative ways to transport goods, which can have a long-term impact on modal choices through investment in establishing sea trade. This can be seen from the probability of using sea trade after the rebellion:

$$\Pr(C_{ij,post} = 1) = \Phi(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,post}}{D^s_{ij,post}} - \mathbb{1}(C_{ij,reb} = 0) i^s), \tag{6}$$

which depends first on the post-rebellion transport cost by land relative to sea ($D^l_{ij,post}/D^s_{ij,post}$). The bilateral sea transport cost $D^s_{ij,post}$ is approximated to be the minimum of the transport costs of steam and sail ships ($\min\{D^{st}_{ij,post}, D^{jk}_{ij,post}\}$).[24] The elasticity of trade with respect to the transport cost γ, normalised by the variation of transport shocks $\sigma = \sqrt{\sigma_l^2 + \sigma_s^2}$, governs how responsive usage of sea trade is to the relative cost of land transport. Second, it depends on the sunk investment cost for sea transport, which may or may not have been incurred during the rebellion. To keep the notation concise, I introduce $i^s = (\gamma/\sigma) \ln I^s$, which measures the effect of sunk investment cost on the probability of trade. If sea trade was used during the rebellion, and therefore sea routes were established ($\mathbb{1}(C_{ij,reb} = 0) = 0$), firms do not need to incur the sunk investment cost in the post-rebellion period, thus increasing the probability of using sea trade afterwards.[25] The probability of using sea trade during the rebellion period is:

$$\Pr(C_{ij,reb} = 1) = \Phi(\frac{\gamma}{\sigma} \ln \frac{D^l_{ij,reb}}{D^s_{ij,reb}} + \mathbb{1}(D^l_{ij,reb} \neq D^l_{ij,pre}) i^l - i^s). \tag{7}$$

As trade routes by sea had not been established, using sea transport required investment i^s during the rebellion. The rebellion could incentivise adoption of sea trade through two channels. First, for locality pairs whose regular inland route was blocked as the rebels occupied prefectures that it previously traversed, finding alternative inland routes entailed an investment cost i^l. Second, as the new route was not the previous unconstrained optimal one, the relative cost of land transport to sea ($D^l_{ij,reb}/D^s_{ij,reb}$) increased. Both raised the relative desirability of using sea transport during the rebellion, which could incentivise roadblocked localities to incur the sunk cost for establishing sea trade. As the decision for using sea trade is linked intertemporally through investment, the temporary increase in the land transport cost could have a long-lasting effect on transport modal choices (see an example of "roadblock effect" in Figure 2). I provide reduced-form evidence of the persistent effect of rebellion on steamship trade from 1867 to 1897 in AppendixE.

With the probability of sea trade, we can estimate the parameters of the model with observed modal choices. However, the data come with some limitations. We only observe trade by one transport method (steamship) and we only observe it immediately after the rebellion. Therefore, I

[24] AppendixC derives the exact expression for the expected cost of sea transport and shows that the minimum approximates well the expected sea transport cost.

[25] Here I assume that after the rebellion, the land route reverted to the one used before the rebellion. I also consider the possibility that the rebellion damaged roads, therefore we need to incur investment cost for a new land route for location pairs whose old route passed through the rebellion-controlled area. The results are very similar.

write the probability of using steamships after the rebellion first conditional on the post-rebellion probability of having sea trade:

$$\begin{aligned}\Pr(S_{ij,post}=1) &= \Pr(C_{ij,post}=1)\Pr(S_{ij,post}=1|C_{ij,post}=1)\\ &= \Pr(C_{ij,post}=1)\Big(1-\big(1-\Phi(\frac{\gamma}{\sigma_j}\ln\frac{D^{jk}_{ij,post}}{D^{st}_{ij,post}})^{T}\Big),\end{aligned} \tag{8}$$

which depends on the relative cost of sail to steam ship and the number of times (T) shocks to sailing ships are realised. To proceed, I write the probability of sea trade after the rebellion conditional on the probability of sea trade during the rebellion:

$$\Pr(C_{ij,post}=1) = \Pr(C_{ij,reb}=1)\Phi(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}) + \big(1-\Pr(C_{ij,reb}=1)\big)\Phi(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}-i^{s}). \tag{9}$$

We can then write the post-rebellion probability of steamship trade, which is observed in data, by combining Equations 7, 8 and 9:

$$\begin{aligned}\Pr(S_{ij,post}=1) =& \Big(1-\big(1-\Phi(\frac{\gamma}{\sigma_j}\ln\frac{D^{jk}_{ij,post}}{D^{st}_{ij,post}})^{T}\Big)\times\\ &\Big(\Phi(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,reb}}{D^{s}_{ij,reb}}+\mathbb{1}(D^{l}_{ij,reb}\neq D^{l}_{ij,pre})i^{l}-i^{s})\Phi(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}})\\ &+\Big(1-\Phi(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,reb}}{D^{s}_{ij,reb}}+\mathbb{1}(D^{l}_{ij,reb}\neq D^{l}_{ij,pre})i^{l}-i^{s})\Big)\Phi(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ij,post}}{D^{s}_{ij,post}}-i^{s})\Big).\end{aligned} \tag{10}$$

The post-rebellion probability of steamship trade is a function of (1) whether the locality pairs had roadblocks, the relative cost of land transport compared to sea during and after the rebellion, the relative cost of steam compared to sail ship after the rebellion and (2) the parameters of the model (γ/σ, I^s and I^l).[26] We can see that the post-rebellion probability of using steamships depends crucially on the relative transport costs of different modes and their change during the rebellion due to roadblocks. The rebellion increased the relative cost of inland transport and the increase hinged on whether the optimal route was blocked by rebellion occupation and the respective increase in land transport cost due to detours, which is in turn determined by the availability of using road, river, or different terrain and their relative costs. If we know the relative transport costs, the parameters of the model can be estimated by maximising the likelihood of observing steamship trade in the data. However, since it is 19th-century China, little is known about the transport costs at the time. In order to obtain this intermediate input to estimate the model, I develop a novel method to estimate historical transport costs, which is detailed in the next part.

B *Estimation of historical transport cost*

The relative cost of using different inland trade routes and their sea alternatives is a key determinant of the differential impact of rebellion on steamship take-up in different locations. While the previous

[26] The probability also depends on the number of times shocks to sailing ships are realised within one year, which is estimated in AppendixD.

literature on transport costs usually infers them from freight rates, lack of data on freight rates in 19th-century China imposes a challenge.

To deal with this problem, I develop a novel method of estimating historical transport costs based on China's postal map in 1903 and data on sea trade in 1904. I allow typical speed of different transport modes (e.g. by land, by sea), variations in speed due to road types, vehicle and terrain, as well as fixed costs associated with transitions between modes (which can be unavailable even in modern times). I divide the estimation into two parts: estimation of land transport (including inland navigation) cost based on the postal map followed by estimation of sea transport cost using information about the usage of steamships and sailing ships.

a Land transport cost

The index to the postal working map in 1903 lists each prefecture in China under a postal district. The postal districts are regional divisions of the Imperial post office, which expanded the mail delivery service from the postal headquarters, usually a treaty port, to inland prefectures (See Figure 3). Under the assumption that the allocation of prefectures to postal districts is made to minimise transport costs to their postal headquarters, we can infer the cost of using different inland transport infrastructure available along the route.

I divide the surface of China into 0.1 degree by 0.1 degree cells (553×826 cells in total, a cell at 30 degree latitude covering about 90 km^2 area) and overlay it with courier routes, rivers and terrain (See Figure B.1). Each cell is assigned a (relative) cost to traverse based on whether it falls in a river, courier route or point of transition between modes or road types. Given a set of transport costs for a courier land route cell, a non-courier land route cell, a river cell, a cell involving land to river modal change and courier to non-courier route transition, and penalties for ruggedness, we can use the Fast Marching Method (FMM) to find the least-cost travelled postal headquarters for each prefecture.

I follow a two-step procedure to pin down the set of transport costs that maps prefectures to the actual postal headquarters. First, I maximise the number of matches between actual and FMM allocations of prefectures to postal headquarters. Second, to amongst the largest number of matches, I choose the set of transport costs that minimises the difference between transport cost to the actual post district headquarters and FMM allocated headquarters.

In the end, 167 prefectures out of 199 can be matched to the actual postal districts compared to 111 when using distance alone. The majority of the unmatched prefectures (26 out of 32) are very close to be matched to their actual headquarters as their neighbours are matched to those headquarters.

b Sea transport cost

From the estimation based on the postal map, we derived the inland transport cost. We would also need to know the transport cost by sea compared to land, as the advantage of using sea transport compared to land and its change during the rebellion is a potential driver for post-rebellion adoption of sea trade.

Sea transport in 19th-century China could use two technologies: sail and steam ships. Sailing ships were also used in rivers, so we can assign the unit transport cost by river estimated from the postal map to sailing ships. The same applies to the cost of transition from land to sailing ship, which is set by the cost of modal change from land to river. For steamships, I use the relative cost of steam compared to sail ships from Pascali (2017), which covers the same historical period, and set the unit transport cost by steam half the cost by sail. Steamships have lower cost per distance travelled than sailing ships, but because of their greater size, a larger fixed cost would be needed for transshipment, so their advantage lies in long-distance trade. To estimate the fixed cost associated with transition from land to steamship, I use a trade report on two treaty ports (Newchwang and Kiaochow) of 1904, which details the use of steam and sail ships for their trade to/from other ports with varying distances.

The probability of using steamship is an increasing function of the cost of sail relative to steam ship, which depends on their transport costs by distance and the cost of transition from land to sailing ship, which we already know, and the transition cost from land to steamship, which needs to be estimated. The probability of having steamship trade varies in a positive direction with distance between two ports, as steamships have lower cost per distance travelled, but potentially a larger fixed cost associated with modal transition. Therefore, we can estimate the transition cost from land to steamship by maximising the probability of observing the use of steam and sail ships for sea trade with varying distances. The detailed estimation can be found in AppendixD.

The estimation results of transport costs are shown in *Panel A* of Table 2. I normalise the cost of travelling by land without any road infrastructure or ruggedness to 1 so that the unit transport costs by other modes is relative to that by plain land. The cost of using courier routes was about a quarter of the cost of non-courier land routes. The cost by sailing ship was about 13% of the cost by non-courier land transport and the cost by steamship about 7%. An increase in terrain ruggedness by one standard deviation was associated with a 20% increase in transport cost. Regarding transition, I convert the cost into equivalence to distance travelled by land. The transition cost from non-courier to courier land route amounted to the cost of travelling by flat land for 1.1 kilometres. The transition between different modes was much more costly. Going from land to sailing ship, there was a fixed cost equivalent to travelling 11 kilometres by land. The transition cost from land route to steamship was about three times the cost to sailing ship, which is reasonable given that steamships came larger in sizes and therefore required a longer transshipment time.

Using the estimated historical transport costs, in AppendixF I estimate the elasticities of trade and migration with respect to distance in historical China. Reassuringly, these elasticities are similar to those estimated with modern data and for other parts of the world.

C *Model estimation and prediction*

With transport costs in 19th-century China in hand, we are ready to estimate the model and use it to predict the probability of steamship trade with and without roadblocks.

Table 2: Estimation of roadblock effect: trade cost, sunk cost and model prediction

Panel A: Estimation results on transport costs

Unit cost relative to flat land		Transition cost in distance by flat land	
Flat land (without courier route)	1.00		
Courier route	0.24	Non-courier to courier land route	1.1 km
Sailing ship	0.13	Land route to sailing ship	11.0 km
Steamship	0.07	Land route to steamship	29.3 km
One std. increase in ruggedness	1.20		

Panel B: Estimation results on trade model parameters

	Parameter	Value
Elasticity of probability of sea trade w.r.t. land/sea cost ratio	γ/σ	0.979
		(0.330)
Sunk cost of new sea route	I^s	7.297
(cost ratio of new/established sea route)		(2.293)
Sunk investment for new land routes	I^l	2.773
(cost ratio of new/established land route)		(2.224)
Observations		82

Panel C: Mean probability of steamship trade after the rebellion

	Observations	Data	Model prediction	
			With roadblock	W/o roadblock
	(1)	(2)	(3)	(4)
Roadblocked pairs	52	0.712	0.720	0.435
			(0.021)	(0.021)
Unaffected pairs	30	0.367	0.420	0.420
			(0.034)	(0.034)

Notes: In *Panel A*, transition costs are measured in equivalence to distance travelled by flat land. In *Panel C*, the model prediction with roadblocks in column (3) provides the mean estimated probability for city prefecture pairs for which the least costly land route was roadblocked by the rebellion, taking into account whether the required detour was costly enough to incur the sunk cost of starting to trade through steamships between those locations, and whether the cost saving once that sunk cost was incurred was large enough to keep trading by steamship after the rebellion. Column (2) provides the actual mean probability observed in the data. Column (4) estimates the same mean probability under a counterfactual where the route had not been roadblocked by the rebellion. Standard errors in parentheses in *Panel B*. Bootstrap standard errors using 100 replicates in parentheses in *Panel C*.

Here I measure roadblocks and their resulting increase in land transport cost by assuming that the prefectures under rebellion occupation were impossible to pass. I calculate the least cost routes for each locality pair in non-occupied regions for each year during the rebellion, and use the year in which the land transport for the pair was affected the most to measure the roadblock of the location pair. Together with the relative transport cost of land compared to sea during and after the rebellion and the relative transport cost of sail compared to steam ship after the rebellion, we can estimate the parameters of the model by maximising the likelihood of observing steamship trade in the data.

The results are presented in *Panel B* of Table 2.[27] The elasticity of using sea transport with respect to the land to sea transport cost ratio is positive as expected, indicating that the probability of sea trade increased when the cost of using alternative mode of land transport in comparison is high. There was a substantial cost associated with initialising sea trade. The cost of using a new sea route was more than 7 times the cost of an existing one. Compared to sea transport, the investment cost for land transport was modest. The cost ratio of using a new land route over an existing route was less than 3.

We can use the parameter estimates in *Panel B* to predict the mean probability of steamship use after the rebellion, which is shown in *Panel C*. The observations are divided into two groups: locality pairs that experienced roadblocks during the rebellion and ones whose usual land routes remained intact. In the data, shown in column (2), the mean probability of steamship trade immediately after the rebellion in 1867 was 0.712 for roadblocked pairs and 0.367 for unaffected pairs. Column (3) shows for comparison the model-predicted mean probability of steamship use. The prediction on the mean probability of steamship use for roadblocked pairs is 0.72, very close to what we observe in the data. The prediction on the unaffected pairs is slightly higher, but overall the model matches well with the observed modal choices. In column (4), I calculate the probability of steamship trade under a counterfactual scenario in which roadblocks during the rebellion are eliminated. As unaffected pairs did not have roadblocks to begin with, their counterfactual probability is exactly the same as in column (3). For the roadblocked pairs, however, their counterfactual probability of steamship use would be only 0.435 without roadblocks, which is very similar to that of the unaffected pairs. The results of the counterfactual estimation suggest that if it were not for the rebellion, the two groups would behave very similarly. With roadblocks, however, the probability of steamship take-up increased by 66%.

6. Conclusion

Concentration of population in a location can remain persistent even when the location is no longer advantageous. Trade costs affect the distribution of economic activities and population across locations by affecting market access. As trade costs change, relative attractiveness of locations also changes. Trade costs can change over time through new transport infrastructures as well as new technologies. New technologies typically require a large sunk investment upfront, which could set them back. Failure to adopt the superior technology, however, could trap populations in sub-optimal locations.

This paper uses the Taiping rebellion in 19th-century China to study population changes after a large but temporary shock to city sizes. In contrast to a large literature on the persistence of relative city sizes after temporary shocks, I find a permanent relative loss in population of about 55% in war-ravaged cities and an increase of 32% in coastal cities after the rebellion. I provide evidence that this is because, in addition to the direct impact of war through death and displacement, the

[27] Estimation excludes trade from/to Shanghai. Because it was surrounded by occupied prefectures, land transport to Shanghai was impossible for more than one year ($D^l_{ij,reb}/D_{ij,reb}$ would be positive infinite). Shanghai was also the only port that had steamship trade with all other ports in 1867. To show that the roadblock effect is not entirely driven by this exceptional example, it is dropped from the estimation.

rebellion affected populations indirectly through trade routes and transport modes. Before the rebellion, as adoption of sea trade was lagging behind its potential, the population continued to decline in coastal regions. The scope of investment for establishing sea routes and building a system of navigation aids for sea trade went beyond the capacity of any individuals. Without coordinated efforts or state interventions, wide participation in sea trade was prohibitive. The rebellion blocked regular inland trade routes, forcing an experiment with steamships, which triggered substantial investment to facilitate maritime trade, moving many trade routes permanently to sea. As trade activities relocated to sea, this catalysed a shift of population towards port cities.

Faced with limited data on 19th-century China (in particular, only having data on trade by steamship after the rebellion), I develop a simple trade model with transport modal and route choices to identify the "roadblock effect." Depending on roadblocks of usual land routes and the feasibility of sea trade alternatives, the rebellion had heterogeneous effects on interregional trade through facilitating investment for sea trade. The estimation of the model requires an additional input: historical transport costs, which I obtained by developing a novel method based on a postal map. The model delivers, via the investment channel, an intertemporal link between temporary increases in land trade costs and permanent shift of transport modes, consistent with observed trade patterns. The "roadblock effect" was quantitatively large, facilitating upgrading transport technology, adjusting trade patterns, and relocating populations trapped in sub-optimal locations.

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AppendixA. Table Appendix

Table A.1: Mapping between postal names and current locations

Postal name (Romanization)	Current location (Pinyin)	Postal name (Romanization)	Current location (Pinyin)
Amoy	Xiamen	Kiukiang	Jiujiang
Canton	Guangzhou	Kiungchow	Haikou
Chefoo	Yantai	Kweiping	Guigang
Chengting	Shijiazhuang	Newchwang	Yingkou
Chinan	Jinan	Ningpo	Ningbo
Chinchow	Jinzhou	Shanghai	Shanghai
Chinkiang	Zhenjiang	Tientsin	Tianjin
Foochow	Fuzhou	Swatow	Shantou
Hankow	Hankou	Wenchow	Wenzhou
Ichang	Ichang	Wuhu	Wuhu
Kiaochow	Qingdao		

AppendixB. Figure Appendix

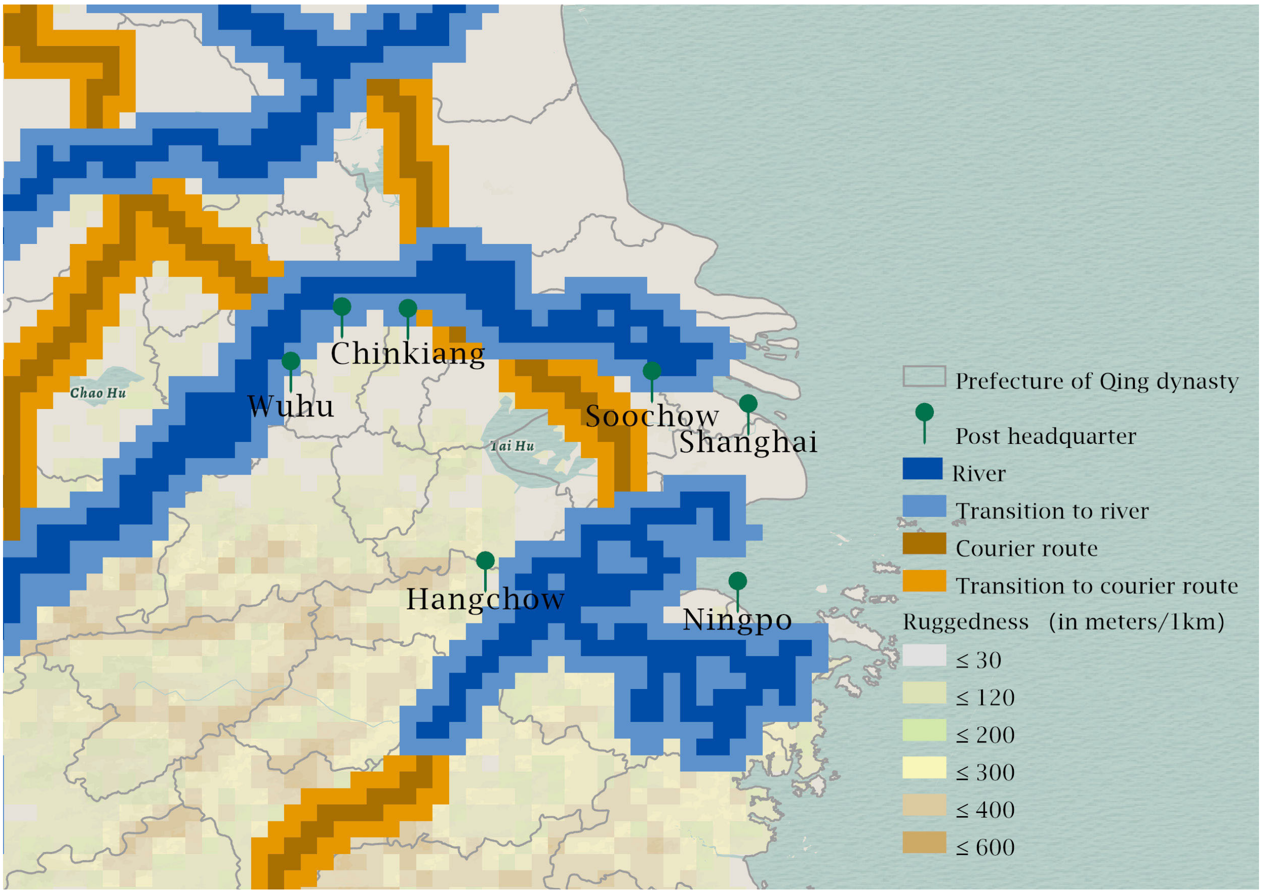


Figure B.1: Transport cost in 19th-century China

Notes: 0.1 degree by 0.1 degree cells covering the land area of China overlaid with rivers, courier routes, terrain ruggedness, transition between land and river, and transition between non-courier land routes to courier routes.

AppendixC. Sea transport cost approximation

This section derives the exact expression for the expected cost of sea transport cost and shows that the minimum of transport cost by steam and sail ship approximates well the expected sea transport cost.

Given Equation 2 and the timing of the realisation of shocks, after realisations of shocks to land and sea transport, firms will choose sea transport if the expected profit by sea is smaller than the profit by land. This is equivalent to:

$$\mathbb{E}\big(\max\{(\tau_{ijt}^{st})^{1-\epsilon},(\tau_{ijt}^{jk})^{1-\epsilon}\}\big) > (\tau_{ijt}^{l})^{1-\epsilon}. \tag{C1}$$

Using Equation 3, we can rewrite Equation C1 as:

$$(I_t^s)^{-\gamma}e^{\eta_{s,ijt}}\mathbb{E}\big(\max\{(D_{ijt}^{st})^{-\gamma},(D_{ijt}^{jk})^{-\gamma}e^{\eta_{j,ijt}}\}\big) > (D_{ijt}^{l}I_t^l)^{-\gamma}e^{\eta_{l,ijt}}.$$

Denote $y=\max\{(D_{ijt}^{st})^{-\gamma},(D_{ijt}^{jk})^{-\gamma}e^{\eta_{j,ijt}}\}$. We have the following:

$$y=\begin{cases}(D_{ijt}^{st})^{-\gamma}, & \text{if } (D_{ijt}^{st})^{-\gamma} > (D_{ijt}^{jk})^{-\gamma}e^{\eta_{j,ijt}};\\ (D_{ijt}^{jk})^{-\gamma}e^{\eta_{j,ijt}}, & \text{if } (D_{ijt}^{st})^{-\gamma} < (D_{ijt}^{jk})^{-\gamma}e^{\eta_{j,ijt}}.\end{cases}$$

Given the log normality assumption of shocks (Equation 5), the probability to choose steamship ship over sailing ship can be calculated as:

$$Pr\big((D_{ijt}^{st})^{-\gamma} > (D_{ijt}^{jk})^{-\gamma}e^{\eta_{j,ijt}}\big)=\Phi\Big(\frac{\gamma}{\sigma_j}\log\frac{D_{ijt}^{jk}}{D_{ijt}^{st}}\Big). \tag{C2}$$

Also we have:

$$\mathbb{E}\Big(e^{\eta_{j,ijt}}\Big|e^{\eta_{j,ijt}} > \frac{(D_{ijt}^{st})^{-\gamma}}{(D_{ijt}^{jk})^{-\gamma}}\Big)=e^{\frac{1}{2}\sigma_j^2}\frac{\Phi(\sigma_j-\frac{\gamma}{\sigma_j}\log\frac{D_{ijt}^{jk}}{D_{ijt}^{st}})}{1-\Phi(\frac{\gamma}{\sigma_j}\log\frac{D_{ijt}^{jk}}{D_{ijt}^{st}})}. \tag{C3}$$

Combining Equation C2 and C3, we can obtain:

$$\mathbb{E}(y)=\Phi\Big(\frac{\gamma}{\sigma_j}\log\frac{D_{ijt}^{jk}}{D_{ijt}^{st}}\Big)(D_{ijt}^{st})^{-\gamma}+e^{\frac{1}{2}\sigma_j^2}\Phi\Big(\sigma_j-\frac{\gamma}{\sigma_j}\log\frac{D_{ijt}^{jk}}{D_{ijt}^{st}}\Big)(D_{ijt}^{jk})^{\gamma}.$$

Both from Equation C1 and the definition of y, when the shock approaches to 0 ($\sigma_j \to 0$), we have:

$$\mathbb{E}(y)\approx\max\{(D_{ijt}^{st})^{-\gamma},D_{ijt}^{jk})^{-\gamma}\}=\big(\min\{D_{ijt}^{st},D_{ijt}^{jk}\}\big)^{-\gamma} \tag{C4}$$

If we define $(D_{ijt}^{s})=\min\{D_{ijt}^{st},D_{ijt}^{jk}\}$, we can obtain Equation 6. Is this good approximation appropriate given the data? In Section AppendixD, I obtain estimate of γ/σ_j, which is about 3.4. If we assume γ (elasticity of trade with respect to trade cost) is 1, taken from the literature, then implied σ_j is about 0.3, which is close to 0. To further show that estimation results of the trade model is robust to using approximation of sea transport cost, we can calculate the exact $\mathbb{E}(y)$ given estimates of γ and σ_j and compare it with the minimum ($\min\{D_{ijt}^{st},D_{ijt}^{jk}\}$). The resulting estimates are very similar.

AppendixD. Estimation of sea transport costs

Following the set-up of the model (Equation 2, 3 and 5), after each realisation of the shock to sailing ship, firms that have chosen maritime trade choose steamships over junk sailing ships if:

$$\gamma \ln D_{ijt}^{jk} - \eta_j > \gamma \ln D_{ijt}^{st}$$

The shocks to sailing ships are realised for T times within a year. The discrete number of shocks is modelled to rationalise the observed zero trade by steamship and junk sailing ship. Within a year, junk trade does not happen if under the best scenario for junks, steamships are still preferred. This is equivalent to the maximum of $\eta_{j,ijt}$ of T realisations is smaller than $\gamma \ln(D_{ijt}^{jk} / \ln D_{ijt}^{st})$. The normalised maximum of shocks to sailing ships $\max(\eta_{j,ijt}/\sigma_j)$ follows the distribution Φ^T, where Φ is the standard normal distribution. Therefore, we can write the probability of observing no junk trade in year t given sea trade is chosen as

$$\Pr(J_{ijt} = 0 | C_{ijt} = 1) = \Phi(\frac{\gamma}{\sigma_j} \ln \frac{D_{ijt}^{jk}}{D_{ijt}^{st}})^T,$$

where J_{ijt} and C_{ijt} are indicators for junk trade and sea trade respectively. The probability of observing junk trade in year t is therefore:

$$\Pr(J_{ijt} = 1 | C_{ijt} = 1) = 1 - \Phi(\frac{\gamma}{\sigma_j} \ln \frac{D_{ijt}^{jk}}{D_{ijt}^{st}})^T.$$

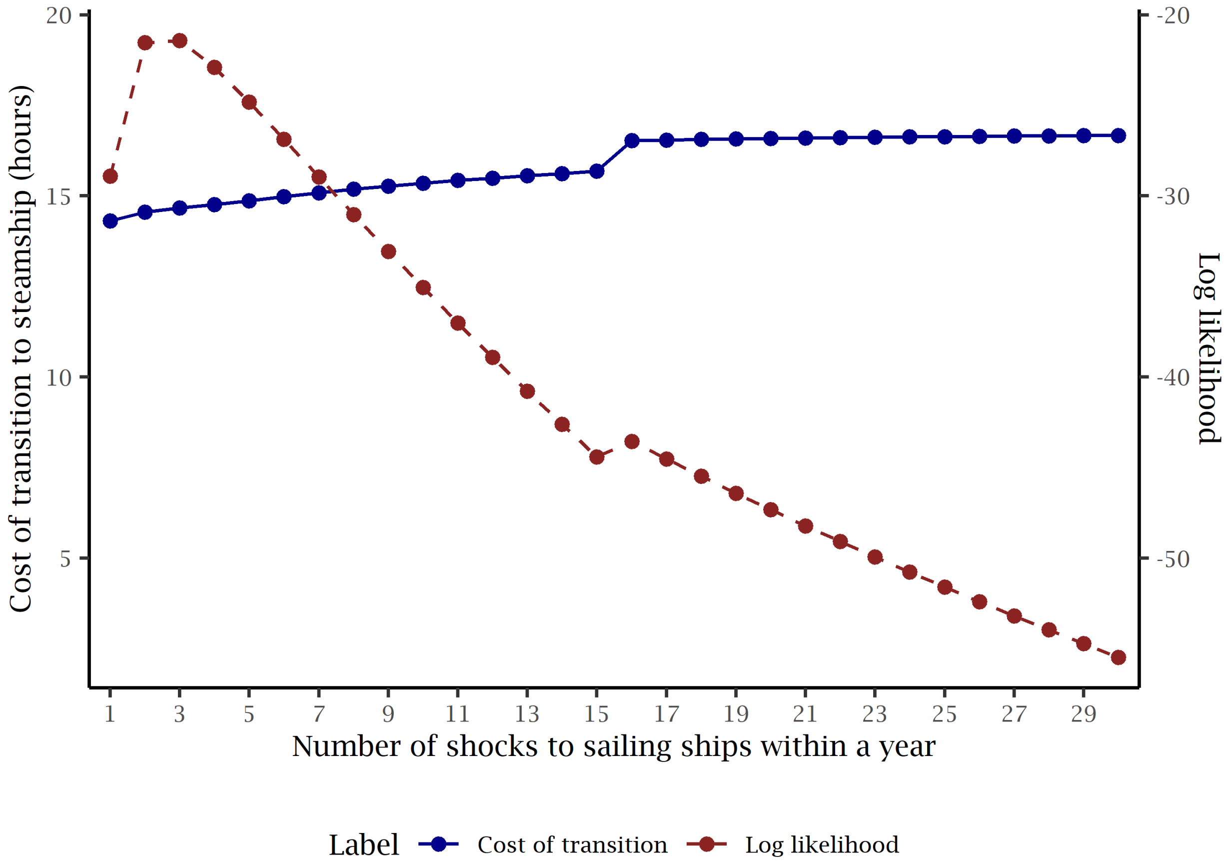
Steamship trade in any given year is observed if at least under the worst scenario for junks, steamship is preferred. This is equivalent to $\min(\eta_{j,ijt}) < \gamma \ln(D_{ijt}^{jk} / \ln D_{ijt}^{st})$ after T realisations of $\eta_{j,ijt}$. We can write the conditional probability that steamship trade happens during year t, indicated by S_{ijt}:

$$\Pr(S_{ijt} = 1 | C_{ijt} = 1) = 1 - \big(1 - \Phi(\frac{\gamma}{\sigma_j} \ln \frac{D_{ijt}^{jk}}{D_{ijt}^{st}})^T.$$

The transport costs for sail and steam ships consist of two parts: the cost by distance and the two-way fixed costs of transition between land and sea vessels. Using the postal map, we get the distance cost and the transition cost for sailing ships. The distance cost of steamships is set to be half the cost of sailing ships according to Pascali (2017). I estimate the fixed cost associated with transition between land and steamship, for different numbers of realisations of shocks to sailing ships within one year, by maximising the probability of observing steam and sail ship use in two ports for their trade with other locations with varying distances.

Figure C.1 plots the estimated cost of transition between land and steamship with the corresponding value of log likelihood for different numbers of realisations of shocks to sailing ships. Shocks being realised every four month ($T = 3$) matches the data the best, where the maximised log likelihood function reaches the highest value. Table C.1 shows the maximum likelihood estimation results on the cost of transition between land and steamship when we assume that the shocks to sailing ships are realised every four months. With the speed of travelling by land without courier

Figure C.1: Log likelihood estimation of transition costs



Notes: The estimated cost of transition (in hours) is based on normalisation of land transport speed to 4 kilometres/hour. The cost of transition shown here includes the cost of switching from land to steamship, and from steamship to land.

Table C.1: Estimation of transport cost by steamship

	Parameter	Value
Elasticity of probability of steamship ship w.r.t. sail/steam cost ratio	γ/σ_j	3.444
		(0.626)
Cost of transition between land and steamship		14.664
		(1.268)
Observations		27

Notes: Shocks to sailing ship assumed to realise every four months. Land transport speed normalised to 4 kilometres/hour. The estimated cost of transition is time spent (in hours) on transition from land to steamship, and from steamship to land combined.

route normalised to 4 kilometres per hour, the time spent on transition between land and steamship is about 14.7 hours, which is about 2.67 times the time spent on transition between land and sailing ship.

AppendixE. Reduced form evidence on roadblock

This section provides reduce-form evidence on the persistent effect of roadblock on steamship trade. I estimate the following:

$$S_{ijt} = \mathbb{1}\big(\beta \ln \frac{D^l_{ijt}}{D^s_{ijt}} + \delta \text{roadblock}_{ij} + \iota_{ijt} \geq 0\big),$$

where S_{ijt} is an indicator for steamship trade between port i and j in year t. Assume ι_{ijt} follows standard normal distribution, we have:

$$\Pr(S_{ijt} = 1) = \Phi\big(\beta \ln \frac{D^l_{ijt}}{D^s_{ijt}} + \delta \text{roadblock}_{ij}\big).$$

This equation looks at whether locality pairs that had roadblocks during the rebellion ($roadblock_{ij} = 1$) have a systematically higher probability of steamship use in the post-rebellion periods controlling for the transport cost of land relative to sea. Table D.1 shows the estimation results from 1867 to 1897. Because steamship trade was only allowed in treaty ports, to compare steamship take-up in 1867, I only use locality pairs that were both active treaty ports in 1867. To keep the sample consistent over time, I also restrict the observations to the active ports in 1867 for later years.

Table D.1: Roadblock effect on steamship trade : baseline sample

	Dep. var.: Probability of steamship trade						
	1867	1873	1877	1882	1887	1892	1897
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log ($Dist_{land}/Dist_{sea}$)	1.032**	0.406	0.831**	0.405	0.168	0.274	0.383
	(0.435)	(0.362)	(0.355)	(0.364)	(0.362)	(0.379)	(0.417)
Roadblock	1.168***	0.889***	0.679**	0.818***	0.644**	0.827**	0.828**
	(0.307)	(0.285)	(0.286)	(0.288)	(0.298)	(0.325)	(0.353)
Constant	-1.700***	-0.696	-1.075**	-0.523	0.125	0.173	0.244
	(0.648)	(0.532)	(0.513)	(0.530)	(0.527)	(0.542)	(0.595)
Observations	98	98	98	98	98	98	98

Notes: Estimation is based on treaty ports that were functioning in 1867 (except trade between river ports), so that the sample is consistent over time. Robust standard errors in parentheses. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

We can see that roadblocked pairs have a much higher probability of steamship use in 1867. At the means, the probability of steamship use is 0.79 for roadblocked pairs, compared to 0.36 for unaffected pairs. Although both groups have a higher tendency to use steamships (captured by the constant term) over time, the difference between roadblocked pairs and unaffected pairs is remarkably persistent even after three decades in 1897, which is the last year we observe trade.

An explicit aim of the rebels was to cut off supplies to the imperial capital. The flows of goods from rebellion occupied area to the imperial capital through regular land routes were curbed, which forced Qing government to find ways to transport tribute grain by sea. I argue that this also affected indirectly and differently modal choices of bilateral trade flows between unoccupied locations. I

Table D.2: Roadblock effect on steamship trade : exclude trade from/to rebellion region to Tienstin

	Dep. var.: Probability of steamship trade						
	1867	1873	1877	1882	1887	1892	1897
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log ($Dist_{land}/Dist_{sea}$)	0.986**	0.448	0.891**	0.428	0.280	0.382	0.481
	(0.446)	(0.372)	(0.359)	(0.372)	(0.365)	(0.380)	(0.418)
Roadblock	1.179***	0.916***	0.656**	0.838***	0.678**	0.864***	0.861**
	(0.319)	(0.296)	(0.295)	(0.299)	(0.306)	(0.332)	(0.361)
Constant	-1.594**	-0.776	-1.183**	-0.566	-0.0966	-0.0361	0.0551
	(0.674)	(0.559)	(0.529)	(0.554)	(0.547)	(0.561)	(0.613)
Observations	92	92	92	92	92	92	92

Notes: Estimation is based on treaty ports that were functioning in 1867 (except trade between river ports), but excludes bilateral trade of ports that were near rebellion-occupied prefectures (Shanghai, Hankow, Chinkiang, Kiukiang) with Tienstin. Robust standard errors in parentheses. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

investigate this possibility by excluding trade between ports that were near occupied prefectures and Tienstin in Table D.2. The results are very similar to Table D.1, suggesting that modal changes were not unique to transport of tribute grain and roadblocks affected much broader exchange of goods across the whole country.

The rebellion affected modal choices through long-term investment to facilitate sea trade due to roadblocks, but the warfare could also increase sea trade in the long run by destroying road infrastructure. To separate the effect of the two, in Table D.3, I calculate the post-rebellion least cost land routes assuming that road infrastructure in rebellion-occupied region was not functional afterwards. The difference between roadblocked pairs and unaffected pairs remains as large after controlling for the possibility that the rebellion damaged some roads permanently.

Previous tables look at steamship trade between treaty ports that were active in 1867. In Table D.4, I instead include trade between treaty ports as long as they were functioning ports in the corresponding year. The sample size increases over time as there were more treaty ports opened. Also we see that the sharp distinction between roadblocked location pairs and unaffected pairs was only present for the initial pairs that were opened as treaty ports before 1867. For ports that were opened after 1873, even if they had roadblocks, since steamship trade was not allowed at the time, the rebellion did not lead to adoption of steamships in the long run. Although they may have turned to sailing ships when regular land routes became blocked, the advantage of sailing ships over land transport was not large enough to shift trade routes permanently to sea. The results in Table D.4 suggest that both the advance in technology (i.e. introduction of steamships) and the impetus to change necessitated by roadblocks are essential for China's final transition to sea trade in the late 19th century.

Table D.3: Roadblock effect on steamship trade : broken routes

	Dep. var.: Probability of steamship trade						
	1867	1873	1877	1882	1887	1892	1897
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Log ($\hat{Dist}_{land} / Dist_{sea}$)	0.987**	0.292	0.778**	0.371	0.157	0.372	0.410
	(0.437)	(0.371)	(0.364)	(0.372)	(0.371)	(0.383)	(0.421)
Roadblock	1.162***	0.889***	0.682**	0.819***	0.645**	0.832**	0.835**
	(0.307)	(0.285)	(0.286)	(0.288)	(0.298)	(0.326)	(0.354)
Constant	-1.681**	-0.562	-1.046*	-0.498	0.131	0.0288	0.187
	(0.674)	(0.557)	(0.542)	(0.554)	(0.553)	(0.560)	(0.614)
Observations	98	98	98	98	98	98	98

Notes: Estimation is based on treaty ports that were functioning in 1867 (except trade between river ports), so that the sample is consistent over time. The relative transport cost by land ($\hat{Dist}_{land} / Dist_{sea}$) takes into account that road infrastructure (i.e. courier routes) within rebellion-occupied region was unusable afterwards. Robust standard errors in parentheses. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

Table D.4: Roadblock effect on steamship trade : all pairs

	Dep. var.: Probability of steamship trade						
	1867	1873	1877	1882	1887	1892	1897
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$Dist_{land} / Dist_{sea}$	1.032**	0.406	0.623**	0.376	0.296	0.634***	0.705***
	(0.435)	(0.362)	(0.254)	(0.257)	(0.255)	(0.246)	(0.207)
Roadblock	1.168***	0.889***	0.360*	0.330*	0.188	0.361*	0.0273
	(0.307)	(0.285)	(0.197)	(0.197)	(0.194)	(0.189)	(0.159)
Constant	-1.700***	-0.696	-1.239***	-0.914**	-0.607*	-0.996***	-1.104***
	(0.648)	(0.532)	(0.363)	(0.367)	(0.363)	(0.344)	(0.282)
Observations	98	98	188	188	188	202	302

Notes: The sample includes all pairs of treaty ports that were active in the corresponding year (except trade between river ports). Robust standard errors in parentheses. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

AppendixF. Estimation of trade and migration gravity

In this section, I estimate the distance elasticities of trade and migration in historical China using transport cost estimated in Part B of Section 5.

A. Trade gravity

Using the set-up of the model developed in Section 5, we can derive the gravity equation of trade:

$$\ln X_{ijt}^{st} = \psi + \zeta_{jt} + \xi_{it} - \gamma ln D_{ijt}^{st} + \eta_{s,ijt} \ , \tag{F1}$$

where $\psi = -(1-\epsilon)\ln \alpha$, $\zeta_{jt} = (1-\epsilon)\ln c_{jt} + \ln N_{jt}$, $\xi_{it} = \ln Y_{it} - (1-\epsilon)\ln P_{it}$. However, different from the standard setting where we observe bilateral trade by all transport methods, here we only observe trade by steamship. Regressing natural logarithm of value of trade by steamship on transport costs is likely to generate a biased estimate of the elasticity of trade with respect to distance γ.

One source of the bias is that the shorter the distance, it is more likely that maritime trade is carried out by sailing ship. I correct this bias using the probability of steamship use conditional on sea transport ($Pr(S_{ijt} = 1|C_{ijt} = 1)$). Moreover, there could be a bias stemming from the correlation between the distance of sea transport and the size of the market that uses steamships for sea trade. This is because steamships were only available at treaty ports, which were large ports allowed for foreign trade. For shorter distance trade, in which sailing ships had an advantage, inland locations could export their goods through the closest ports by sail, which were not necessarily treaty ports. For longer distance trade however, it may worth the trouble transferring the merchandise to a treaty port to be shipped by steamship, whose average cost decreases with distance, even for inland locations that were not close by. Therefore, longer distance trade by steamship disproportionately attracts and therefore includes goods from a larger market.

To correct for this bias, I find for each pair of treaty ports, all the combinations of prefectures that would optimally choose to export and import from the treaty ports by steamship. Assume that nearby prefectures have similar wage levels, and that the income at the destination Y_{it} is proportional to its population L_{it}. Free entry condition pins down the equilibrium number of firms at the origin $N_{jt} = L_{jt}/(\epsilon f)$, which is also proportional to its population. Therefore, I can correct for the correlation between steamship trade distance and market size by summing over the product of the population at the origin and destination: $\sum_{o,d \in \mathbb{S}_{i,j}} L_o \times L_d$, where $\mathbb{S}_{i,j}$ is the set of prefecture pairs o,d that optimally choose to transport goods by steamship from the treaty ports i,j. The adjusted value of trade between treaty ports by steamship corrected for these two sources of bias is therefore:

$$\overline{X}_{ijt} = \frac{X_{ijt}}{Pr(S_{ijt} = 1|C_{ijt} = 1)\sum_{o,d \in \mathbb{S}_{i,j}} L_o \times L_d}.$$

Another source of bias comes from selection on pairs of trade that choose sea transport over land transport. Prefecture pairs that have a smaller land to sea transport cost ratio would use sea transport if they receive large positive shocks for sea transport (higher $\eta_{s,ijt}$). As the land to sea transport cost ratio can be correlated to transport costs by steamship, this generates a correlation between the error term ($\eta_{s,ijt}$) and the transport cost ($\ln D^{st}_{ijt}$) in Equation F1. This bias can be corrected using the Heckman selection framework. From the set-up of the model, we can write the first stage selection of sea transport as a function of the relative cost of land transport to sea and the sunk investment cost of sea trade:

$$C_{ijt} = \mathbb{1}\Big(\frac{\gamma}{\sigma}\ln\frac{D^{l}_{ijt}}{D^{s}_{ijt}} - \mathbb{1}(C_{ij,reb} = 0)i^{s} + v_{ij}\Big), \qquad v_{ijt} \sim N(0,1),$$

where $v_{ijt} = (\eta_{s,ijt} - \eta_{l,ijt})/\sigma$. The expected value of trade by steamship controlling for selection bias is:

$$\mathbb{E}[ln\overline{X}_{ijt}|C_{ijt} = 1] = \psi + \zeta_{jt} + \xi_{it} - \gamma lnD^{st}_{ijt} + \mathbb{E}[\eta_{s,ijt}|C_{ijt} = 1].$$

Denote $\alpha_v = \gamma/\sigma \ln(D^{l}_{ijt}/D^{s}_{ijt}) - \mathbb{1}(C_{ijt0} = 0)i^{s}$, we have:

$$\begin{aligned}\mathbb{E}[\eta_{s,ijt}|C_{ijt} = 1] &= \mathbb{E}[\eta_{s,ijt}|v_{ijt} > -\alpha_v] \\ &= \mathbb{E}[\sigma v_{ijt} + \eta_{l,ijt}|v_{ijt} > -\alpha_v] \\ &= \sigma\mathbb{E}[v_{ijt}|v_{ijt} > -\alpha_v] \\ &= \sigma\lambda(\alpha_v),\end{aligned}$$

where $\lambda(\alpha_v) = \phi(\alpha_v)/\Phi(\alpha_v)$ is the inverse mills ratios. We can use the estimates from *Panel B* of Table 2 to predict $\lambda(\alpha_v)$.

Table E.1: Trade gravity

	Dep. var.: Log (value of trade by steamship)				
	(1)	(2)	(3)	(4)	(5)
Log (*Dist*)	2.035*	0.316	-0.307	-2.027	-2.217**
	(1.134)	(1.214)	(1.141)	(1.215)	(1.084)
Inverse mills ratio					7.248***
					(1.590)
Adjust trade by sail		Yes		Yes	Yes
Adjust market size			Yes	Yes	Yes
Origin FE	Yes	Yes	Yes	Yes	Yes
Dest FE	Yes	Yes	Yes	Yes	Yes
Observations	111	111	111	111	111
R-squared	0.715	0.669	0.722	0.717	0.776

Notes: Estimation based on bilateral trade by steamship between treaty ports in 1877 and 1882. Market size is calculated based on prefecture population in 1880. All specifications include time variant origin and destination fixed effects. Robust standard errors in parenthesis are clustered in origin-destination pair. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

Table E.1 presents the estimation results on elasticity of steamship trade with respect to transport costs using a sample of bilateral trade by steamship in 1877 and 1882 with the market size calculated using prefecture population in 1880. I regress the natural logarithm of value of trade by steamship on logarithm of transport costs by steamship, controlling for time variant origin and destination fixed effects. Column (1) estimates the correlation in the data between steamship trade and distance. The positive coefficient on distance indicates that in the data there is a positive association between the value of steamship trade and distance. In column (2), I correct for the fraction of trade carried out by junk sailing ships. The estimated elasticity becomes less positive. In column (3), after controlling for the factor that longer distance steamship trade includes exchange of goods between a larger market, the trade elasticity becomes negative. Column (4) controls for both trade by sailing ship and market size, and the estimated trade elasticity becomes negative, with magnitude similar to what was found in the literature. When further accounting for the selection bias of sea transport over land transport, in column (5), the coefficient estimate on the trade elasticity does not change much but becomes statistically significant.

B. Migration gravity

In this part, I estimate the following migration gravity equation:

$$\ln L_{ijt} = \chi + \eta_{it} + \psi_{jt} - \kappa \ln D_{ijt} + \nu_{ijt}.$$

The dependent variable is the natural logarithm of the migration flow from location i to j at time t. Historical migration flows are rarely available. Here I construct a new data set of migration flows in historical China based on studies that trace the origin of contemporary villages. Historically, many villages in China were founded by clans from outside areas where living conditions worsened. Thanks to the tradition of keeping a rich family history, Cao (1997) was able to obtain information about migration villages regarding the place of origin of their founders and formation time. We can use the number of villages at location i founded by people from location j at time t to proxy for the migration flow from i to j at t.[28]

I present the estimation results on the gravity equation of migration using the number of migration villages to proxy for migration flows in Table E.2 and Table E.3. In Cao (1997), the destinations are counties. For the majority of villages, we only know the origin province and for some we know the prefectures or counties. In column (1) of Table E.2, I present estimation results using all available origin and destination pairs. Migration flows respond negatively to transport cost, as expected and the elasticity is about -1.5. The study by Cao (1997) focuses primarily on migration villages in Kiangsi province, but also includes nearby prefectures in other provinces. To the extent that migration to prefectures outside Kiangsi may have different patterns, in column (2), I restrict the sample to only migration flows to Kiangxi province. The resulting elasticity is about -1.3. In column (3), I restrict the sample to only county to province pairs, where the location of the province is proxied by the provincial centroid. The elasticity for this restricted sample is slightly larger (in absolute term), about -1.8. For all specifications, I allow the origin and destination fixed effects to vary by time, but the distance elasticity can also vary over time.[29] Therefore, I divide the sample into two periods in column (4) and column (5). The results show that over time migration

[28]The implicit assumption here is that the initial population when the villages were founded is similar across villages. For a subset of villages where their recent population is available, I calculate the implied annual population growth rate to confirm that this is a reasonable assumption.

[29]The migration time frame is between 1643-1722, 1643-1796, 1723-1796 or 1796-1912.

flows respond more to transport costs. In Table E.3, I aggregate the destinations from counties to prefectures, which leaves us with fewer observations, but the estimated distance elasticities are similar. They are also comparable to the estimates obtained using modern data and for other parts of the world.

Table E.2: Migration gravity: county destination

	Dep. var.: Log (number of villages)				
	All (1)	Kiangsi only (2)	Province only (3)	1643-1722 (4)	1723-1796 (5)
Log (*Dist*)	-1.485*** (0.353)	-1.271*** (0.306)	-1.796*** (0.548)	-0.990** (0.445)	-1.552*** (0.396)
Origin FE	Yes	Yes	Yes	Yes	Yes
Dest FE	Yes	Yes	Yes	Yes	Yes
Observations	113	93	62	45	48
R-squared	0.894	0.837	0.942	0.823	0.854

Notes: Column (1) to (3) include time variant origin and destination fixed effects. Robust standard errors in parenthesis. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.

Table E.3: Migration gravity: prefecture destination

	Dep. var.: Log (number of villages)		
	All (1)	Kiangsi only (2)	Province only (3)
Log (*Dist*)	-1.598* (0.781)	-1.292* (0.590)	-2.128** (0.776)
Origin FE	Yes	Yes	Yes
Dest FE	Yes	Yes	Yes
Observations	42	27	32
R-squared	0.935	0.923	0.956

Notes: All specifications include time variant origin and destination fixed effects. Robust standard errors in parenthesis. ***, **, and * indicate significance at the 1, 5, and 10 percent levels.