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Reconstructing the Transport Network of Ancient China and its Relationship to Social Networks

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Abstract

This study reconstructs ancient China's transport system, exploring its intersection with societal networks. We begin by procuring population data indicative of years 2, 742, 1102, and 1522. The transportation matrix, inclusive of roads, rivers, and canals, is subsequently reconstituted. In continuation, we ascertain the transport accessibility for heavy goods. Our accessibility model reveals that history lends itself to a more coherent explanation through quantitative research. We then deploy a gravity model to examine the correlation between transport systems and social networks. The model delineates how transport, particularly travel duration, influenced societal interconnections. The implemented gravity model further highlights the steady deterrent of travel time, suggesting that transport infrastructure might sustainably govern social networks on a historic spectrum. Finally, our research draws on the analysis of five key capitals throughout history, along with other connections inadequately modeled by the gravity approach, to discuss the self-perpetuation effects of social networks. We discern that cities with elevated political stature or a sizable population/economic foundation tend to exhibit a more robust self-reinforcing influence on their social networks.

Keywords: Historical Transportation, Accessibility, Ancient China, Social Networks, Gravity Model.

1. Introduction

1.1. Transportation Accessibility

Changes within the transportation matrix exert substantial and enduring effects on society, with a prominent impact on the economic sphere. Investigations into historical accessibility contribute to more robust quantitative analysis,

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aiding in isolating and encapsulating the causality and correlation between transportation systems and societal structures within a historical framework.

General accessibility metrics, as represented in Equation (1), are commonly employed to quantify the aggregate availability of opportunities at a specific location (Fuhrer, 2019). The derived accessibility value hinges on two primary factors: first, the generalized travel costs, and second, the spatial dispersion of opportunities, which can be denoted by variables such as population, employment, and other factors. In this context, the accessibility at location *i* is construed as the cumulative sum of all opportunities across all locations, adjusted by their respective cost factors. The accessibility value can be divided into two contributions: local contribution calculated as $\text{Opportunities}_i \cdot f(\text{cost}_{ii})$ and contribution from other sites calculated as $\sum_{j\neq i} \text{Opportunities}_j \cdot f(\text{cost}_{ji})$. The influence of transportation costs for traveling to different places is captured by cost function *f*.

$$\text{Accessibility}_i = \sum_{j=1\cdots n} \text{Opportunities}_j \cdot f(\text{cost}_{ji}) \tag{1}$$

The quantification of historical changes induced by transportation includes examining impacts on population dynamics, fluctuations in land or property prices, labor market shifts, alterations in the economic structure, variations in productivity metrics, and issues pertaining to poverty and growth. Among these, the majority of contributions relate to employment and population, with the least focus on the economic system (Fuhrer, 2019). For instance, Tschopp et al. (2003) engaged in a discourse on the interplay between accessibility and demographic transitions, utilizing Switzerland's population data from 1850 to 2000. Similarly, Garcia-López et al. (2015) furnished evidence for the causal effect of highway and railway infrastructure on the suburbanization of the populace in European cities.

1.2. Studies on Historical Accessibility and Social Network

Investigative studies into historical transportation are scarce due to data limitations. Batten's detailed work in "To the Ends of Japan: Premodern Frontiers, Boundaries, and Interactions" (2003) stands as an exception. He re-categorized the historical transportation network, encompassing political and military interactions, networks for bulk and prestige goods, and channels for information and international communication. Varied methodologies warrant deployment for simulating different transport types. Fuhrer (2019) addresses historical accessibility modeling, spanning Switzerland and adjacent regions from 1720 to 2010. Fuhrer elaborates on reconstructing historical transport networks and correlating travel times, illustrating applications of these findings in terms of state outreach and productivity enhancements in Switzerland.

Investigations into ancient social networks are proliferating, spurred by the growth of digital humanities. Yet, recent related research predominantly centers on political and literary explorations within specific facets of these ancient social networks. A dearth of studies exists that link social networks to historical transportation systems. Wang (2022) conducted a statistical analysis, revealing that a politician's support for state-building escalates with the geographic expanse of his kinship network. Hsu (2018) meticulously reconstructed the network of antiquity collectors from the 1090s to the 1120s, providing a micro-level analysis of this pivotal epoch in antiquity collecting. Yan (2018) embarked on an empirical investigation into the entirety of the Song Dynasty's political network, examining the core figures' status, party structure, and the evolution of time sequence diagrams across diverse historical periods, offering comparative analyses and elucidations of various historical issues and perspectives.

The interrelation between transportation and social networks has garnered escalating interest in recent years. Larsen (2005) delved into the prospective effects of evolving spatial patterns within social networks on future travel forms and intensities. De Souza e Silva (2010) introduced the notion of Locative Mobile Social Networks (LMSNs), juxtaposing them with traditional transportation and communication networks, as well as Mobile Social Networks (MSNs). Expanding upon this, Boniface (2015) scrutinized evidence linking transport's influence on social interactions to health outcomes. Chen (2015) introduced an instrument for evaluating and optimizing public transportation systems via social network analysis in megacities. Wang (2022) probed into the role high-speed rail services play in fostering cross-city technological innovation collaborations. Notwithstanding these developments, research explicitly centered on the historical interplay between transportation and social networks remains limited.

1.3. Chinese Dynasties and Studies Concerning Their Transportation Network

This paper explores historical transportation in China during the four primary united dynasties: the Han (202BC-9AD, 25-220AD), Tang (618-907AD), Song (960-1279AD), and Ming (1368-1644) dynasties. China was first united under a single emperor in 221 BC, culminating in the creation of the inaugural national primary road system. Although this dynasty endured for merely 14 years, the subsequent Han dynasty benefitted from the evolving national road system over its extensive four-century reign, considered a golden age in Chinese history. The Tang dynasty represented another seminal epoch for the development of historical transportation. The Grand Canal, initially constructed by the preceding short-lived dynasty, was revamped, and re-routed during the Tang dynasty for taxation and capital supply purposes. The Song dynasty, distinguished by one of the medieval world's most prosperous and advanced economies, witnessed significant investment in joint-stock companies and multiple sailing vessels, given the guaranteed monetary returns from the robust overseas and domestic trade via the Grand Canal and Yangtze River (Ebrey, Walthall & Palais, 2006). The Ming Dynasty was the final dynasty before the advent of Western revolutionary transportation vehicles.

This research quantifies accessibility based on the ancient transportation system and examines the association between transportation and social networks. By investigating historical data on an unprecedented temporal scale, we aim to unearth some enduring influences. While previous historical studies have furnished the data utilized in this research, the majority of the analysis has been qualitative in nature. This research discerns that accessibility can serve as a quantitative indicator of transportation and economic conditions in ancient periods, and the influence of historical transportation on social networks can indeed be probed.

1.4. Structure of this Paper

The remainder of this paper is partitioned into four sections. Section 2 delves into the methodologies of data collection and corresponding processing. Section 3 elucidates the accessibility modeling and its resultant findings. Section 4 expounds on the regression analysis between transportation and social networks. Lastly, Section 5 draws conclusions from the research and contemplates potential avenues for future work.

2. Data Processing

2.1. Spatial Differentiation of Study Area

As delineated in Table 1, five types of data factor into our accessibility computation. Firstly, normalization of the study unit for the accessibility calculation supplies requisite location information for the study areas. Given the historical flux of administrative divisions and city locations, a standardization of the unit area is mandated. We bisect the entire study area into 1,777 squares, with each square encompassing an area of 2,500km^2 (50*50km). This division was selected as the unit size aligns closely with the smallest administrative division during the imperial China epochs. Typically, each dynasty encompassed approximately twenty provincial centers, hundreds of prefectural centers, and thousands of county centers. As illustrated in Fig. 1, the blue squares overlaying the population points represent the normalized division of the study area.

Table 1. Historical Data Utilized in this Research.

Data Category	Details
Normalized Study Area	1777 normalized study area/squares
Population	Population Distribution Data of Year 2, 742, 1102, 1522. (Bol, 2011)
Transportation	Roads in Han Dynasty (Chen, 1982); Roads in Tang Dynasty (Academia Sinica, 2020; Chu, 2014); Courier Routes in Ming Dynasty (Bol, 2011) Natural Rivers (Academia Sinica, 2020); The Grand Canal (Bol, 2011)
Velocity	Speed of different vehicles. (Lyu, 2015)
Geography	Digital Terrain Model of China. (CAS, 2003)

2.2. Population

The population of each unit square is derived from the sum of the population points residing within its area. A minority of population points not housed in any unit square are attributed to the nearest one. As depicted in Fig. 1, the population distribution for the years 2, 742, 1102, and 1522 are procured (Bol, 2011). Each population point symbolizes approximately 10,000 individuals. Despite variations in the units and methods of population census across different dynasties, these adjusted population figures provide a sufficiently reliable depiction of the historical population distribution.

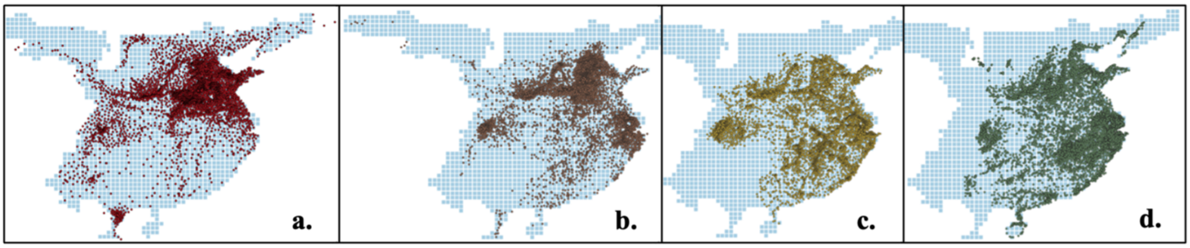


Fig. 1. Population Distribution (1 point represents 10,000 people):
(a). 4673 points in Year 2 of the Han Dynasty; (b). 5320 points in Year 742 of the Tang Dynasty;
(c). 5550 points in Year 1102 of the Song Dynasty; (d). 8813 points in Year 1522 of the Ming Dynasty.

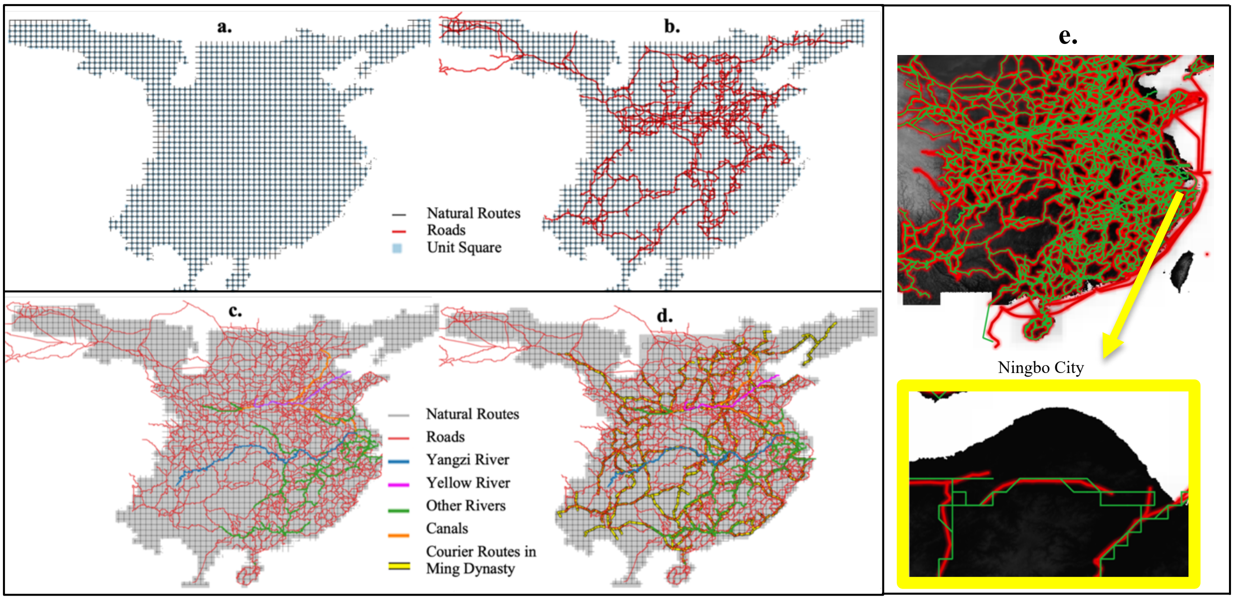


Fig. 2. Transportation System for Years 2, 742 & 1102, and 1522.
(a). Natural routes connecting all unit squares; (b). Transportation system for Han Dynasty (Year 2);
(c). Transportation system for Tang and Song Dynasty (Year 742&1102); (d). Transportation system for Ming Dynasty (Year 1522);
(e). Adjusted (green) and Original Routes (red) around Ning-Bo City

2.3. Transportation

The transportation system encompasses natural routes, roads, and rivers/canals. As illustrated in Fig. 2-a, the formulated natural routes network represents the mode of transportation in the absence of any existing infrastructure. The natural routes should serve as a foundational network for all calculated periods to assure all units are interconnected prior to the construction of the artificial road infrastructure. In these natural routes, where geography is a pivotal factor for travel, individuals can traverse at a relatively slow speed while bearing goods. We presuppose that travel speed by foot on these natural routes will be only a third of wagon travel on roads. We connect each study unit with its four neighboring units and compute the exact speed along the natural routes, considering the changes in geographical height. The application of the velocity data and geographical height data is elaborated in the travel time computation in Section 3.1.

Chen (1982) is a trailblazer in the study of Chinese historical transportation, having completed a map detailing the national road system during the Han dynasty. In our current work, depicted in Fig. 2-b, we have digitized his contributions and amalgamated them with the natural routes network, thereby formulating the transportation network for the Han dynasty. Given the rudimentary state of river transportation technology during this era, only road transportation is considered for the Han dynasty.

The Tang dynasty marked an era when national roads connected most prefectural centers. As shown in Fig. 2-3, the road system data was compiled by Yen (1985) and digitized by Chu (2014). Yen's seminal work, "Mapping Research on Transportation of Tang Dynasty", took over 40 years to complete and is widely regarded as the pinnacle of research in this field. Drawing from an extensive array of historical documents, Yen was able to recreate the comprehensive transportation system of the Tang Dynasty. Chu (2014) digitized the transportation information collected in Yen's work, culminating in the "Basic Framework of Chinese Civilization in Time and Space" published by Academia Sinica. River data was sourced from various open data platforms. Given the variable speeds across different rivers, we categorized them into three types based on travel speed: the Yellow River, the Yangtze River, and others, which include the Grand Canal. These rivers are all significant waterways spanning multiple prefectures.

The Song Dynasty is considered to maintain the same transportation infrastructure as the Tang Dynasty, predicated on the assumption that by the Tang era, virtually all counties were interconnected. In the absence of notable advances in vehicle technology, the transportation system would remain relatively unchanged. Referencing Bol's courier routes from the Ming Dynasty (2011) depicted in Fig. 2-d, we superimpose these pathways on the Tang and Song transportation maps, thereby facilitating accelerated transit speeds along these courier routes.

Several constraints regarding the road network data exist. A significant portion of this research was dedicated to refining the road data to facilitate plausible and precise travel time computations. The road data is sufficiently detailed, but lacks classification. Differential speeds should exist for major roads, but the absence of historic documentation prevents accurate speed differentiation. Consequently, we assigned an average speed to all roads. Another issue pertains to connectivity. The original intention of this database was for historic mapping, not quantitative network studies. Road locations are adequately precise, but the data lacks a graph structure, hence connections based on proximity are presumed. Initially, we delineate essential geographic values and other characteristics, including road length, slope, travel speed, and travel time. Following this, as illustrated in Fig.2-e, road shapes are adjusted in proximity to hypothesize plausible "interchanges". This creates a connected network enabling the computation of minimum travel times between any pair of cities.

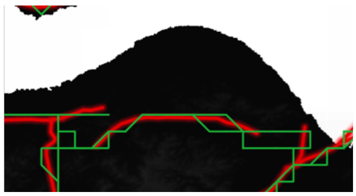


Fig. 2-e. Adjusted (green) and Original Routes (red) in NingBo Area

3. Accessibility Modelling

3.1. Accessibility Calculation

A considerable amount of scholarly work exists that lays out distinct specifications for accessibility as articulated in Equation (1). The earliest attempts usually proportionate locations based on their sizes, as proposed by Stewart-Warntz (1958) and Hansen (1959). The accessibility function is conceptualized as a gravity-oriented approach where the cost function is a decay function with a weight element, as illustrated in Equation (2). Here, A_i denotes the accessibility at location *i*, considering all *j* locations within [*1...n*] and their featuring opportunity points O_j, with generalized costs c_{ji} weighted by a negative exponential weight factor ω. The higher the absolute value of ω, the steeper the decay function is, hence opportunities distant from location *i* have diminished influence. The lower the absolute value of ω, the smoother the cost function *f*'s graph becomes, and the reduction of the value of opportunities distant from location *i* is less significant.

Same to our previous research (Li, 2021), as depicted in Equation (2), the accessibility A_i uses population P_j to symbolize the opportunities O_j. In a conventional ancient agricultural society, the total population at a specific location is perceived as proportional to the amount of consumption and production (Fuhrer, 2019), with no other comprehensive indices accurately reflecting the actual economic condition. The study only considers travel time as the cost, where t_{ji} represents the potential minimum time cost (days) required to travel from prefecture *j* to *i*.

$$A_i = \sum_{j=1\cdots n} O_j \cdot e^{-\omega \cdot c_{ji}} = \sum_{j=1\cdots n} P_j \cdot e^{-0.21 \cdot t_{ji}} \quad (2)$$

Generalized time costs in this research are weighted by a negative exponential factor ω, which is 0.21. This choice is based on prior research on another agricultural era: Fuhrer's (2019) historical accessibility model for Switzerland in 1720, given the lack of better data. After adapting Fuhrer's model, parameters in Equation (2) are chosen such that the curve follows a flat, nearly linear path, accounting for overnight stays during multi-day travels. The decay factor ($e^{-0.21 \cdot t_{ji}}$) for a two-week journey is around 0.05, and for trips longer than two weeks, the decay factor is nearly zero. Since most trips in ancient China extended beyond two weeks, employing 0.21 for the exponential factor ω does not significantly alter most calculations. Referencing historical records, Yen (1995) estimated that the capital city's floating population during the Tang Dynasty was at least 50,000. With the chosen parameter ω, we calculate the capital's floating population as 50,926 for the year 693, and 109,261 for the year 742, consistent with historical records. The regression results discussed in Section 4.3 further suggest that the selected parameter ω is reasonably adopted.

Travel time is contingent on speed. As depicted in Table 2, speed varies based on the type of vehicle for road travel and the specific locations for river travel. The impact of elevation is also considered for road journeys. A slope factor equation is extrapolated from the work of Franz Johann Maschek and Eduard Bokelberg (Fuhrer, 2019). The actual speed, V_1, on a segment with slope α, is defined in Equation (3), where V denotes the average speed listed in Table 2. Speed data for ancient vehicles is derived from a Tang dynasty law that stipulated daily travel distances for different vehicles. Given the consideration of slope influence, geographical height data is also utilized. As indicated in Equation (4), road slopes are computed based on height data, where ΔH represents the change in height, and L represents the length of the specific route section. This paper's accessibility aims to simulate significant goods flow, hence, the speed employed on roads is wagon speed, and the speed used on rivers pertains to goods-carrying.

$$V_1 = V \cdot (1 - 2 \cdot \sin(\alpha)) \quad (3)$$

$$\sin(\alpha) \approx \tan(\alpha) = \Delta H / L \quad (4)$$

Table 2. Speed of Ancient Vehicles (Unit: kilometers/day; Lyu, 2015)

Road Types	Speed on Roads	Rivers	Down Speed	Up Speed with Goods	Up Speed without Goods
Natural Routes	5	Yangze River	50	20	25
Manmade Roads	15	Yellow River	75	15	20
Courier Routes in Ming Dynasty	30	Other Rives, Canals	35	22.5	30

In ancient times, individuals typically had around 12 hours daily for travel, influenced primarily by necessities for rest and sunlight, a crucial factor for several ancient travel methods. We also applied the shortest path algorithm for travel time computation. It's possible that certain preferred routes existed in ancient China that affected travelers' choices, potentially reducing the efficiency of the shortest path. However, long-distance journeys during that period often spanned weeks or months, rendering the time cost variations between preferred routes and the shortest path negligible. It's highly unlikely that a preferred route would have necessitated a considerably longer travel time, which would not have been practicable for travelers in that era. Furthermore, there is a dearth of historical data to facilitate a comparison of travel volumes on different routes.

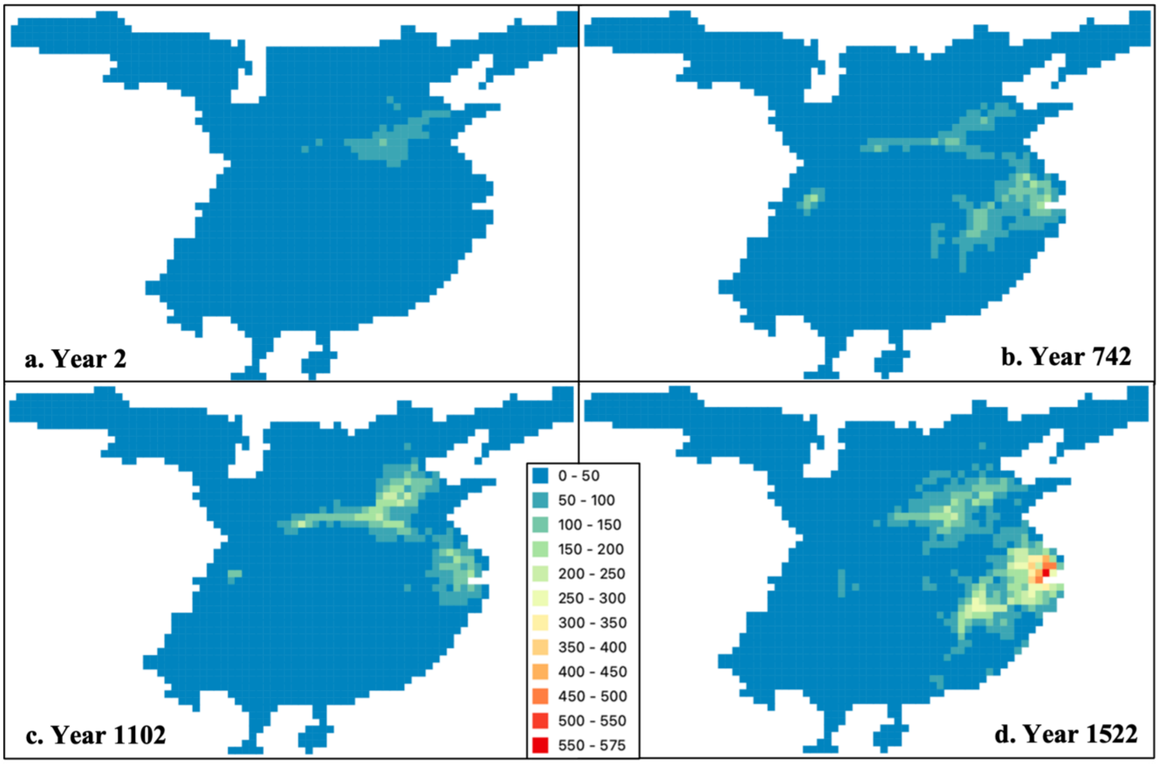


Fig. 3. Accessibility Values for Years 2, 742, 1102, and 1522. (Units: economic opportunities contributed by 10,000 people)

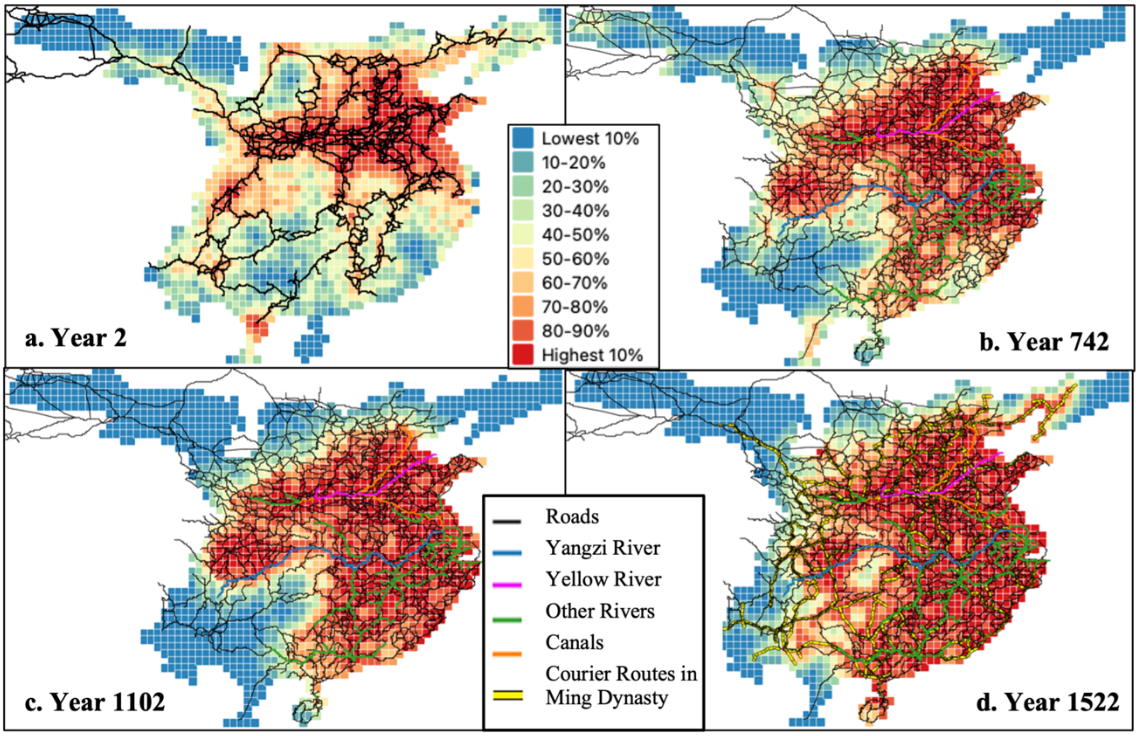


Fig. 4. Grouping by Accessibility Values and Corresponding Transportation System.

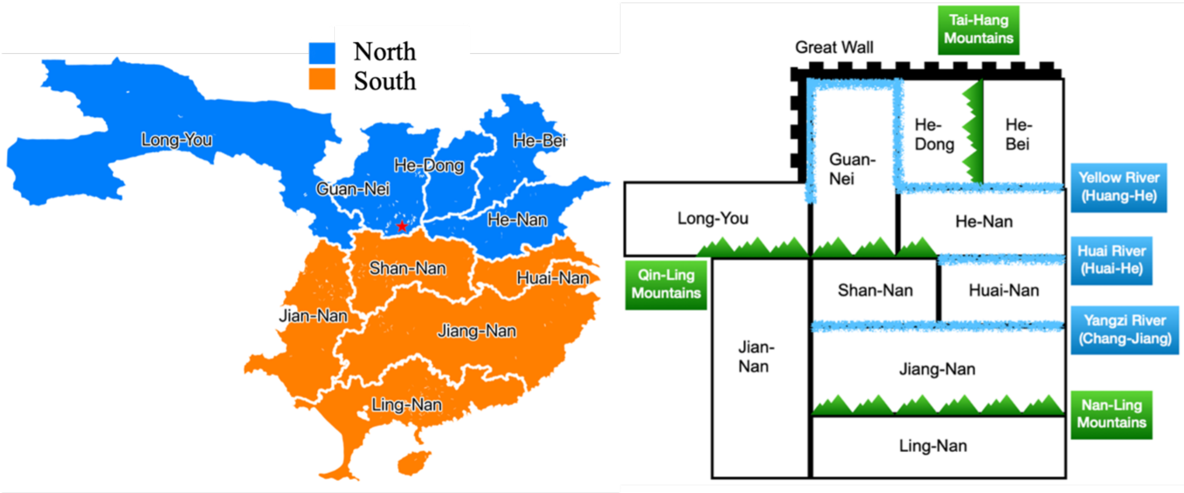


Fig. 5. Provincial Division of Tang Dynasty.

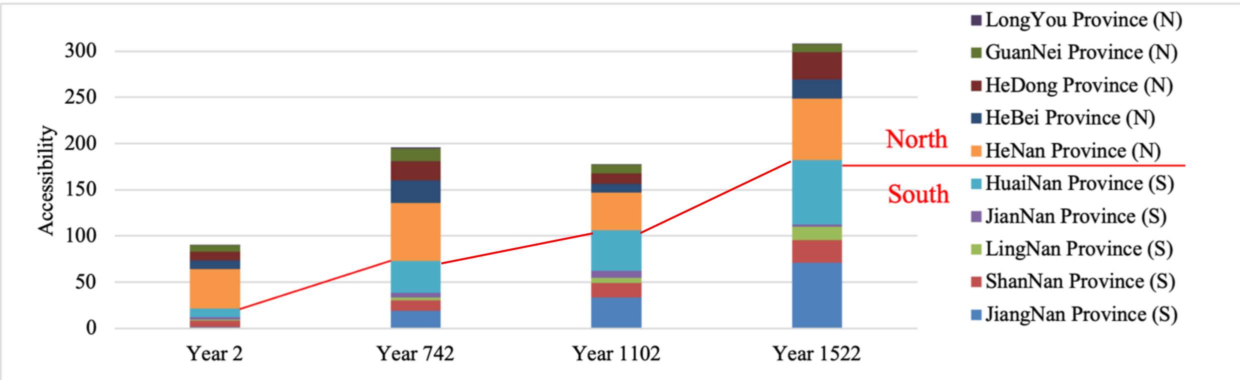


Fig. 6. Average Accessibility Value for Different Provinces.

3.2. Accessibility Results

Using the methodologies and functions outlined in Sections 2 and 3.1, we computed the accessibility values for the years 2, 742, 1102, and 1522. Fig. 3 reveals that northern prefectures initially had relatively high accessibility. Interestingly, another accessibility center gradually emerged in the southern prefectures around the Yangtze River Delta, aligning with historical accounts of the economic center's shift from north to south around the Tang dynasty.

Transportation infrastructure's role in enhancing accessibility is clear. As illustrated in Fig. 4, the primary drivers of accessibility improvements differ across periods. The road system of the Han dynasty, the river and canal system of the Tang and Song dynasties, and the courier routes of the Ming dynasty all contribute to increased accessibility for neighboring locations.

We also discuss the average accessibility value for units situated in various provinces, according to the provincial division of the Tang dynasty. The right of Fig. 5 shows that Tang dynasty provincial divisions were based on geography. The entire nation was divided into ten provinces according to six major rivers and mountain ranges, ensuring each province formed a relatively isolated area. Some of these provincial border divisions are still in use today. As depicted in Fig. 6, the share of total accessibility accounted for by southern provinces has grown over time. This trend likely influenced and resulted from the economic center's shift from Henan Province in the north to Jiangnan Province in the south.

4. Accessibility and Social Network

4.1. The China Biographical Database (CBDB)

The China Biographical Database, a collaborative project among Harvard University, Academia Sinica, and Peking University, is a freely available relational database. As of August 2022, it contains biographical information for roughly 521,442 individuals, predominantly from the 7th to the 19th centuries. Crucially, it records the native place of most individuals and assigns an index year, an analytical tool based on the estimated year of birth. The database also accounts for social relationships between individuals, as indicated by historical records. These relationships span various categories, including familial, social, academic, political, and literary. The database contains the most records pertaining to influential figures and those associated with them.

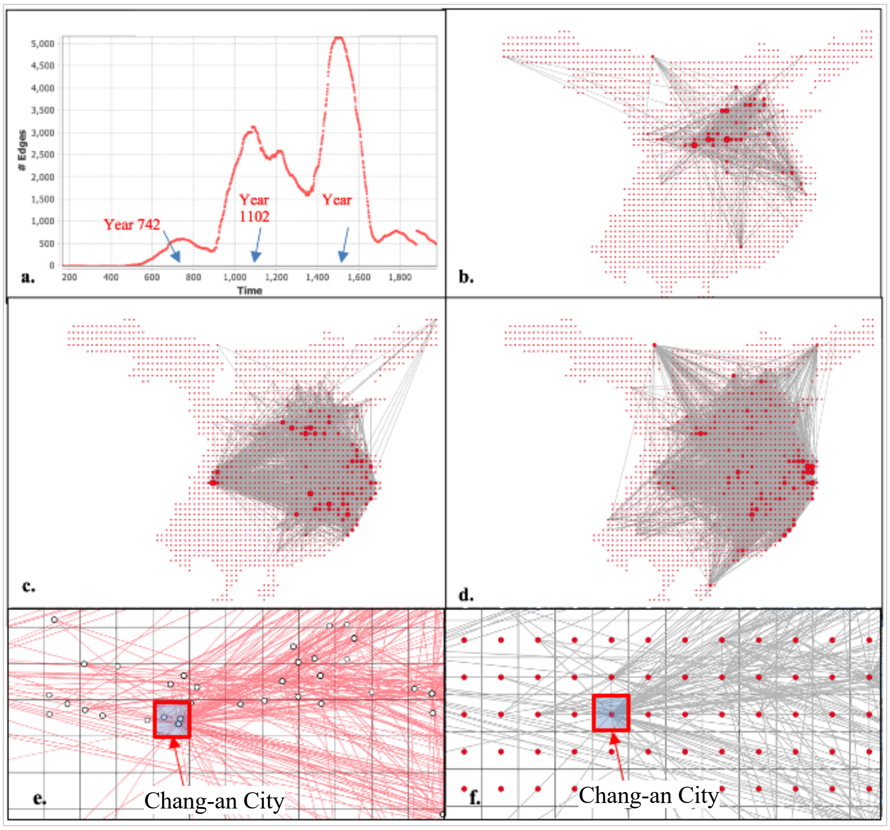


Fig. 7. Processing of the Social Network Data.
(a): Number of Edges (Self-loops Excluded) in the Social Connection Networks between Cities for Different Time Range of 100 Years;
(b)-(d): Social Connection Networks between (b) Years 692-792, (c) Years 1052-1152, (d) Years 1472-1572;
(e): Original Social Networks between individuals around Chang-an in 742; (f): Connection Networks between cities around Chang-an in 742.

We extracted 89,990 social links (excluding kinship relationships) connecting 36,642 individuals from the database. Due to the absence of essential details like native places or index years for certain individuals, we only considered 57,326 social links. As illustrated in Fig. 7-a, these links are predominantly from the Tang, Song, and Ming dynasties. The substantial number of recorded individuals from these three periods enhances the database's representation of the upper-class social networks. Analyses of social networks will focus on the Tang, Song, and Ming dynasties, as these periods align closely with available population data and calculated transportation and accessibility metrics.

We processed the 57,326 social links further by replacing individual nodes in the social network with their corresponding native cities, as demonstrated in Fig. 7-(e) and (f) for the processing Chang-an area. This step produced a city-based social connection network that mirrors the interpersonal connections among their populations. Hereafter, this city-based network will be referred to as the "connection network" to distinguish it from individuals' social networks. Based on the connection network, we determined the degree of each city. Fig. 7-(b), (c), (d) depict the social connection networks among different cities between Years 692-792, Years 1052-1152, and Years 1472-1572, with dot size representing the degree number in each period. These total degree numbers include the "self-loop" of social connections within the same city.

4.2. Growing Geographical Scope of the Social Connection Network

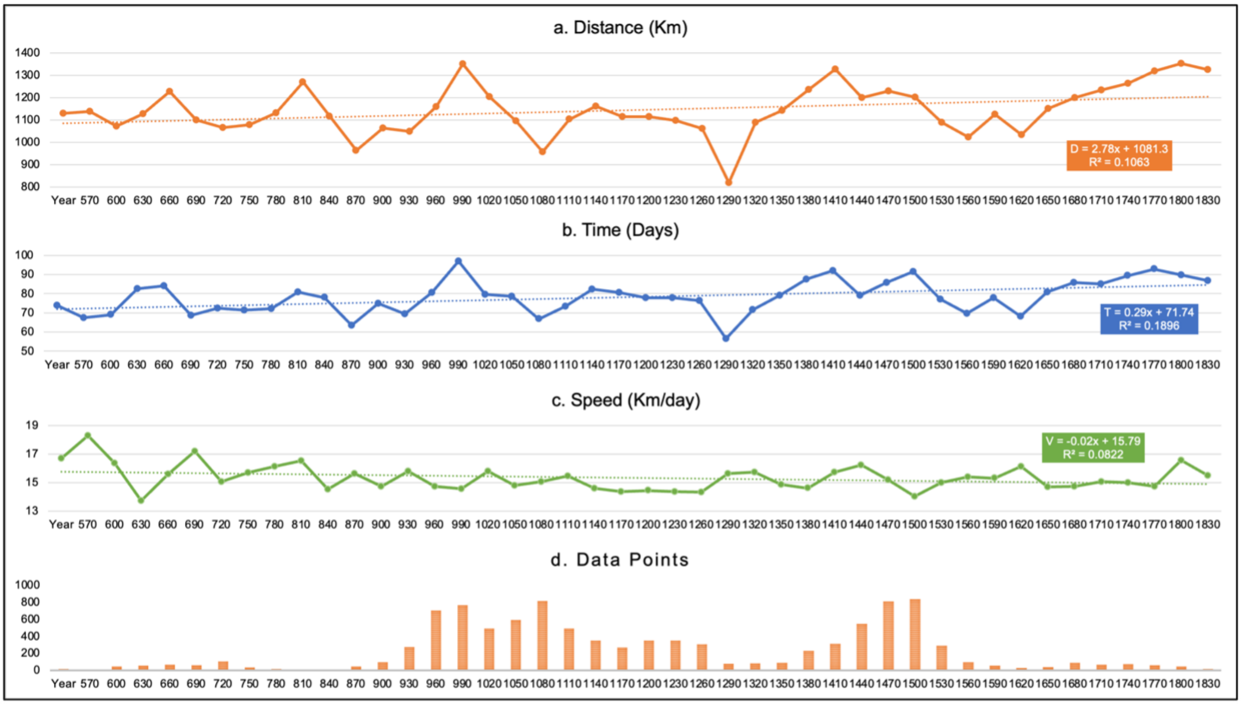


Fig. 8. Regression Results for Average Values of 30 Years Range on Top 20% Longest Social Network Links
(a): Average Geographical Distance; (b): Average Time; (c): Average Speed; (d): Data Number

The city-based social connection network reflects the capacity or intention to communicate across geographical boundaries. To quantify this ability's evolution over time, we conducted a regression analysis on average geographical distance (straight line distance), travel times, and travel speeds for selected links within every 30-year interval. To minimize the impact of social connection loops, we considered only the links ranking within the top 20% longest group. Despite noticeable fluctuations in the trends depicted, the regression, shown in Fig. 8-a, does provide a glimpse of the overall historical evolution. The average geographical distance for the top 20% of links expands with time, indicating a growing ability to communicate across larger geographical separations. Fig. 8-b and 8-c display corresponding travel time and speed calculations. A declining speed trend suggests limited advancements in long-distance travel, especially in remote areas distant from population clusters. Without a revolutionary breakthrough in transportation, the average speed will likely decrease as travel scope increases.

4.3. Gravity Models for Connection Networks Between Cities

As depicted in Equation (5), we propose a gravity model to interpret the social pull between two cities. The degree of social links between cities *i* and *j* is anticipated to be positively correlated with their populations and inversely related to their distance. Here, we employ the travel time between the two cities as a negative indicator. Equation (6) is formulated to conduct the linear regression analysis. As demonstrated in Table 4, the regression results bolster our assumptions that the gravity model is applicable to social networks in ancient times.

$$D_{ij,\tau} = c' \frac{(P_{i,\tau})^{\alpha}(P_{j,\tau})^{\beta}}{(t_{ij,\tau})^{\gamma}} \tag{5}$$

Hence

$$ln\ (D_{ij,\tau}) = \alpha\ ln(P_{j,\tau}) + \beta\ ln(P_{j,\tau}) - \gamma\ ln(t_{ij,\tau}) + \text{c} \tag{6}$$

where,

$D_{ij,\tau}$: Degree of the social links between the city pair *i,j* for the period τ,
$P_{i,\tau}, P_{j,\tau}$: Population of the city i or j for the period τ,
$t_{ij,\tau}$: Travel days needed from city i to j for the period τ,
α, β, γ : Calculated parameters and intercept of the linear regression,
c', c : Constant.

Table 4. Regression Details and Results for the Gravity Model

Study Period	Cities Pairs #	Social Links #	R^2	α	β	γ	c
692~ 792	569	1166	0.128	0.161**	0.219**	0.095*	-0.163
1052~ 1152	2566	9635	0.105	0.182**	0.214**	0.318**	1.063**
1472~ 1572	4379	12293	0.190	0.183**	0.240**	0.208**	0.169*

Note: ** P-value <0.01, * P-value <0.05.

The computed values of α and β might theoretically represent the different roles played by the first city and its counterpart in creating their social links. However, our model does not attribute any specific significance to the order of the considered city pair, thus definitive conclusions cannot be drawn from this model and its resulting outcomes. The computed γ for the period 1472-1572 is 0.208, which is near the negative exponential factor ω utilized in the accessibility calculation, standing at 0.21. Due to data scarcity for distant periods, as shown in Fig. 7-b, most social links considered for the 692-792 period are confined within a relatively compact area, where the largest population cluster was located at that time. Therefore, it is plausible that the computed γ is smaller than 0.21 since shorter travel distances will induce a lesser travel decline between cities. However, the computed γ for the period 1052-1152 exceeds 0.21. One viable explanation for this less than ideal result may lie in inconsistent data collection due to its corresponding historical backdrop. For the other two periods, national or provincial-scale wars did not occur. Even if any war arose, the affected area was limited to a few prefectures or just one province. In 1125, the Song Dynasty ceded control over its northern half to the Jurchen-led Jin Dynasty during the Jin–Song Wars. More than half of the cities under study today might not have any relevant data since then. Owing to the enormous population loss and change during the protracted war, the social network and population data collected for the 1052-1152 periods cannot accurately reflect those turbulent times. Therefore, the regression performance appears inconsistent. Assuming there should be no significant change in the negative exponential factor for accessibility calculation during ancient times, it is plausible that the computed γ of the most recent period 1472-1572 is the most accurate due to its relative precision and accessible data volume. The computed γ validates that our adopted accessibility function is reasonable.

To gauge the efficacy of the proposed gravity model and analyze the discrepancies between the regression and recorded data, the difference ratio $R_{ij,\tau}$ is defined as shown in Equation (7), to compare the observed degree value of the social links and the calculated degree based on our regression results.

$$R_{ij,\tau} = \frac{|D_{ij,\tau} - D_{ij,\tau}'|}{D_{ij,\tau}'} \tag{7}$$

where,

$R_{ij,\tau}$: Defined difference ratio of the social links between the city pair *i,j* for the period τ,

$D_{ij,\tau}$: Observed degree of the social links between the city pair *i,j* for the period τ,
$D_{ij,\tau}{}'$: Estimated degree of the social links between the city pair *i,j* for the period τ.

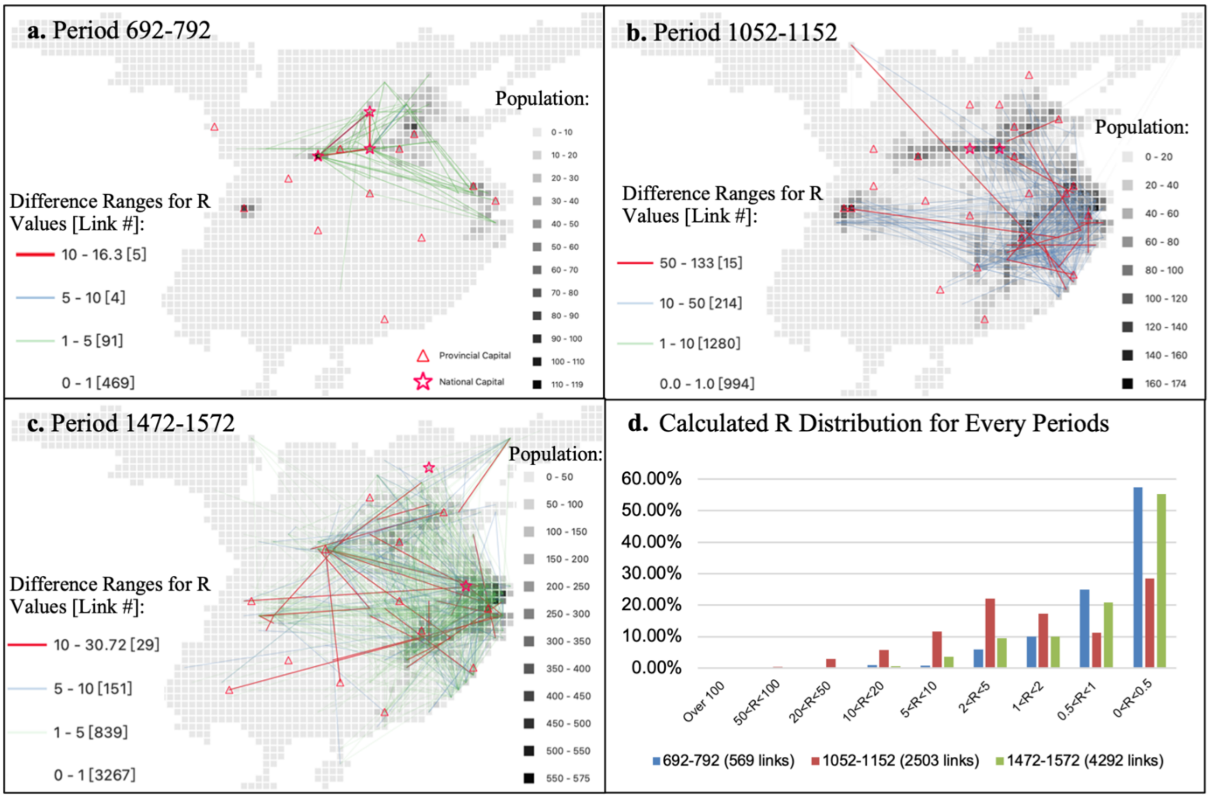


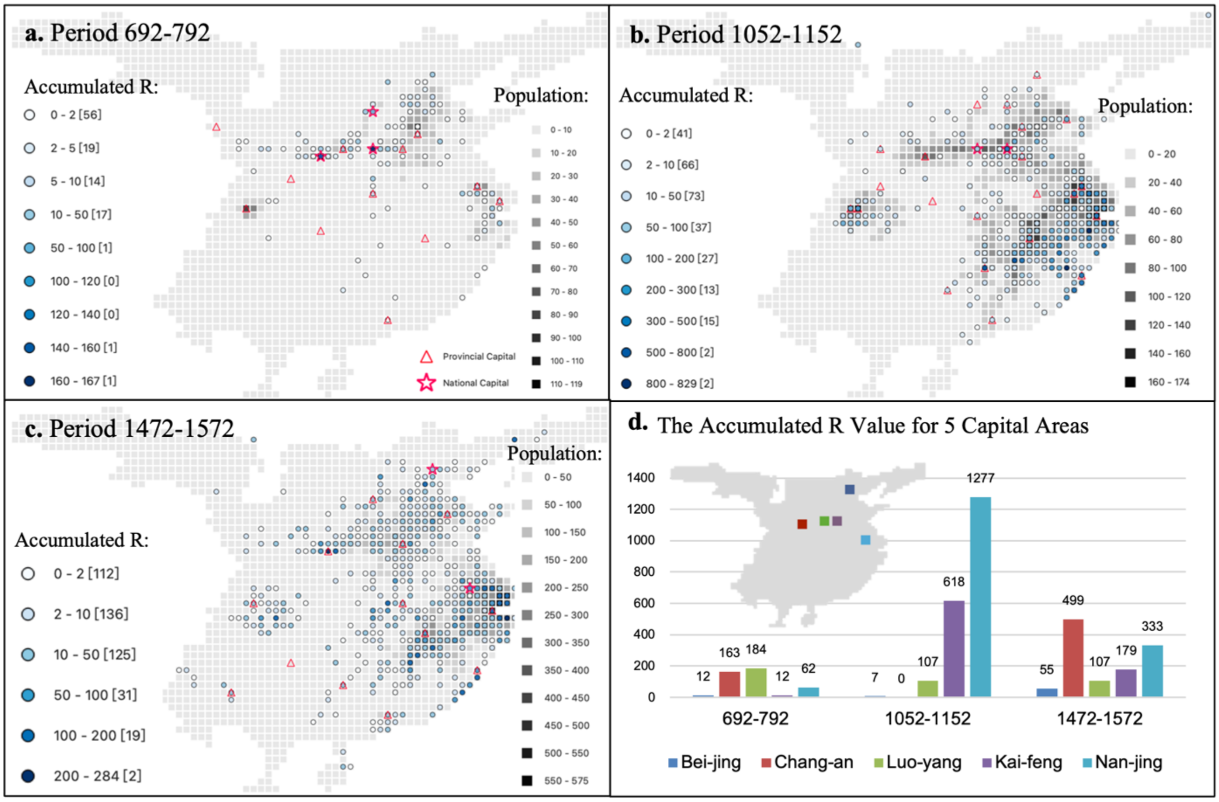
Fig. 9. Difference Ratio $R_{ij,\tau}$ Between the Observed and Calculated Degree of Social Links in Different Periods.

As illustrated in Fig. 9-d, about 82% of the links in the period 692-792, 39% of the links in 1052-1152, and 76% of the links in the period 1472-1572 have an R ratio value of less than one. Especially for the periods 692-791 and 1472-1572, more than 50% of the links have an R ratio value of less than 0.5. This suggests that the discrepancy between the calculated degree value and observed degree value is relatively small, indicating the gravity model can provide a good explanation for most of the considered links.

However, there are also many groups of links with relatively large R values. Links with R values greater than 1 are marked in Fig. 9-a, 9-b, and 9-c. In these figures, the background grey color for each city represents the population. The national and provincial capitals are also highlighted on the map. All these highlighted social links with a higher R value are connections between cities with a higher political ranking or larger populations. For example, in Fig. 9-a, the top links with R values greater than 10 are connections between the three national capitals.

This suggests that the difference between the observed degree value and the calculated one may be due to the self-reinforcing nature of social networks. Unlike transportation networks, social networks tend to become richer with time. Individuals who have established cross-regional social connections are likely to form more such relationships over time. These self-propelling, amplifying effects are currently not incorporated into our gravity model. Therefore, it is reasonable that there are groups of links where the observed degree is larger than the calculated degree. Social networks between cities with a higher political ranking or larger population are likely to have a stronger self-reinforcing characteristic. To verify this assumption, as shown in Fig.10, the accumulated value of the difference ratio ($\sum_j R_{i,j,\tau}$) for cities is calculated.

Fig. 10. Accumulated Value of Difference Ratio ($\sum_j R_{i,j,\tau}$) for Different Cities in Different Periods.



The difference ratio $R_{ij,\tau}$ of links between city i and j is assigned to both cities i and j. The accumulated difference value ($\sum_j R_{i,j,\tau}$) for different cities is shown in Fig.10-a, 10-b, and 10-c for different periods. It is evident that most cities with higher difference values have a higher political ranking or a larger population.

In Fig. 10-d, five important capital areas are listed with their accumulated values. To account for location errors between our modeled cities and historical capitals' actual locations, the accumulated values shown in Fig. 10-d are the sum of the capital city and its eight neighboring cities. Chang-an and Luo-yang were the capitals during the Tang period 792-792. As these two capitals were the most significant population centers and the highest political centers, they have the largest accumulated values compared to other cities. Kai-feng was the capital during the Song period 1052-1125. However, Nan-jing, the political and economic center for the southern parts of China, emerged as the leading city. This shift can be attributed to two reasons: first, the Song dynasty's economic center had shifted from the north to the south; and second, the Song dynasty lost control of its northern provinces, including the capital Kai-feng, from 1125. Given that the Song dynasty boasted one of the most prosperous and advanced economies in the medieval world, the maximum accumulated value is almost 4-6 times higher compared to the other two periods. Nan-jing and Bei-jing were the capitals during the Ming period 1472-1572. All these five cities have a relatively higher accumulated R value.

This analysis and arguments for different cities support our assumptions that the social networks between cities enjoying a higher political ranking or having a larger population intend to have a stronger self-reinforcement characteristic. However, according to Fig. 10-d, there is hardly any relationship between the accumulated difference value ($\sum_j R_{i,j,\tau}$) for the same area in different periods. This means that the self-reinforcement of social networks is not consistent across all periods. A city's enduring history of self-reinforcement does not make it invulnerable to external disruptions. Subsequent periods of widespread warfare can effectively halt or neutralize its social connectivity with other cities. Such chaotic conflicts often entail considerable population decline, extensive migration, and a downturn in economic allure. These factors not only disrupt pre-existing social ties but also pose significant challenges for the formation of new social connections. Therefore, in the historical context of ancient China, the consistency of social networks for different periods is not strong because of the frequent wars. The chaotic wars between the three studied periods brought destructive changes to the social networks and, of course, stopped the self-reinforcement of the original social network.

In conclusion, our proposed gravity model could fit well for most social links but failed to describe the self-reinforcement of social networks which is in turn depending on large events, such as wars. A higher political ranking and larger population will enable a city to have a more significant self-reinforcement effect on its social networks. Detailed data indicating the political ranking and times series-based population development is necessary to improve our model.

5. Conclusion and Future Work

Transportation has a long-term impact on society. This research reconstructed the transport network in ancient China and studied the quantification of historical transportation based on accessibility modeling. Further, a gravity model is formulated to explain the relationship between transportation and social networks.

Firstly, the paper demonstrated that accessibility could also be utilized to explain population interactions in ancient periods. The accessibility reflected the economic shift process, and the quantifying analysis proves that the geographical scope of the social network grew with time development during ancient China. At the same time, we show that the historic development of a city is important. Improving accessibility might not lead to immediate rapid impacts but the central role of cities will to some degree remain even after centuries even if the political and economic importance of the city has been in decline.

This research also demonstrates that history can be explained better based on this kind of quantifying study. Using quantitative research methodologies for historical analysis enabled us to analyze the long-term relationship between transportation and our quantitative historic data allowing us to calculate specific values that can be used for comparisons across disparate periods and contexts, including modern societies. In contrast, qualitative historic research often encounters difficulties in establishing comparable effects due to its inherently subjective nature.

Secondly, we employ a gravity model to elucidate the relationship between transportation and social networks. The gravity model effectively correlates with the majority of cities, suggesting that the intensity of social connections between two cities should be directly proportional to their populations and inversely proportional to their distance from each other. Furthermore, the parameter calculated for travel cost aligns closely with the negative exponential factor used in our accessibility calculation. This congruity substantiates the rationale behind our chosen accessibility function. In an era predating the advent of telecommunications technology, advancements in long-distance communication were largely mirrored in the progression of transportation technology. The necessity of tangible transportation mediums such as letters was paramount for remote communication. This study accentuates the pivotal role that transportation played in shaping social connections during ancient times.

The utilized gravity model shows how transportation, especially travel time, shaped social networks. It can be asserted that there is also a cyclic effect between transportation and social networks, as also known from the land-use and infrastructure dynamics in modern times. The article does not explicitly present a dedicated data analysis focusing on the cyclic interplay between transportation and social networks, this inference can be reasonably drawn based on a careful examination of the visualized data in Fig.4, Fig.6, and Fig.7. Specifically, these figures highlight shifts in transportation accessibility and changes in social network structures. The establishment and preservation of the Grand Canal during the Tang Dynasty, for instance, may have catalyzed a noticeable southward migration of social networks in the ensuing Song and Ming periods. This, in turn, seems to have influenced the geography of transportation accessibility, thus playing a role in redefining the economic epicenter. In essence, while not directly presented, the cyclical interaction between transportation and social networks becomes discernible through a nuanced interpretation of the provided data.

The utilized gravity model also shows a fairly constant role of travel time deterrence. This is consistent with our analysis shown in Fig.8. The is significant further traveling speed improvement until the introduction of modern vehicles. This study emphasizes that on a historical scale, the transportation infrastructure may induce long-dominated social networks. The dramatic changes that travel opportunities reshaped societies began recently in modern times. Modern transportation generated more spatially dispersed social networks because their member can make use of a broader region for their housing needs without coordination with other members. People can maintain contacts, maybe even entire networks at remote locations (Axhausen, 2003). This spatial dispersion will create rapidly changing dynamics of the social networks since members have more opportunities to meet new people and establish contacts.

Finally, we discuss the self-reinforcement effects of social networks, which the proposed gravity model may not describe well. Our findings suggest that cities with elevated political rankings or larger populations and economic foundations possess the potential for more pronounced self-reinforcement effects within their social networks. However, a city's enduring history of self-reinforcement does not make it invulnerable to external disruptions. Subsequent periods of widespread warfare can effectively halt or neutralize its social connectivity with other cities.

Future research endeavors could further delve into the exploration of historical social networks. A significant avenue for future study involves replacing the gravity model with a model that takes into consideration economic and political indicators, thereby providing a better understanding of the self-reinforcement effects within social networks. Also, the travel time function can be modeled in other forms, such as the impedance function based on the threshold.

Additionally, other inherent characteristics of social networks, such as their "small world" nature, warrant further investigation. Considering the consistent role of travel time deterrence within the area studied, another prospective research topic is a focus on the pivotal period surrounding the advent of motorization.

The development of a multi-modal accessibility measure, based on the pre-established network, could cater to a myriad of research objectives, including the exploration of trade connections in ancient times. While the accessibility value can, to an extent, signify a location's potential for economic opportunity capture, such as the ability to trade with other regions, it's crucial to recognize that the real historical landscape may have been significantly more intricate. For instance, trade networks between different cities might have been deeply interconnected with their respective political standings, as a considerable portion of trading activities during ancient times may have been propelled by political underpinnings. Such complexities in the interaction between economic and political networks certainly warrant further academic exploration.

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