Transportation Accessibility of Ancient China and Its Socioeconomic Impact

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Doctor of Philosophy

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古代中国の交通アクセシビリティとその社会経済的な影響

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Abstract

The impact of transportation system development on human society is widely recognized. Yet the limitation of qualitative assessments highlights the critical need for a quantitative approach for a deeper understanding of the history and the prediction of future changes. However, the challenge of such a quantitative approach is often exacerbated by the notable shortage of data and appropriate methodology. This is particularly challenging for a long-term historical study. To address this issue, this study aims to refine the data availability and methodologies employed in the analysis of long-term historical transportation systems and their social impacts, with a particular focus on ancient China.

The thesis has three main contributions: a comprehensive and open-access database combining massive historical transportation and social data of ancient China from the Han Dynasty to the Ming Dynasty, robust mathematical models and methods for analyzing transportation accessibility and other social indicators with the aforementioned database, and a comprehensive quantitative analysis on the impact of transportation systems on the society including population dynamics, social connections, imperial examination, exile destination, and more.

First, data processing serves as the foundational stage of the study, aimed at compiling and analyzing historical transportation records to map the evolution of diverse transport networks consisting of roads, rivers, and canals, throughout successive Chinese dynasties. By digitizing the data with a Geographic Information System (GIS), it is possible to calculate the travel time matrix in the ancient age. Moreover, this study also includes a broad spectrum of historical data to study the socioeconomic repercussions of transportation infrastructure, including demographic data, social links, wars, imperial examination, exile destinations of government officials, pandemics, and more. This comprehensive and open-access database shall serve as a critical and standard resource for future historical inquiries. Chapter 7 describes the database and demonstrates how to use it to analyze social activities.

Transportation accessibility modeling forms the cornerstone of the research. Based on the extensive historical demographic data and travel time metrics estimated with a standard mathematical model, this study yields a nuanced understanding of transportation accessibility across different historical periods. It sheds light on the transition of economic centers from north to south in ancient China and positions transportation as a catalyst for economic redistribution and development. Transportation accessibility is also utilized for the evaluation of the most important transportation infrastructure in ancient China, i.e., the Grand Canal. The methodology developed by this analysis may offer a valuable framework for evaluating the impact of other historical infrastructures. Chapters 3 and 5 thus contribute to the calculation of transportation accessibility in different periods.

A notable finding of this study is how transportation-induced demographic shifts are indicative of a society's developmental trajectory, particularly in response to wars and natural disasters that have been primary drivers of immigration in history. Chapter 4 illustrates that the role of transportation accessibility as a catalyst maybe not just a facilitator but also an accelerator for immigration.

Chapter 6 explores the impact of transportation on the formation of social links, by developing a Modified Gravity Model (MGM) to explain the phenomenon. Notably, it was discovered that the parameter indicating travel time deterrence in the MGM varied minimally across various dynasties in ancient times, essentially remaining close to a constant value. This finding aligns with a previous study on ancient Switzerland, suggesting that the travel time deterrence parameter may be consistent for most ancient ages. The stability of this parameter not only validates the accessibility model applied but also lays a methodological groundwork for determining the transportation deterrence parameter using data on historically recorded social networks. To address the limitations of the MGM, machine learning techniques are applied, which may uncover overlooked mechanisms of social link formation, such as the self-reinforcement effect. This approach offers a more nuanced understanding of the forces that shape social networks. Additionally, an alternative accessibility-based model has been developed to shed light on the impact of non-transportation factors on long-distance travel behaviors. The model introduces a generalized social deterrence parameter, providing a novel perspective for historical analysis and highlighting the significant influence of factors beyond travel time on social dynamics.

Transitioning from a historical analysis to the context of contemporary China, Chapter 8 explores the trajectory of urban development throughout Chinese history, with a particular focus on the transformative impact of transportation advancements. This includes the construction of the Grand Canal and the introduction of the railway system. The subsequent analysis highlights the significant role of transportation and connectivity in shaping the spatial governance of modern China. The contemporary relevance of this study was showcased through discussions with international experts and government officials at a knowledge-sharing forum organized by UN-Habitat.

Chapter 9 concludes the thesis. The appendix includes technical descriptions of some models used by this study, programs developed, and a report on the overseas internship at UNESCO and the Project Based Research (PBR), which underscores potential future applications of this study for modern society and beyond.

In summary, this thesis studied transportation accessibility and presents a thorough investigation on the impact between transportation networks and social dynamics in ancient China. Utilizing an interdisciplinary methodology that integrates transportation engineering, historical analysis, network science, and machine learning, it unraveled the enduring historical socioeconomic effects of transportation infrastructure and provided discussions on future studies.

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1. Introduction

In a world where the past intertwines with the present, our story begins at the very roots of human civilization. Picture a scene from ancient times, where the survival and flourishing of our species hinged on the ingenious development of transportation. This is not just history; it is the starting point of our quest. As our story unfolds, we venture into the realm of a unique transdisciplinary approach. Here, we are not just researchers but explorers, navigating through uncharted territories of knowledge. Our journey then leads us to the core questions that propel our research ship. We are like detectives in an ancient world, piecing together clues to uncover the truths about our objectives and the contributions we hope to make. As we conclude this chapter, we are like captains overviewing a detailed map of our upcoming voyage. It is an invitation to readers to join us on this enlightening journey. As we stand at the threshold of this exploration, we realize that this is more than a study; it's a confluence of past and present, theory and practice, journeying through the lanes of transportation, urban development, and historical dynamics.

1.1 Evolving Society and Transportation

The interrelationship between transportation and societal evolution forms a rich mosaic that has defined historical trajectories and will undeniably shape the future. Throughout the annals of time, the advancement of human civilization has been inexorably linked to the constraints imposed by geology, yet the forward march of transportation technology has increasingly freed us from these earthly bonds. The essence of this dynamic was aptly summarized by Will and Ariel Durant in 1968 [1], who posited that the significance of geography will diminish over time, and the continuous evolution of transportation infrastructure is destined to alter the fabric of civilization. Yet, it is apparent that the erstwhile overriding influence of geography is gradually giving way to the sweeping changes brought about by advancements in transportation and information technology. The inception of sailing technology in the fifteenth century heralded the Age of Discovery, setting the stage for the subsequent Industrial Revolution in the seventeenth century. As we look forward, the relentless innovation in transportation promises to transform the societal and civilizational landscape once more. This shift highlights the critical need for scholarly investigation into the historical ramifications of accessibility and its far-reaching effects. Such academic endeavors are crucial for unraveling the intricate relationship between transportation technologies and societal change throughout history. This complex interplay is at the heart of historical analysis and forms the cornerstone of this research initiative.

1.1.1 Transportation and Evolving Human Species

Throughout the annals of human history and the unfolding tapestry of societal development, a subtle yet profound thread weaves its way: **transportation**. Far from being merely a physical means of movement, transportation has acted as a catalyst for civilizational advancement and societal evolution. Since humanity's initial steps on the historical stage, we have witnessed numerous moments of transformation and progress. Particularly noteworthy, as highlighted in Yuval Noah Harari's *Sapiens: A*

Brief History of Humankind, are the three pivotal revolutions that have shaped our journey: the Cognitive, Agricultural, and Industrial Revolutions [2]. Each of these revolutions is intimately tied to the development of transportation. This subsection delves into how transportation played a crucial role in the Cognitive Revolution, distinguishing us from other species, and examines the profound impacts of transportation's evolution across different eras on society, culture, and the economy.

The primary contribution of transportation to the Cognitive Revolution was its enhancement of **information flow**. The success of human society as the most successful species on Earth is largely attributed to our ability to cooperate in teams. In *Sapiens* Harari posits that the defining revolution that set us apart from other species was the Cognitive Revolution. Through the invention of shared abstract concepts, we achieved unity with large groups, allowing for the division of labor and the generation of significant energy to surpass other species. However, the first step in uniting and collaborating within groups is communication among individuals. Initially, this is highly dependent on oral transmission among people. Later, the maturation of human written language extended the scope of asynchronous communication beyond oral transmission, allowing information to be disseminated through written texts on shared media, significantly amplifying the reach of communication. Both these modes of information dissemination – oral transmission and text – heavily depend on the mobility of people or letters. In this sense, the conditions of transportation directly influence the scale of personnel and information flow, thereby determining the extent of community unification and the level of societal specialization.

The evolution of transportation has played an indispensable role in shaping human society, from the earliest days of oral traditions to the modern era of digital communication. Its impact on information dissemination, societal organization, and cultural exchange has been profound, proving that transportation is not just a means of moving people and goods, but a driving force in the advancement of civilizations.

1.1.2 Transportation and Evolving Civilization

Transportation has long been a key factor in human history, influencing the flow of information and goods and directly affecting the development levels of different regions. Before the Industrial Revolution, despite the invention of various means of transport that facilitated regional movement, such as the ancient Silk Road and the Grand Canal in China, these methods were unable to overcome the geographical barriers between continents. This limitation severely restricted the circulation of information and material resources.

Jared Diamond, a scholar renowned for his multidisciplinary approach, highlighted in his 1997 publication *Guns, Germs, and Steel*, how societies on the Eurasian continent often held an advantage in historical interactions and collisions between different continental civilizations [3]. This advantage was particularly evident in the fields of technology and culture. He attributed part of this dominance to Eurasia's abundant natural resources and extensive population base. The frequency of interactions between societies and the potential for technological progress is closely related to population size and societal mobility. The Eastern Mediterranean region and East Asia of the Eurasian continent, serving as centers of technological and cultural creation, propelled the development of the entire continent through networks such as the Silk Road and the Spice Route.

The development journey of gunpowder and firearms serves as a prime example of this phenomenon. The invention by the Chinese was improved upon by the Arabs before being introduced to Europe, where it underwent further refinement. Eventually, this technology returned to China in the form of the "Frankish cannons," a process that spanned approximately five hundred years. This example demonstrates the impact of transportation on the speed of technological dissemination: the transmission of Eurasian civilizational achievements was rapid, whereas the spread in Africa and the Americas was slower, partly due to differences in geographical shapes.

While geographical factors are significant, transportation plays a crucial role in overcoming these geographic limitations. The horizontal spread of the Eurasian continent, with similar climatic conditions at the same latitudes, reduces transportation costs, thereby facilitating more frequent and efficient exchange. Thus, transportation not only plays a role in uniting groups but also has a decisive impact on the development of human society. It is not just a tool for moving people and goods; transportation has been a driving force behind the unity of societies and the progression of human civilization [3].

1.1.3 Transportation and Evolving Global Metropolises

As shown in Figure 1-1, the flux of urban centrality across Eurasia's vast expanse is a tale not merely of economic might or political dominion but fundamentally of transportation evolution. The historical trajectory of metropolitan prominence depicted in the visual chronicle underlines the decisive role transportation has played in the rise and waning of the world's great cities. From the early agrarian-based societies flanking the fertile crescent to the sprawling metropolises abutting the coastal edges in the contemporary era, the shift in urban gravitas reflects the changing veins of transportation networks.

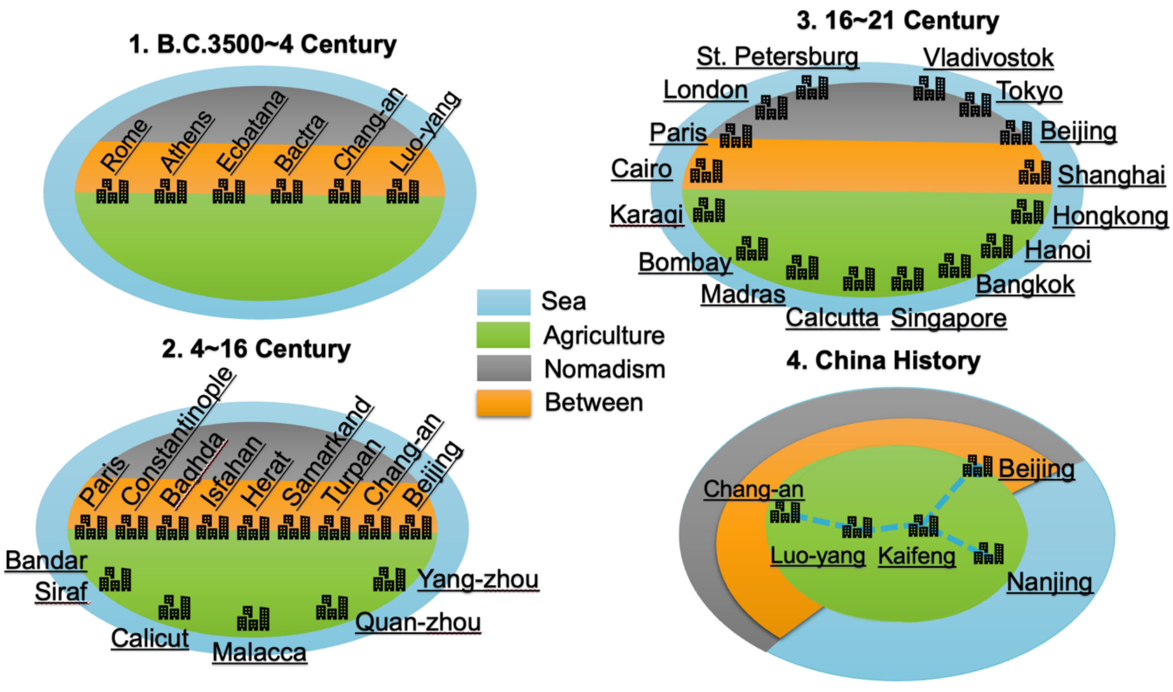


Figure 1-1. The dynamic shift in the distribution of major cities through history ([4], Fig 8, P43; Fig 20, P73).

In the pre-4th century landscape, the cradle of civilization gave rise to cities like Rome, Athens, and Luoyang, which were strategically perched at the confluence of agricultural heartlands and nomadic frontiers. This positioning near the threshold of contrasting ways of life was no accident but a conscious choice influenced by the transportation modalities of the era. The Silk Road, an emblematic route that stitched together a tapestry of diverse cultures and economies, dictated the geographical clustering of these early urban giants.

As the sails of maritime prowess caught the winds of innovation between the 4th and 16th centuries, the world witnessed the burgeoning of coastal cities like Calicut and Malacca. These cities harnessed the maritime Silk Road, translating sea-faring advancements into commercial and cultural prosperity. Yet, the preeminence of land-routed metropolises persisted, underscoring the enduring influence of overland transportation infrastructure.

The Industrial Revolution catalyzed a paradigmatic overhaul. The surge in maritime technology engendered an unprecedented dependence on oceanic transport and trade, manifesting in the urban pivot towards coastal regions. Modern behemoths like Tokyo, Shanghai, and Bombay emerged, drawing their lifeblood from the sea and relegating the once-dominant inland metropolises to historical footnotes.

China's urban evolution encapsulates this transformative narrative most vividly. With the inception of the Grand Canal, the dynastic capitals progressively migrated from the interior city of Chang'an, moving eastward through Luoyang, Kaifeng, and ultimately to the coastal proximity of Beijing. This internal migration within a single civilization underpins the overarching thesis: transportation is the cornerstone upon which urban destiny is built [4].

This examination of urban ebb and flow across Eurasia, guided by the hand of transportation, offers a profound lesson: the arteries of connectivity—be they silk roads or sea lanes—have perennially sculpted the socioeconomic landscape. As society stands on the cusp of new eras of transportation innovation, from hyperloops [5] to autonomous vehicles, this historical lens provides invaluable foresight into the potential urban transformations on the horizon. The research herein not only enriches historical and sociological discourse but also informs contemporary and future urban planning and transportation policy, ensuring that the legacy of transportation's formative impact on urban development is duly recognized and integrated into the fabric of progress.

1.1.4 A Conceptual Exploration on Accessibility: From Geographical Determinism to Transportation Determinism

The unfolding narrative of human civilization is often interpreted through various lenses of determinism, suggesting that our collective journey is shaped by prevailing forces that, in turn, are influenced by antecedent factors. Among these, the concept of accessibility as a determinant of societal development stands as a thought-provoking consideration rather than a definitive theory. This conceptual framework illustrated in Figure 1-2, while not exhaustive, invites us to reflect on how the changing modes of accessibility have influenced the course of human history.

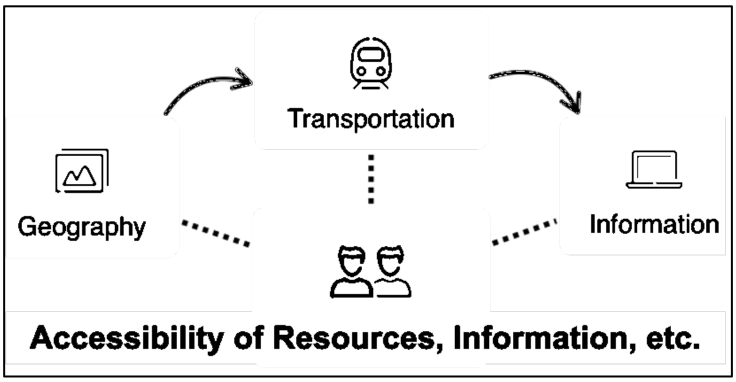


Figure 1-2. Constraints of Accessibility: from Geography to Information (own work).

Figure 1-2 serves as a visual representation of this contemplative model, illustrating the transitions from geographical to transportation and subsequently to information determinism. At the center of the schema is 'Accessibility', signifying its role as a transformative force in societal evolution. This diagram encapsulates the underlying theme: the pivotal role of accessibility in determining the flow and exchange of resources and information.

In the era delineated by geographical determinism, the physical attributes of the land were perceived as the primary influence on the development of societies. Mountains, rivers, and fertile plains were not merely the determinants of human settlement, cultural diffusion, and empire building, but also the constraints for accessibility and communication, indicating the foundational role of the Earth's topography in shaping human endeavors.

Transitioning to the age of transportation determinism, the diagram's 'Transportation' node reflects the revolutionary impact of movement and connectivity. The development of transportation – from footpaths to seafaring vessels to railroads – redefined accessibility, enabling societies to overcome geographical barriers and extend their influence far beyond their immediate environments. This expansion of reach brought about an unprecedented exchange of goods, ideas, and cultures, fundamentally altering the dynamics of power and progress.

In the current epoch, the 'Information' node indicates the advent of information determinism, where the digital revolution has further collapsed the constraints of distance and time. Information accessibility has become the new frontier of human interaction, with the Internet and telecommunications networks enabling instant connections across the globe. The diagram thus posits that in the information age, it is the availability and dissemination of information that is the primary driver of societal advancement.

It is important to emphasize that this representation is an evolving hypothesis, a scaffold upon which further scholarly inquiry can be constructed. The diagram and the associated narrative do not claim to be a definitive explanation but rather catalyze further discussion and analysis. It invites us to ponder how accessibility in its various forms has continuously redefined the possibilities for human development.

In essence, this model posits that while the mediums of accessibility have evolved, the fundamental principle that 'accessibility determines potential' remains a constant. The societies that have managed to maximize accessibility – whether it be to natural resources, transport routes, or information – have often been the ones to lead the way in the annals of history. As we advance further into the information age, the challenge lies in ensuring that the benefits of this newfound accessibility are equitably distributed, lest the disparities of the past be perpetuated in new forms.

This conceptual exploration of accessibility serves as a reminder of the fluidity of determinism and the ever-changing engines of human progress. It is a humble contribution to the ongoing discourse on the factors that shape our world, an invitation to consider how we, as a society, can navigate the complexities of accessibility to forge a more connected and equitable future.

1.2 Motivation of This Research

In light of the proposed theoretical framework of accessibility's determinism in the evolution of civilizations, this dissertation is situated as a scholarly inquiry into the historical accessibility of ancient societies and its socio-economic ramifications. The focus of this academic investigation is to elucidate the concrete mechanisms by which accessibility has sculpted the infrastructural and societal contours of early human settlements.

The exploration into the annals of antiquity is pivotal, for it provides a historical lens through which one can discern the embryonic stages of accessibility's influence. The author endeavors to map out how primeval populations engaged with their natural environments to forge pathways of commerce, cultural exchanges, and economic networks. The scrutiny of historical accessibility is posited as a crucial analytical tool, offering a window into the operational dynamics that have steered the course of human progression.

Furthermore, the socio-economic consequences derived from this historical accessibility are far-reaching, impacting urban development, societal stratification, and transnational interactions. The dissertation aims to dissect how the differential access to resources and information has historically equipped or constrained various societies, thereby contributing to an intricate understanding of the inequalities and forces that have sculpted the narrative of mankind.

The relevance of such a study to the author's doctoral research is magnified by the contemporary ramifications of these historical insights. In an era where digital inequities and imbalanced resource distribution pose significant challenges to the ideal of ubiquitous accessibility, the lessons from bygone eras assume critical importance. This dissertation, with its concentration on the historical accessibility of ancient societies and their socio-economic impacts, aspires to make a scholarly contribution to the discipline of historical sociology and to offer a pertinent discourse on the enduring issues of access, equity, and societal advancement.

The dissertation underscores the contention that the paradigm of accessibility has been, and remains, a driving force in the narrative of human history. With this scholarly work, the author aims to not only advance academic discourse but also to provide a meaningful framework for understanding and addressing the persistent challenges of accessibility that confront contemporary global society.

However, related studies on quantitative historical transportation are rarely done. The main reason is the lack of historical data. Different from the previous research in this field, this thesis contributes in the following ways:

1. Historical Studies Based on Quantitative Analysis. Most studies on historical transportation are done descriptively. This research rebuilds the historical transportation system and calculates the historical accessibility to picture historical transportation in a more precise way.
2. Ex-post Research based on Historical Transportation. Usually, ex-ante studies are more common than ex-post studies as they happen at the time when money has been distributed. Nevertheless, ex-post analysis is usually more comprehensive because it is based on the facts of changes induced by transportation.
3. Long Scale of Time Range. Most studies on accessibility focus on the modern age. This research is based on the massive data collected more than 1000 years ago. It is believed that the long scale of time range can be useful to draw a universal conclusion.
4. Large Geographical Scope. The research subject – China, had a long history as a unified empire, which has a unified culture and nation. These kinds of characteristics can reduce the political border effects. It is easier to show the differences between transportation methods in the broad geographical scope. More details on the research subject will be discussed in Section 1.3.

The originality of this research also brings its challenges. Just like the reason why related work is rarely done, the available historical data is not complete nor accurate. Therefore, on the one hand, data collecting work needs to be done, including filling the historical blank with pertinent related data. Moreover, proper models and methods in engineering and socioeconomics should also be established. It is necessary to use some estimated data instead of known values and understand some resemble assumptions rather than confirmed facts. Nevertheless, completeness, scientific rigor, and accuracy, should also be considered, which might be the biggest challenge of this research.

The methodology of this study is inspired by the principles of engineering, which aim to systematize and refine processes to achieve maximum efficiency. Engineers, with a meticulous eye for detail, craft machines, structures, and complex systems to meet precise functional demands. In transportation engineering, well-conceived infrastructure is pivotal for enhancing local socioeconomic strength while optimizing resource utilization. Cost-benefit analyses are indispensable in evaluating infrastructure projects, requiring engineers to quantify and elucidate the intricate links between transportation and societal dynamics to inform the pursuit of optimal engineering solutions.

In contrast, the core substance of this research is akin to the work of historians, who sift through historical records to decode the underlying currents that have shaped the progress of civilizations—currents that are often not immediately apparent. This research departs from modern studies by venturing into the depths of the past to trace the enduring effects of transportation over broad chronological and geographical scopes. Our history is punctuated by several landmark revolutions in transportation technology, each heralding new possibilities for mobility and promising solutions to longstanding transportation challenges. Nonetheless, persistent issues like congestion continue to plague our societies. The fleeting relief brought by new transport capabilities is often quickly offset by rising demand, leaving fundamental problems unresolved. Therefore, this research endeavors to synthesize the features of diverse transport modes into a coherent framework and scrutinize their enduring impacts, with a particular focus on historical data. Understanding the past provides a clearer lens through which to view and shape the future.

This inquiry begins with an analysis of eras amenable to quantitative evaluation, seeking to discern the foundational impact of transportation over extensive periods—not just decades, but centuries and millennia. The relative simplicity of ancient societies offers a transparent window for examining the relationships between transportation and various social indices. The sustained influence of transport on society can be authenticated through the analysis of data spanning centuries. Take, for instance, the construction of the Grand Canal, which has left a lasting imprint on Chinese history by gradually shifting the nation's economic and political centers.

Despite the intrinsic value of this historical approach, researchers face significant challenges, notably the scarcity of uninterrupted data. Even with thorough data collection efforts, the study is constrained by intermittent historical data points, which hinders the construction of a seamless narrative of progression. However, the typically incremental nature of change in ancient societies allows for the extrapolation of historical trends by examining key periods. By leveraging representative data such as demographic statistics related to economic output and consumption, and social networking data for analyzing cross-regional communication, this study aims to overcome the limitations of data scarcity and shed light on the sophisticated interplay between transportation and societal growth.

This research delves into the quantitative assessment of ancient China's transportation accessibility and its socioeconomic implications, with a focus on population distribution and social networks. It also explores the broader effects of historical transportation on the distribution of government officials, exile destinations, the production of poetry, and the spread of pandemics. Throughout, we underscore accessibility as the linchpin of social advancement. The discourse on contemporary transportation development in China and its paramount importance in spatial planning worldwide underscores the enduring significance of transportation throughout history and across the globe. Through these discussions, we aspire to create a conduit linking modern and ancient societal transportation developments via the concept of accessibility. By understanding the impact of transportation in the past, we can derive insights for future societal advancements predicated on the features of emerging modes of transport.

1.3 Research Questions and Subject

1.3.1 Research Question in Detail

The profound impact of transportation on the fabric of society is an assertion easily made yet demands empirical substantiation. This research delves into the depths of this assertion, as highlighted in Section 1.1, seeking to validate it through a rigorous quantitative analysis. Three fundamental questions serve as the cornerstone of this investigation:

Q1. What metrics effectively quantify **transportation** networks throughout history and how have these evolved?

Q2. How can the long-term **influence of transportation** networks on society be quantified?

Q3. What methodologies enable the isolation and identification of the **causal or correlative links** between transportation and societal evolution?

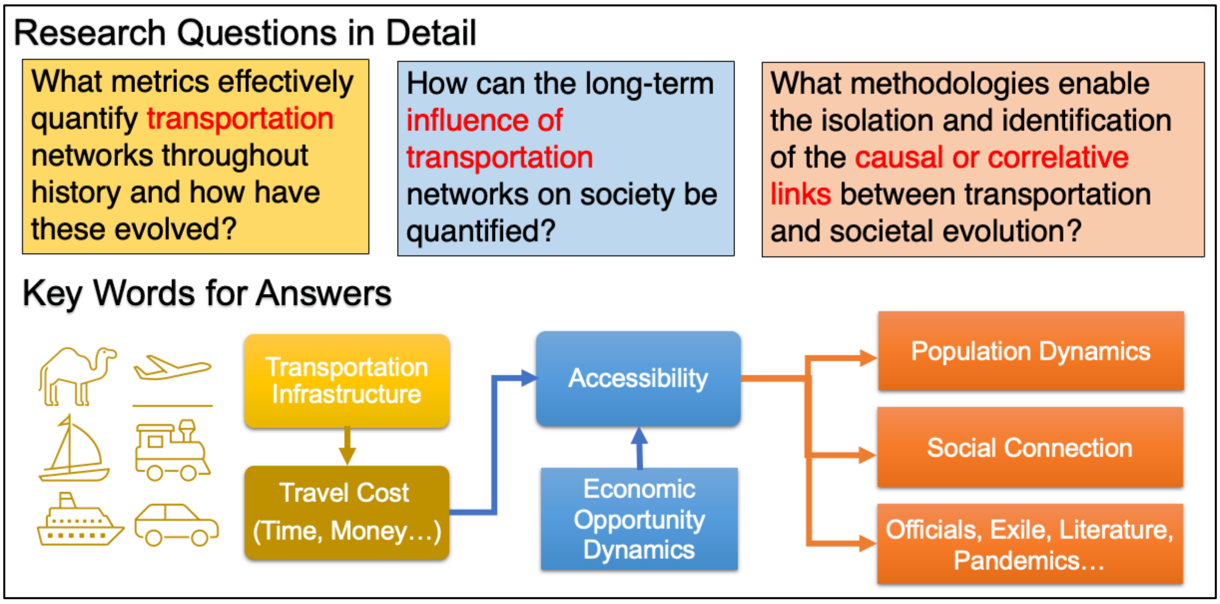


Figure 1-3. Research questions in detail and key words for answers.

Addressing the first inquiry, this study adopts travel cost, with a particular focus on **time cost**, as the primary quantifiable metric. The assessment of transportation network functionality necessitates a comprehensive evaluation of the vehicles pivotal during the relevant historical periods, including their inherent characteristics. For ancient Chinese epochs, this research focuses on terrestrial wagons and riverine ships, examining their capabilities to enhance the mobility of commodities and individuals. Such mobility is characterized by variables including speed, operational range, and cost, with velocity serving as the paramount measure for appraising the contribution of different transportation modes. A detailed exposition of these metrics is presented in Sections 3.1 and 3.2.

The second question places the concept of **accessibility** at its core, which also constitutes the central theme of this research. Alterations in accessibility across various locales precipitate shifts in population dynamics, societal linkages, and the dispersion of governance, among other social variables. The intent behind all transportation infrastructure and vehicular development is to augment the movement of people, goods, and information. It is crucial to recognize that all movement is purposeful, dictated by the distribution of resources and populations that define the origins and terminations of transit. Transportation shapes the cost of movement, while social dynamics influence its direction. This synergy, encapsulated in the term Accessibility, offers a genuine reflection of transportation realities and their societal repercussions. Within the constraints of historical data, this study prioritizes population distribution, with the relevant theoretical frameworks discussed in Section 2.1 and the operational definition of Accessibility elaborated in Section 3.3.

The third and perhaps most pivotal question leads to the crux of this research. Accessibility is envisaged as the conduit between transportation and societal structures. Capturing this interplay necessitates an analysis of which social changes can be attributed to transportation influences. Economic dynamics and inter-regional communication emerge as principal facets of this exploration. Given the absence of ancient economic indices comparable to modern Gross Domestic Product (GDP) measures, population dynamics serve as proxies for economic vitality in agrarian-based societies. Consequently, the movement and interactions of Chinese elite networks offer insights into historical patterns of long-distance communication, as these were typically undertaken by individuals with sufficient means and motivation for travel. These indicators are instrumental in delineating the transformative effects prompted by transportation accessibility. Additional indicators employed in this study aimed to elucidate changes in other societal dimensions during the Tang dynasty, further illustrating the intricate tapestry of historical societal transformation driven by the evolution of transportation.

1.3.2 Research Subject: Why Ancient China?

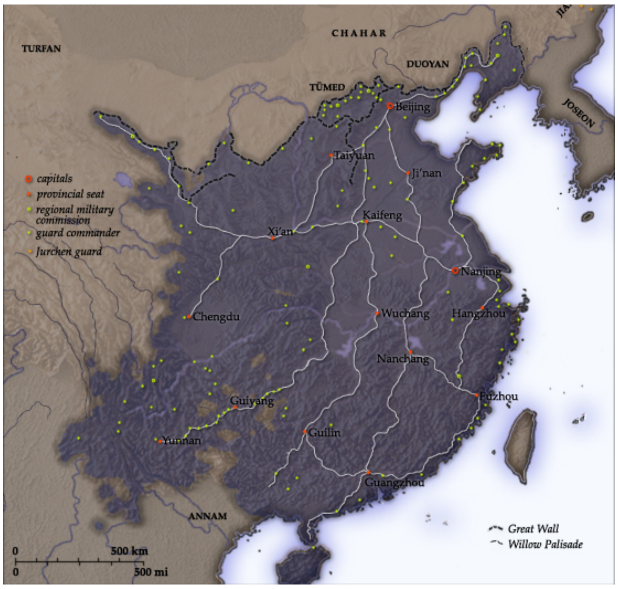
This research systematically explores the ancient periods preceding the last dynasty, a time marked by the introduction of Western technology and significant societal transformation. Chapter 5 offers a comprehensive overview of all periods for which data is available. However, the Tang dynasty is pivotal for encompassing all necessary discussions, including population dynamics, social networks, and border aspects. This section elucidates why China especially the Sui-Tang Periods is the focal point of our study. To investigate historical accessibility over extensive time and geographical scales, several critical factors are considered:

Reaon 1. Political Stability: We prioritize a large, unified empire with enduring political homogeneity, as this minimizes the influence of political borders on our study.

Reaon 2. Historical Transportation Data: It is essential to have complete and sufficient documentation on historical transportation for a thorough analysis.

Reaon 3. Societal Data: Comprehensive social data, such as population dynamics and social networks, are crucial for understanding the interplay between transportation and society.

Reaon 4. Continuous Transportation Development: The history of transportation development, marked by significant milestones, underscores the importance of transportation changes.



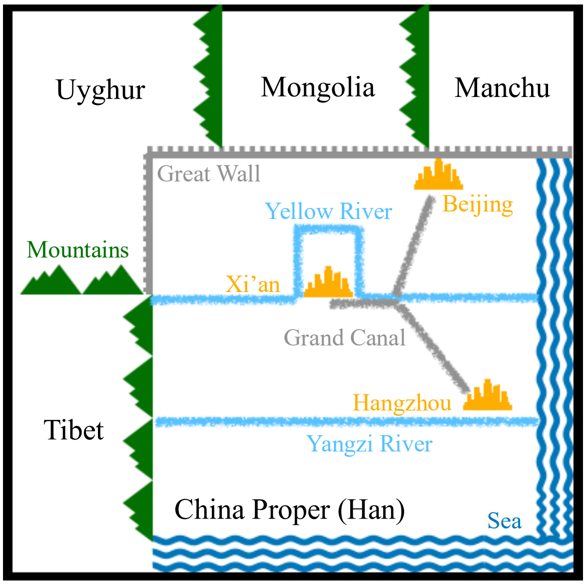


Figure 1-4 (Left). Approximate extent of China Proper during the late Ming Dynasty [6].
Figure 1-5 (Right). Spatial Structure of China during the Qing Dynasty ([7], Fig2).

Firstly, China's historical political stability is noteworthy. Since its unification in 221 B.C. by the first emperor, China has predominantly been a unified empire. As illustrated in Figures 1-4 and 1-5, China can be categorized during the Qing Dynasty into five distinct regions based on national composition: China Proper (Han), Tibet, Uyghur, Mongolia, and Manchu. Despite fluctuating boundaries across dynasties, China Proper (Han) consistently remained central to the empire, housing over 90% of the population. Figure 1-4 delineates China Proper as the primary geographical scope of this research. The shared culture and political structure within this region imply minimal boundary effects. Geographically, China Proper is relatively isolated, bordered by the sea in the south and east, the Great Wall in the north, and mountains in the west. This geographical setting contributes to cultural and political homogeneity, a trend that persists into modern times, enabling continuous research.

Table 1-1. Revolutionary Changes in Transportation in the History of China.

Age	Represent Year (C.E.)	Revolutionary Changes in Transportation
Qin-Han Age (221B.C.~220 C.E.)	2	The first national road system was built.
Shui-Tang Age (581 C.E.~907 C.E.)	742	The Grand Canal was built.
North Song Age (960 C.E.~1127 C.E.)	1102	The economic center was shifted to the south.
Yuan Age (1271 C.E.-1368 C.E.)	1290	The first global trade system was once built, the trade with other countries reached the highest level in ancient times.
Ming-Qing Age	1820	Trade with other countries is almost stopped.

(1368 C.E.~1912 C.E.)		Regional division of production was formed.
Modern Age (1912 C.E.~1978 C.E.)	1934 1978	Western transportation technology was introduced.
Contemporary Era (1978 C.E. ~ Now)	2016	International communication reaches the highest level.

Secondly, historical transportation and societal data in China are readily accessible. China's rich tradition of historical record-keeping enhances the availability of such data. Although firsthand documentation on historical transportation is limited, extensive research reconstructing China's historical transportation network supports this study. Accessible social data, like population dynamics, enriches our understanding. The earliest existing national population census data dates back over 2000 years, with further details discussed in Section 3.1.

Table 1-1 showcases key transportation changes in Chinese history, serving as a vital reference for selecting the appropriate study area. The table emphasizes ancient periods, with specific years chosen based on data completeness, such as population distribution. Stable political and economic conditions in the empire, often reflected in the thoroughness of data, typically enabled comprehensive national population censuses.

1.3.3 Transportation and Urban Development in Ancient China?

The enduring influence of transportation on urban development from ancient times to the present, can be reflected in its role in shaping cities, economies, and political strategies. In ancient China, transportation networks like the Grand Canal played a pivotal role in determining the economic and political centers. The Sui and Tang dynasties saw the rise and fall of capitals like Chang'an and Luoyang due to transportation shifts. Environmental crises and political changes led to shifts in economic hubs along the canal, with cities like Kaifeng rising to prominence.

During the Northern Song period, Kaifeng emerged as a major economic and trade hub due to its location on the Grand Canal [8]. The Song Dynasty's shift to Hangzhou marked a significant movement towards the Jiangnan region, benefiting from thriving port trades. The Yuan dynasty further developed the Grand Canal, shifting the economic center eastward and boosting cities like Tianjin. The Ming and Qing dynasties saw the rise of commercial cities in the Jiangsu-Zhejiang region, propelled by the Grand Canal.

The strategic locations of port cities like Shanghai, Tianjin, and Guangzhou became more significant with the opening of international trade ports following the Opium War. These cities grew due to their maritime and riverine trade advantages, along with their roles as administrative and economic centers. The integration of railways and shipping networks in the modern era transformed these cities into manufacturing hubs, attracting rural populations, and leading to rapid urban expansion.

Cities in North and Northeast China evolved around transportation hubs, reflecting a shift towards commercial and industrial roles [9]. The traditional layout of cities along the Grand Canal and major rivers evolved with the development of ports and railways, leading to a reorganization of urban functions. This highlights the critical role of transportation in urban planning and development, a trend that continues in contemporary times.

1.4 Structure of This Thesis

The thesis presented in Figure 1-6 endeavors to quantitatively address the research inquiries posited in Section 1.2. Chapter 1 lays the groundwork by elucidating the thesis's motivation, significance, and overarching context.

In Chapter 2, we delve into previous research and foundational theories. Section 2.1 explicates the pivotal concept of Accessibility, while Section 2.2 explores research related to historical modes of transportation. The intricate relationship between transportation systems and societal dynamics, with a particular focus on population trends, is highlighted in Section 2.3.

Chapter 3, dedicated to the Sui-Tang Periods, responds to the initial two research questions posed in Section 1.2. It begins with an overview of the modeling process, encompassing historical data management (Section 3.1), computation of travel times (Section 3.2), and defining accessibility (Section 3.3). Subsequently, it presents and interprets the results of this model. Discussions on Accessibility across different modes of transportation, including roads, rivers, and canals, are found in Section 3.4, where the Grand Canal's role is also substantiated. Further, Sections 3.5 and 3.6 delve into provincial and individual-level Accessibility, respectively.

Chapter 4 investigates the correlation between transportation and population dynamics during the Sui-Tang Periods. It examines population trends and influential factors in Section 4.1, conducts regression analysis and its optimization in Section 4.2, and deliberates on the societal implications of the developed model in Section 4.3.

Chapter 5 shifts the focus to the historical accessibility in other ancient periods, namely the Han, Song, and Ming dynasties. Section 5.1 underscores the importance of studying these eras. Section 5.2 elucidates the data sources available, and the reconstructed transportation networks, followed by the accessibility results in Section 5.3 and discussion in Section 5.4.

Chapter 6 presents a comprehensive exploration of the role of social networks and accessibility among the elite in ancient China, revealing their significant impact on transregional economic and societal structures. Beginning with Section 6.1, it highlights the crucial role of elite social networks in shaping economic and political landscapes, establishing a foundational understanding of their importance in historical research. Section 6.2 transitions to the methodology of gathering and processing historical data for social network analysis, emphasizing the meticulous approach required to uncover the social fabric of ancient times. In Section 6.3, the chapter navigates through different Chinese dynasties, illustrating the evolution of social connections and their societal impacts over centuries. Section 6.4 introduces analytical models to quantify and visualize these connections, underscoring the influence of transportation and travel time. Section 6.5 expands on this by exploring machine learning insights into the "self-reinforcement effect" within populous city interactions. Section 6.6 focuses on the accessibility model, examining societal openness to long-distance travel and its influence on political and economic systems. Finally, Section 6.7 concludes by summarizing the key findings and their implications, encapsulating the interconnectedness of transportation, social engagement, and societal dynamics in ancient China, and how the elite's movements and connections shaped the historical landscape.

The seventh chapter introduces the historical accessibility database developed within this study. Section 7.1 explains the general contents of the database. The following sections broaden the related applications of this database. It discusses the distribution of government officials and its correlation with historical accessibility in Section 7.2, the spatial distribution of literary poets and its connection to historical accessibility in Section 7.3, and the frequency of historical pandemics concerning transportation accessibility in Section 7.4.

Chapter 8 explores the trajectory of urban development throughout Chinese history, with a particular focus on the transformative impact of transportation advancements. This includes the construction of the Grand Canal and the introduction of the railway system in Section 8.1. The subsequent analysis in Section 8.2 highlights the significant role of transportation and connectivity in shaping the spatial governance of modern China. The contemporary relevance of this study was showcased through discussions with international experts and government officials at a knowledge-sharing forum organized by UN-Habitat. Section 8.3 presents integration between the theoretical research and onsite practice at international organizations.

Finally, Chapter 9 synthesizes the thesis, highlighting its key conclusions and contributions. These include methodological advancements in historical studies, qualitative insights into ancient China, and the exploration of transportation's multifaceted social impacts.

The appendix attached includes technical descriptions of some models used by this study, programs developed, and a report on the overseas internship at UNESCO and the Project Based Research (PBR), which underscores potential future applications of this study for modern society and beyond.

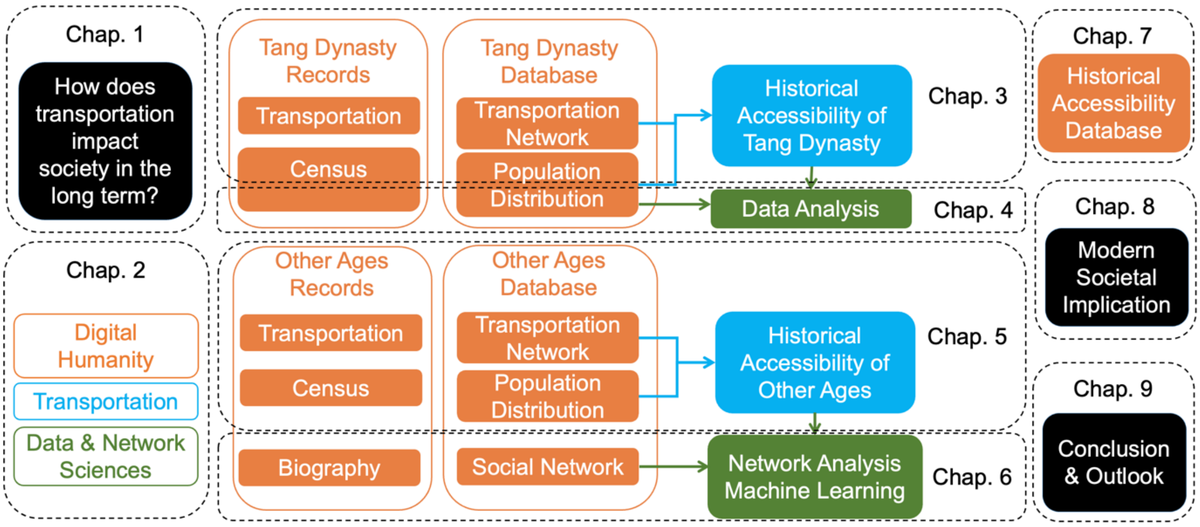


Figure 1-6. Structure of This Thesis.

2. Literature Review

As we turn the page to Chapter 2, imagine entering a grand library of time, where each book and scroll unravels the mysteries of transportation and its profound impact on civilizations. This chapter is our lantern, illuminating the paths walked by scholars before us. Our first stop in Section 2.1 is a room dedicated to the essence of our study: Transportation Accessibility. This section is like a historian's journal, chronicling the evolution of thought and understanding in this critical area. Next, we shift our gaze to a gallery of historical research on transportation in Section 2.2. Envision rows of artifacts and texts, each telling a story of past journeys and methodologies. This section is akin to a time-traveler's conversation with historians, exploring the rich data that forms the backbone of our analysis. As we delve deeper, we encounter a crossroad where transportation meets society in Section 2.3. Imagine a bustling ancient marketplace where ideas of the past and present intersect. This section is a dialogue between eras, revealing how contemporary concepts can shed light on the societal dynamics of ancient times.

2.1 Transportation Accessibility

Accessibility is a crucial term in transport research, In the literature, it is generally defined by some formula like Equation (2-1). It quantifies the total availability of opportunities in a particular location. The value of accessibility depends on generalized travel costs $f(\mathrm{cost}_{ij})$ and the spatial distribution of opportunities $\mathrm{Opportunities}_j$ which can be indicated by population, jobs, or other factors. Accessibility in location *i* is the sum of all opportunities in all places *j* weighted by the cost between *i* and *j*. The value of accessibility can be viewed as the sum of two kinds of contributions: *local contributions* $\mathrm{Opportunities}_i \cdot f(\mathrm{cost}_{ii})$ and *remote contributions* from other places $\sum_{j\neq i} \mathrm{Opportunities}_j \cdot f(\mathrm{cost}_{ij})$. The influence of other places is captured by cost function *f*.

$$\text{(General definition)} \quad \mathrm{Accessibility}_i = \sum_j \mathrm{Opportunities}_j \cdot f(\mathrm{cost}_{ij}). \tag{2-1}$$

A variety of different approaches to defining the cost function were formulated in mathematical terms [10]. The first attempts typically weigh the locations according to their size, as Stewart-Warntz (1958) [11] measured in Equation (2-2) and Hansen (1959) [12] measured in Equation (2-3). The size is measured with respect to quantities such as population, resources, etc. The separation is measured with respect to distance, travel cost or time, and other similar spatial impedance variables, simulated by a gravity-based approach, and *b* is a pre-defined constant. The cost function is a decay function.

$$(\mathbf{Stewart-Warntz's\ Defination}) \quad \mathrm{Accessibility}_i = \sum_j \mathrm{Size}_j \cdot \mathrm{Seperation}_{ij}^{-b}. \tag{2-2}$$

$$(\textbf{Hansen's Defination})\quad \text{Accessibility}_i = \sum_j \text{Size}_j \cdot \exp\left(-b \cdot \text{Seperation}_{ij}\right). \tag{2-3}$$

Other researchers took a different approach from the above tracks. Ingram (1971) [13] defined the Accessibility at location *i* as the sum of the spatial separations from all other locations *j* to that location, shown in Equation (2-4). Allen et al. (1993) first proposed the normalization of Accessibility, which produces the mean spatial separation. As shown in Equation (2-5), based on which, they developed a new index E for a given area by integrating the integral accessibility index over the points within the area, which is given in Equation (2-6). Their assumption of equality except spatial difference reflects the transportation contribution only. This means a centralized location in the transportation network will tend to have lower accessibility than a peripheral one. In order to inquire about the interplay between transportation and society, this approach is not useful for this study.

$$(\textbf{Ingram's Defination})\quad \text{Accessibility}_i = \sum_{j \neq i} \text{Seperation}_{ij}. \tag{2-4}$$

$$(\textbf{Allen et al.'s Defination})\quad \text{Accessibility}_i{}' = \frac{1}{n-1} \sum_{j \neq i} \text{Seperation}_{ij}\,. \tag{2-5}$$

$$E = \frac{1}{n} \sum \text{Accessibility}_i{}' = \frac{1}{n(n-1)} \sum_i \sum_{j \neq i} \text{Seperation}_{ij}\,. \tag{2-6}$$

Except for the consideration of spatial separation only, most of the recent formulations of accessibility indicators are particularly suited to address a specific transportation problem. In general, there is no single best formulation. Among the recent literature, travel cost, potential, cumulative opportunities, and network efficiency indicators are the most used [14][15].

The most models illustrates below took the population as the indicator for opportunities. Travel cost is widely used in accessibility studies [16], a calculated weighted average travel time from each location to all destinations, as shown in Equation (2-7) [17]. The gravity-based approach is another type of common accessibility measure, which is a potential indicator. The opportunities or accessibility interacted between different locations are positively related to the destination's size and inversely proportional to some power of distance or travel cost between both locations. A general formation is included in Equation (2-8). Cumulative opportunities indicators estimate Accessibility in terms of opportunities available within predefined limits of travel time or distance [18]. Calculation of daily Accessibility is a good example, in which most traffic is limited to trips within a specific time range like several hours. For example, the daily round trip can be simulated when the time range is set as 4 hours, as shown in Equation (2-9), where $\delta_{ij} = 1$ if travel time is less than 4 hours and $\delta_{ij} = 0$ otherwise. Network efficiency accessibility indicators is an entirely different approach, which takes the traffic flow and other realistic factors into consideration. Therefore, this approach recognizes the gap between actual travel time and ideal travel time measured as “as the cow flies” travel time using an ideal transport infrastructure. Its formulation is shown in Equation (2-10) [19].

$$(\textbf{Weighted Travel Time})\ \text{Accessibility}_i = \frac{\sum_{j=1}^{n} \text{Population}_j}{\sum_{j=1}^{n} \text{Time}_{ij} \cdot \text{Population}_j}. \tag{2-7}$$

$$(\textbf{Gravity}-\textbf{based})\ \text{Accessibility}_i=\sum_{j=1}^{n}\frac{\text{Population}_j}{(\text{Distance or Cost})_{ij}^{\alpha}}. \tag{2-8}$$

$$\text{Daily\_Accessibility}_i=\sum_{j=1}^{n}\text{Population}_j\cdot\delta_{ij}\,. \tag{2-9}$$

$$\text{Efficiency\_Accessibility}_i=\sum_{j=1}^{n}\frac{\frac{\text{Actual\_Travel\_Time}_{ij}}{\text{Ideal\_Travel\_Time}_{ij}}\cdot\text{Population}_j}{\sum_{k=1}^{n}\text{Population}_k}. \tag{2-10}$$

In this research, due to the data incompleteness, we chose the cost function mainly depending on travel time only. Due to the large scale of the research subject, it is more realistic not to consider spatial separation as a linear weighted factor. Equation (2-7) might not be a good approach to take. It is also not proper to just consider the trips within a specific time range because of the broad scope, which makes a solution like Equation (2-9) out of consideration. There is also no data to simulate the gap between actual travel time and the ideal travel time. Therefore, the method of Equation (2-10) is also not possible.

In this research, the accessibility function is a gravity-based approach in which the cost function is a decay function with a weight factor, as shown in Equation (2-11). Generalized time costs are weighted by an exponential factor β, which is similar to Hansen's accessibility approach. The details of factor selection and definition will be discussed in Section 3.3.

$$(\textbf{Defination used in this study})\ \text{Accessibility}_i=\sum_{j}\text{Population}_j\cdot\exp\left(-\beta\cdot\text{Time}_{ji}\right). \tag{2-11}$$

Besides the recent research on the mathematical formulation, several theoretical studies on the concept of accessibility need to pay attention to. Scholars often make a distinction between person accessibility and place accessibility. Even if the two terms are used interchangeably, and both notions are often referred to as accessibility, it is necessary to clarify the difference between them [20]. Person accessibility is an attribution of a person: a person has Accessibility or not to a specific set of locations. Place accessibility, in turn, is an attribution of location: a location is accessible or inaccessible for a particular set of people or from a specific set of other locations [21][22][23]. In this research, accessibility means place accessibility.

Due to vehicles' effects, geographical conditions, and other factors, travel cost differs according to different directions, despite the same route. The general formation as Equation (2-1) measures the active Accessibility, which indicates how easy the specific location i to reach others (the cost from i to j). In contradistinction, passive accessibility describes how easy it is to be reached by others (the cost from j to i). Which accessibility definition should be used mainly determined by what kind of traffic flow is preferred to be simulated. In this research, the described transportation is mainly the traffic flow of massive goods. Whether a specific location can reach goods or not relies more on whether the goods can be transported to this location. Therefore, the general form of accessibility calculation is passive accessibility, as shown in Equation (2-11).

Some researchers brought up the concept called General Accessibility [24], which is only possible if massive data is available, and the developed model should be close enough to reality. Accessibility developed now is usually just measured for a particular place by a particular mode for a particular purpose at a particular time in a particular year. General Accessibility is derived as a theoretical ideal that would be measured for all places, all modes, and all purposes, at all times, over the lifecycle of transportation infrastructure. It is posited that more general access measures better explain spatial location phenomena. Even though historical accessibility research cannot reach this kind of accuracy, the comparison study over different periods can be considered a contribution to General Accessibility.

2.2 Historical Study on Transportation

Many researchers have made outstanding contributions to accessibility research. Nevertheless, most of them are focused on modern times, among which many of them are ex-ante studies for the evaluation of planned infrastructures. Nowadays, ex-ante studies are politically more relevant than ex-post studies as they happen at a time when money has been distributed amongst competing projects. The ex-post studies on completed projects, especially for the ancient time, are very few. In this section, two kinds of historical studies on transportation will be discussed: the descriptive or collective studies dedicated to restoring the transportation system in the past, and the quantitative studies devoted to the analysis based on the historical data. The main works are as shown in Table 2-1. They are classified into four groups based on their different research approaches (Traditional collection, Mapping Atlas, and GIS digitalization) and research subjects (China or other regions).

Table 2-1 Previous Research on Historical Transportation of China and Other Regions

Topics	Researcher / Institution / Research Works	Significance
Traditional Study	Bai Shouyi, Chinese Transportation History (1937) [26]	First comprehensive study on this field
	Yan Gengwang, Mapping Research on Transportation of Tang Dynasty (1985) [27]	Most outstanding and comprehensive research in historical transportation
Atlas Study	Tan Qixiang, The Historical Atlas of China (1982) [28]	Mapping on primeval administrative divisions
	Chen Cheing-Siang, Historical and Cultural Atlas of China (1982) [29]	First atlas related to historical transportation
	Wang Jiaoe, The Concise Historical Atlas of China's Transport Network (2018) [30]	Latest comprehensive atlas
Digital Study (GIS)	Fudan & Harvard University, China Historical Geographic Information System (CHGIS) [31]	First work on GIS study of historical China
	Academia Sinica, Basic Framework on Chinese Civilization in Time and Space [32]	GIS work on historical Foundation of this research
	Chu Kaiyu, Tang Dynasty Transportation Map and Movement through the Tang Empire (2014) [34]	
Study on Other Regions	Batten, B., To the Ends of Japan: Premodern Frontiers, Boundaries, and Interactions (2003) [35]	Distinguish of different traffic flow in ancient Japan
	Raphael Fuhrer, Modelling Historical Accessibility and Its Effects in Space (2019) [36]	The latest study on Switzerland; Foundation of this research
	Dalgaard, Carl-Johan and Kaarsen, Nicolai and Olsson,	The latest study on the

	Ola and Selaya, Pablo. Roman Roads to Prosperity: Persistence and Non-Persistence of Public Goods Provision. (2018) [37]	Road System of Roman Empire
	Wahl, Fabian. The long shadow of history: Roman legacy and economic development - evidence from the German limes (2015) [38]	
	Zhou J., Yang Y., Webster C. Legacies of European 'Belt and Road'? Visualizing transport accessibility and its impacts on population distribution (2019) [39]	

Because the research subject is specifically decided, the descriptive studies and collective studies described in this section are all about Ancient China. Even though China had a tradition of historical studies and documentaries, historical transportation studies almost had no position. Fragments of the documentary on transportation are intended to introduce etiquette sets, which cannot reflect transportation's actual situation. The specialized studies on historical transportation began in the early 20th century [25]. Bai Shouyi's "*Chinese Transportation History*" (1937) was considered as the first comprehensive study on this field [26]. Yan Gengwang took over 40 years to finish "*Mapping Research on Transportation of Tang Dynasty*" [27], which is approved as the most outstanding work in this field. Yan restored the whole picture of the transportation system during the Tang Dynasty based on massive historical documents, with discussions on the impact of transportation on politics, economy, military, and culture. His research is an excellent foundation for this thesis. The digital map utilized in this thesis is also drawn based on his research.

As for the cartography studies on Ancient China's transportation system, the following are the crucial references for this thesis. Before the 1980s, the Chinese academic circles were not able to systematically compile historical and cultural atlases. Most of the works were limited to territorial changes confined to dynastic boundaries and primeval administrative divisions. Tan Qixiang's "*The Historical Atlas of China*" (1982) [28] placed the foundation for research in this field. Chen Cheing-Siang's "*Historical and Cultural Atlas of China*" (1982) [29] is the first book related to historical transportation, which compiled a set of maps for each prominent dynasty, especially Han, Tang, Song, Ming, and Qing, to show the territorial extent, administrative divisions, population, cities, transportation, industries, personages, and products. Wang Jiao et al.'s "*The Concise Historical Atlas of China's Transport Network*" [30] is the latest research on the historical transportation network of ancient and modern times. The atlas of ancient times includes roads, canals, and international transportation. The atlas of modern times include railways, airlines, roads, waterways, and pipe transport.

With the development of computer technology, especially the Geographic Information System (GIS), more and more researchers have devoted themselves to historical transportation digitalization. "*The China Historical Geographic Information System (CHGIS)"* [31] initiated by Harvard University is one of those first attempts: a free database of placenames and historical administrative units for Chinese Dynasties. "*Basic Framework of Chinese Civilization in Time and Space*" published by Academia Sinica [32] aims to construct an integrated GIS-based application infrastructure within China's spatial extent, in the timeframe of Chinese history, and with the contents of Chinese civilization. There are also many types of research contributing to the "*Harvard WorldMap"* [33], which is an online, open-source mapping platform developed to lower barriers for scholars who want to explore, visualize, edit, and publish geospatial information. Several data sources for this research were obtained from this platform. The data on historical transportation used by this thesis is done by Chu Kaiyu [34], who digitalized the transportation information collected in Yan Gengwang's "*Mapping Research on Transportation of Tang Dynasty"* (1985). Details on the data management are discussed in Section 3.1.

Analytical research on historical transportation is rarely done due to the lack of related data. Batten, B.'s "*To the Ends of Japan: Premodern Frontiers, Boundaries, and Interactions*" (2003) [35] recontacted the historical transportation network into different categories, including political and military interactions, the network for bulk goods, the network for prestige goods, information network and international communication. Different approaches should be utilized for simulations of different types of transportation. Raphael Fuhrer (2019) [36] deals with the modeling of historical Accessibility, covering Switzerland and neighboring regions from today until 1720. Fuhrer details methods to reconstruct historical transport networks and corresponding travel system times and shows applications of such results regarding state reach and productivity gains. Fuhrer's research is one of the studies on historical transportation on a large scale and extended range of time, which was an excellent reference for this research. Details of Fuhrer's model and its application in this research are discussed in Chapter 3.

Various studies have been done on the Roman Road system, which offers a unique perspective on the historical influence of transport infrastructure on economic and urban development, providing valuable insights into the interplay between historical legacies and contemporary socio-economic landscapes. Dalgaard et al. [37] explore the long-term impact of ancient Roman roads on modern road infrastructure and economic activity across Europe. It utilizes a comprehensive dataset on Roman road networks and examines their correlation with present-day road infrastructure and economic outcomes. Their study reveals both persistent and non-persistent influences, providing insights into the enduring legacy of historical infrastructure on contemporary economic geography. Wahl [38] investigates the lasting influence of Roman road networks on the development of French cities. By analyzing the alignment of modern French road networks with ancient Roman roads, Wahl [38] demonstrates a significant correlation. It suggests that historical transport networks set path-dependent trajectories, influencing urban development patterns and the spatial distribution of economic activity in France. Zhou et al.'s research [39] provides a historical perspective on Europe's transport networks and their influence on population distribution. It compares the Roman and Medieval European transport infrastructures with China's modern Belt and Road Initiative. The study uses historical maps and population statistics to analyze the evolution of transport networks and their varying impacts on economic prosperity and population growth in Europe, emphasizing the role of multiple factors in sustainable development.

2.3 Interplay between Transportation and Society

This section introduces the theoretical foundations of new economic geography, which is related to transportation geography and the interplay between transportation and society. The first related research on transport and land use interaction started roughly 200 years ago [40]. As Thisse [41] summarized, there have been three main developments in past research:

1. Land use and urban economics started with von Thünen [40] in 1826. The main idea is that transportation is necessary for the economy but at costs. Producers and consumers will make spatial decisions corresponding to the transportation network.
2. The nature of competition across space started with Hotelling [42] in 1929. The main idea is

that every unit of space can only be used by one agent. Due to the difference between locations or other characteristics, some space is more popular than others, which means competition existing.

3. New economic geography and the emergence to describe economic agglomeration started with Krugman [43] in 1991, which intended to model the dispersion and agglomeration with the increase of mobility. Decreasing transportation costs allows agents to separate the producing location with consumers.

Related to the interplay between transportation and society, Fuhrer (2019) [36] did an extensive study, which looks at the current state of the art in ex-post analyses dealing with quantification of transport induced changes (including economy and society, excluding environment) worldwide. The addressed topics include the effect on population dynamics, land or property prices, the job market, the economic structure, different measures of productivity, and poverty/growth issues. Most researched topics are related to jobs and population.

As for this research, due to the lack of related data on ancient times, it is hard to find a comprehensive index that can reflect the actual economic situation. In general, the total population at a specific location is proportional to the amount of consumption and production [44]. Therefore, in this research, the population dynamics is considered as the significant index for inquiry. Its correlation with accessibility is discussed in Section 5.1. The following are previous research on the interplay between population dynamics and transportation.

Tschopp, M. et al. (2003) [48] discussed the interaction between Accessibility and demographic change based on Switzerland's population data from the censuses 1850-1990. With their further research, Tschopp, M. et al. (2006) [49] found out that the influence of accessibility and spatial development differs considerably over time and space. Baum-Snow (2007) [45] assesses how new limited-access highways have contributed to the central city population decline. Portnov et al. (2011) [46] demonstrates the temporal relativity of location attributes, even for small territorial divisions in Switzerland. However, the results also shows that both absolute and relative location attributes have weakened over time as population growth predictors, apparently due to improving road infrastructures and growing motorization. Garcia-López et al. (2013) [47] estimate the effects of highways on Spanish cities' suburbanization. They also use Spain’s historical road networks – Roman roads, 1760 main post roads, and 19th century main roads – to construct candidates for use as instruments. Garcia-López, M. et al. (2015) [51] provides evidence for the highway and railway infrastructure's causal effect on the suburbanization of the population in European cities. Kotavaara, O. et al. (2012) [52] research on the effect of Accessibility and population change, and their study show that population change was strongly related to road potential accessibility. Airport accessibility also had high importance, whereas railway accessibility did not have any significant effect [52].

3. Accessibility of Sui-Tang Age

In Chapter 3 of our tale, we embark on a pioneering journey to model the historical accessibility of the Sui-Tang era. Imagine this chapter as a meticulous expedition, where every step in our modeling process is a trek through the annals of history, unveiling the intricacies of ancient travel and connectivity.

We start in Section 3.1, akin to unearthing hidden relics. Here, we delve into the historical data that form the backbone of our model. Picture us as historians and data scientists, scrutinizing ancient records, ensuring their accuracy and relevance. This section is the foundation stone, ensuring the strength and reliability of the entire structure we're building.

Moving to Section 3.2, we step into the shoes of ancient travelers, calculating the time they would have spent journeying across diverse terrains. This part of our adventure discusses the methods used to estimate travel times, considering various modes of transportation – from foot to horseback, to boats. We navigate through the geographical and infrastructural landscapes of the era, a critical endeavor for accurate accessibility measurements.

In Section 3.3, we unveil the core of our quest – the specific accessibility model employed in our study. Here, we're like architects, outlining the theoretical framework and computational approaches, and adapting them to the context of ancient China. This is where we transform historical data into a living, breathing analysis of past movements and interactions.

Sections 3.4 to 3.6 present a kaleidoscope of analyses from our model. Imagine these sections as different lenses through which we view our findings. In Section 3.4, we explore the impact of various infrastructures – the roads, rivers, and canals – and their roles in enhancing accessibility. It's a deep dive into how these networks served as the lifelines of ancient societies. Section 3.5 offers a panoramic view of the evolving landscape of accessibility. Here, we trace the ebb and flow of connectivity over time, unearthing insights into historical trends and patterns. This is akin to watching a time-lapse of ancient China's development, revealing the pulsating life of its transportation networks. Finally, Section 3.6 brings us to the individual level, where we examine how accessibility varied for different people in this historical setting. This section is a closer look, a more intimate perspective, showcasing the personal experiences of accessibility in the vast canvas of Chinese history.

Through this chapter, we navigate the dense forests of data and theory to emerge with a clear understanding of historical accessibility. It's a journey through time, reconstructing the past to better comprehend the flow of information and goods across ancient landscapes.

3.1 Historical Data

The Sui-Tang Age, represented by data circa 742 C.E., is the primary focus of this research. This period is chosen over earlier times due to the relative abundance of relevant data, particularly in transportation. The earliest national transportation network, established over 2000 years ago, lacks precise data. The Tang dynasty is selected not just for its rich transportation data but also for its comprehensive information on population, social networks, poets, government officials, and other aspects analyzed in Chapter 8. Moreover, the construction of the Grand Canal marks the Sui-Tang Age as a crucial transitional period in ancient China.

This section will discuss the historical data utilized for the historical accessibility modeling of Chinese Sui-Tang Age, including their contents, sources, and necessary corrections. As shown in Table 3-1, there are mainly four types of data contributing to the calculation of Accessibility.

Table 3-1 Historical Data Used in this Research.

Topic	Details	Source
Administration	Tang Prefectures in 741 (within China)	HGIS, Harvard University [53]
	Tang Prefectures in 741 (within Vietnam)	Academia Sinica, Taiwan [32]
Population	Population Distribution Data of Year 609	"History of Chinese Population (Sui-Tang and Five Dynasties)", Dong GuoDong, Fudan University Press [54]
	Population Distribution Data of Year 639	
	Population Distribution Data of Year 740	
	Population Distribution Data of Year 742	
	Population Distribution Data of Year 813	
Transportation	Roads System in 741	Academia Sinica, Taiwan [32]
	Yellow River and Yangzi River	Natural Earth Database [55]
	Grand Canal	Peter K. Bol, Harvard University. [56]
Geography	Digital Terrain Model (DEM) of China (250m)	Resources and Environment Science Data Center in the Chinese Academy of Science [57]

Because there is no more detailed data than the data at the prefectural level, the administrative prefecture is the unit of accessibility calculation, which provides the necessary location information. Because the primary sources of prefecture data are both incomplete, composition work is done. As shown in Figure 3-1-a, there are 353 prefectures from two primary sources. The red and grey part is the prefectures located in modern China, and the green area is located in Vietnam. All the prefectures were the approximate administrative divisions of the Tang Dynasty. There are 25 prefectures with no population data through the Five Periods, as shown in the grey part of Figure 3-1-a. Those 25 prefectures will not be taken into accessibility calculations. Other 328 prefectures' center will be first taken as the locations of 328 cities. Based on the assumption that the major road connecting cities, their centers are snapped to the nearest road.

As shown in Figure 3-1, the population data includes all one-hand documented population numbers in the Tang Dynasty. Most of them are corresponding to the prefecture data directly. Population distribution of the former dynasty in 609 is also used; the population distribution on the year is transformed based on the prefectures in the Tang Dynasty. Due to some political and other reasons, there are some missing data on certain prefectures. Based on this fact, the analysis of Accessibility mainly relies on the accessibility results contributed by other cities or prefectures. The calculation process will be discussed in Section 3.2 and 3.3.

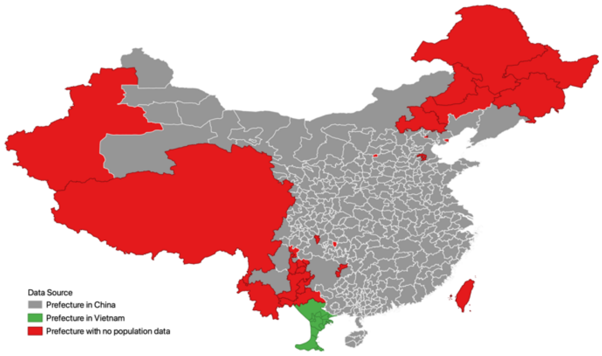


Figure 3-1-a Prefecture Divisions

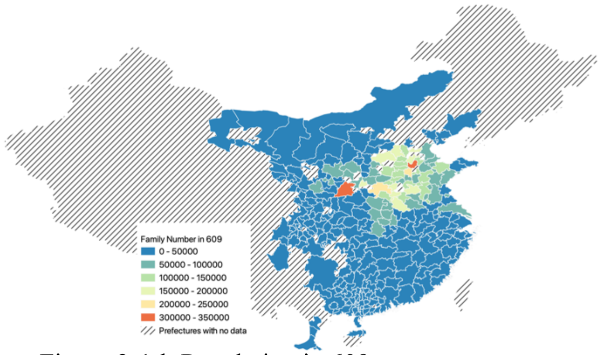


Figure 3-1-b Population in 609

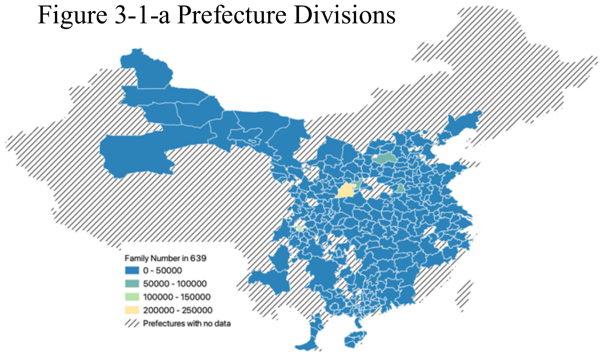


Figure 3-1-c Population in 639

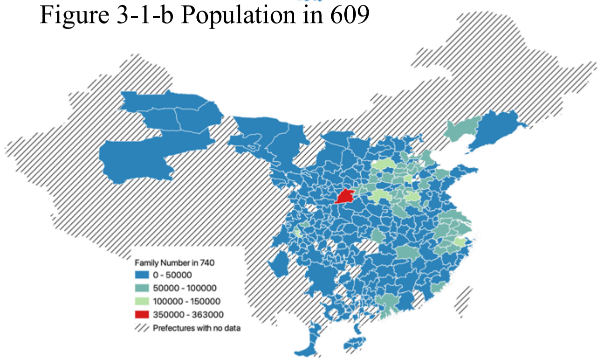


Figure 3-1-d Population in 740

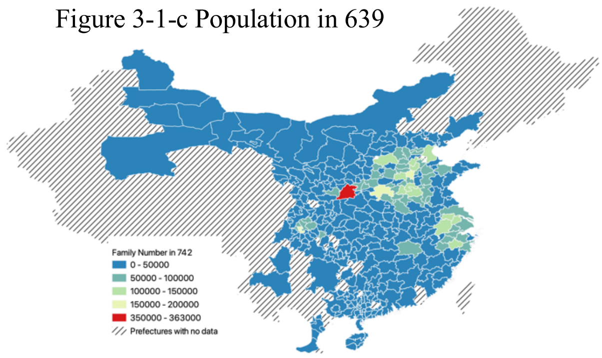


Figure 3-1-e Population in 742

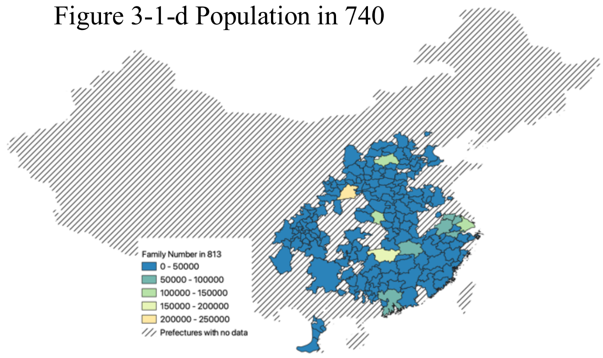
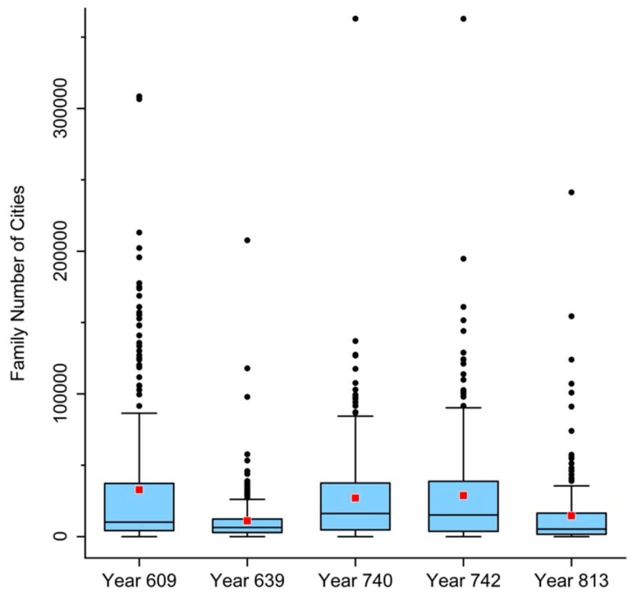


Figure 3-1-f Population in 813



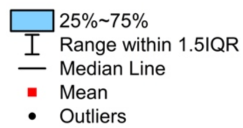


Figure 3-1-g Distribution of Family Numbers of Cities

Figure 3-1 Population Distribution Data
Figure 3-1-a ~ Figure 3-1-g
([54], Plotted by the author)

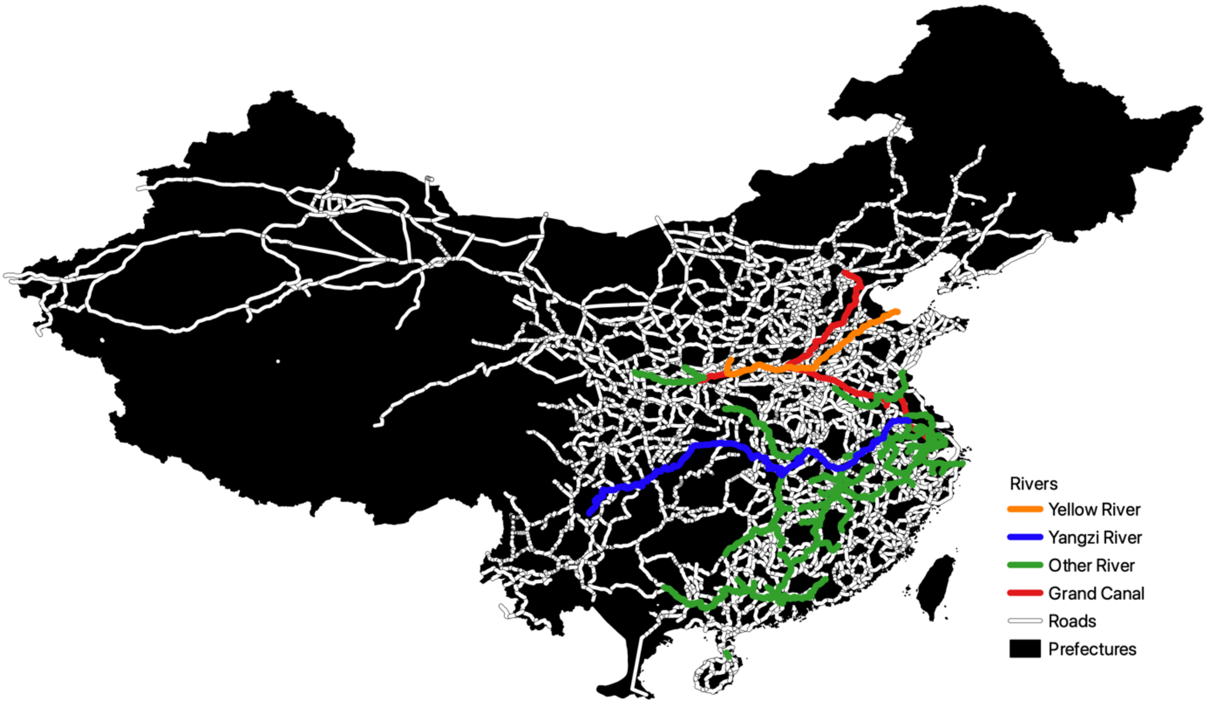


Figure 3-2 Transportation System in the Tang Dynasty
([32][53][55][56][57], Edited and Plotted by the author)

As shown in Figure 3-2, there are two general categories in the Tang Dynasty's transportation system: Roads and Rivers. Because the classified data on roads is not available, all the roads are regarded as homogeneous roads. The factors that can affect the travel speed on roads are height and vehicle type. As for the rivers, there are three categories: Yellow River, Yangzi River, and Other River, including the Grand Canal. The three categories defined different travel speeds along the river. The detailed travel time calculation will be discussed in Section 3.2.

3.2 Travel Time Calculation

This section will discuss the method of calculating the travel time. Due to the enormous geographical scope, most of the trips between two different prefectures took weeks, even months. It is reasonable to adopt the daily travel speed. All the defined Speed is based on the record of a historical document in the Tang Dynasty [58], which clarified the officials' responsibilities to transport goods or information. As shown in Table 3-2, Speed on roads differs with different vehicles, and Speed on rivers differs with different locations. For the calculations in this research, two types of speed are adopted for two different situations: Information Flow (Horse on Roads and Up/Down without Goods) and Goods Transportation (Wagon on Roads and Up/Down with Goods).

Table 3-2 Speed on Roads and Rivers (kilometer/day) [58]

Vehicles on Roads	*Speed on Roads*	*Rivers*	*Down Speed*	*Up Speed with Goods*	*Up Speed without Goods*
Horse	35	*Yangzi River*	50	20	25
Foot/Donkey	25	*Yellow River*	75	15	20
Wagon	15	*Others*	35	22.5	30

The situation and locations define the Speed on rivers. However, the Speed on roads is defined by situation/vehicle and height because the slope is another important factor for road transportation. An equation for the slope factor is derived based on work by Franz Johann Maschek and Eduard Bokelberg [59]. Let V denote the normal speed. The speed V_1 on a segment with slope α is derived by the following Equation (3-1).

$$V_1 = V \cdot (1 - 2 \cdot \sin(\alpha)). \tag{3-1}$$

3.3 Accessibility Function

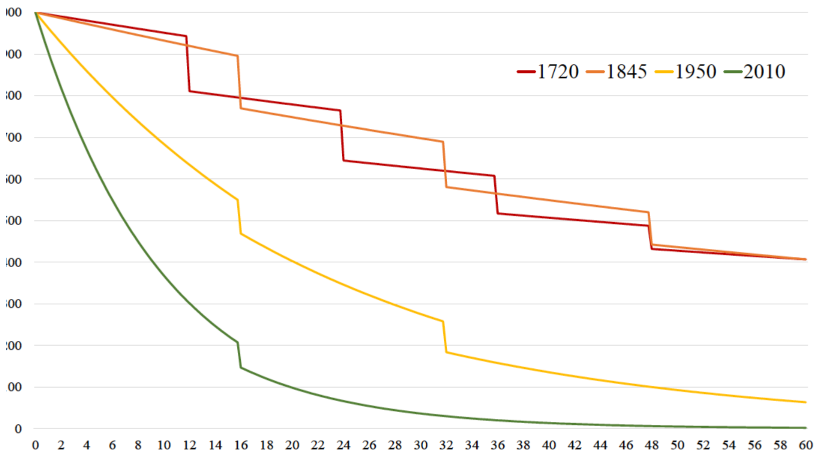
As discussed in Chapter 2, this research's accessibility function is a gravity-based method, shown in Equation (2-11). The opportunities to be counted is population data (Family numbers of prefectures). As described above, the amount of consumption and production in one place is proportional to its local population.

The cost elements considered in this research is travel time. Other costs like safety and monetary costs are not taken into consideration. The resulting time is determined by a shortest-path algorithm utilizing ArcGIS software. The cost function is the gravity-based approach by Hansen [12]. The chosen parameters are based on the previous research on Switzerland's historical accessibility modeling in 1720 done by Raphael Fuhrer [36]. The parameters are chosen so that the graph follows a flat, almost linear path and considers the need to stay overnight during multi-day journeys.

Based on Raphael Fuhrer's work [36] shown in Figure 3-3, the cost functions are depicted using a number of 1000 population reachable without traveling. The graphs show the resulting equivalent of population 1000 weighted by the costs to reach the location. The cost functions are per year only. They do not consider the trip's purpose, neither the income nor social status of the traveler. The travel time is segmented into day-long journeys. Whenever a traveler stays overnight during the journey, the graph jumps to a lower value – accounting for the additional time lost. As for this research, the day's stage duration in Tang Dynasty should be equivalent to the year 1720 as 12 hours due to daylight, quality of roads, and stability of vehicles.

Short-distance and long-distance journeys have significant differences in cost functions. Cost functions for the short-distance journey should be a steep function so that opportunities provided further away are less critical. On the contrary, cost functions for the long-distance journeys are best captured by a relatively flat graph. This reflects that the traveler should be prepared to accept higher generalized travel costs to reach the destination.

Year	Travel time	Equation
1720	tt<12	exp(-0.005*tt)
	tt<24	exp(-0.005*tt-0.15)
	tt<36	exp(-0.005*tt-0.32)
	tt<48	exp(-0.005*tt-0.48)
	tt>48	exp(-0.005*tt-0.6)
1845	tt<16	exp(-0.007*tt)
	tt<32	exp(-0.007*tt-0.15)
	tt<48	exp(-0.007*tt-0.32)
	tt>48	exp(-0.007*tt-0.48)
1950	tt<16	exp(-0.038*tt)
	tt<32	exp(-0.038*tt-0.15)
	tt>32	exp(-0.038*tt-0.48)
2010	tt<16	exp(-0.1*tt)
	tt>16	exp(-0.1*tt-0.32)



a. Cost functions per year: parameters (tt: travel time in hours)

b. Cost functions per year based on a gravity mode. X-axis: travel time in hours. Y-axis: remaining weight of population of 1000.

Figure 3-3 Cost functions and parameters for accessibility calculations of Raphael Fuhrer (2019) [36]

Due to the study area's scope, most journeys considered in this research are long-distance journeys. Most of the journeys exceed the maximum travel time 48 hours in Fuhrer's model. Equation (3-2) is the formula in Fuhrer's model for journeys with more than 48 hours.

$$\text{(Fuhrer's accessibility for 48 or more hours)} \quad A_i = \sum_j P_j \cdot \exp(-0.005 \cdot tt_{ji} - 0.6)\,. \tag{3-2}$$

The constant parameter -0.6 indicates accounting for the additional time lost to stay overnight in 4 days (assuming each day we could travel 12 hours), each day -0.15. This was enough for Switzerland but not for this study since China is much larger and most journeys required 5 or more days. To address this issue, this study replaces the fixed value 0.6 with a variable $0.15D_{ji}$, where D_{ji} is the number of days. By combining with the hour to day mapping Equation (3-3), finally we obtain Equations (3-4) and (3-5) to calculate accessibility throughout this study.

$$tt_{ji} = 12D_{ji}. \tag{3-3}$$

$$\text{(Accessibility used in this study)} \quad A_i = \sum_j P_j \cdot \exp(-0.005 \cdot 12 \cdot D_{ji} - 0.15 \cdot D_{ji})\,. \tag{3-4}$$

$$\text{(That is)} \quad A_i = \sum_j P_j \cdot \exp(-0.21 D_{ji})\,. \tag{3-5}$$

In an ancient agricultural society, the total population of a specific location is proportional to the amount of consumption and production [40]. Therefore, if we took the local population indicates the local accessibility contributions, the floating population of one places could be indicators for remote contributions of other places to this city, which should be consistent with the calculated remote contribution of accessibility in city i, $\sum_{j \neq i} \text{Opportunities}_j \cdot f(\text{cost}_{ij})$. Referencing historical records, Yen (1995) [60] estimated that the capital city's floating population during the Tang Dynasty was at least 50,000. With the chosen parameter of -0.21 in Equation (3-5), we calculate the remote contributions by all the other cities to the capital's accessibility as 50,926 for the year 693, and 109,261 for the year 742, which is consistent with historical records on the floating populations in the capital.

3.4 Accessibility of Different Infrastructures

In this section, different infrastructures or different transportation forms will be discussed. Generally, three types of infrastructures are analyzed: Roads, Natural Rivers, and Canals. It is assumed that people first constructed the road system, then mastered the navigation on natural rivers, and finally could build the Grand Canal. The method to clarify the contribution of natural rivers and the Grand Canal is to calculate the accessibility value of the following three transportation networks: roads only, roads & rivers, roads & rivers & canals. The Grand Canal was finished around Year 609, so the population used to analyze this section adopts the same population data of Year 609. The calculation results based on different travel costs are shown in Figure 3-4 for Accessibility of Information based on information flow speed and Figure 3-5 for Accessibility of Goods based on good transport speed. The prefecture with the red star indicates the national capital. In addition to the geographical map of the prefectures' accessibility value, the value distribution graph is also available for a clearer view of their functions. This graph shows the data distribution, mean value, median value, range of 10%-90%, and 25%-75% are available.

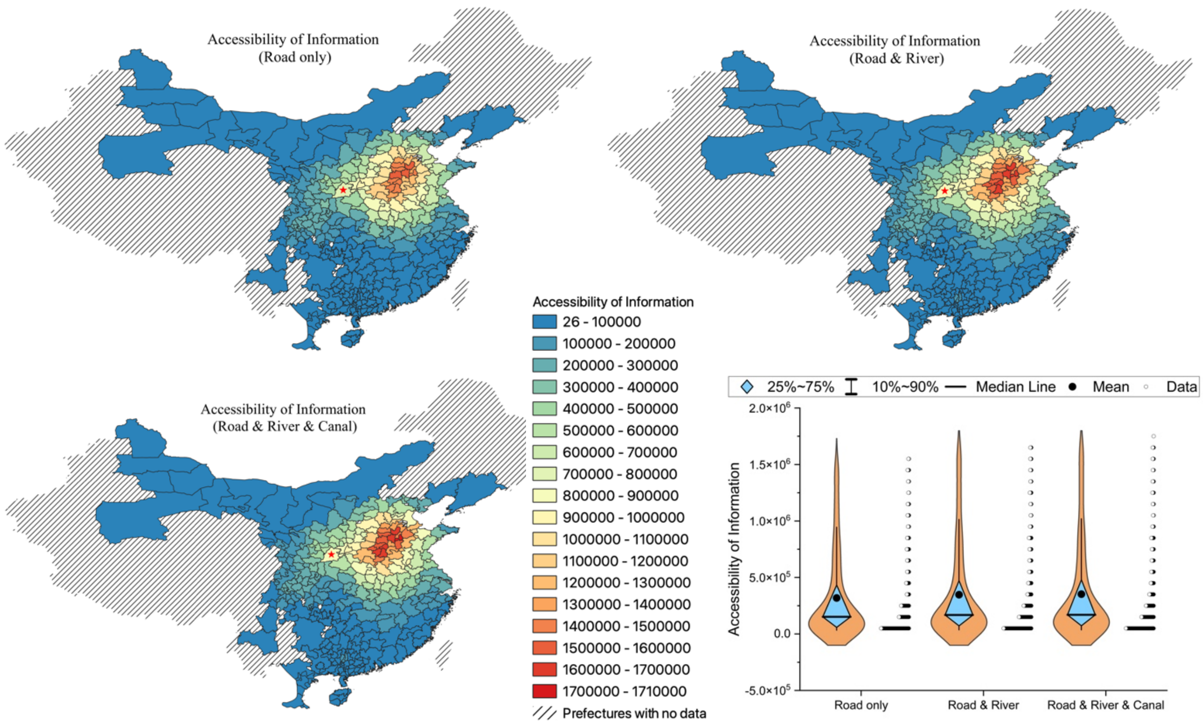


Figure 3-4 Accessibility of Information based on Different Infrastructure (Year 609)

It is easy to understand that the addition of rivers and canals to the road system will increase in accessibility. To quantify this intuition, we use Equation (3-6) to denote the increased ratios due to the additions of rivers and canal by ΔA_i^{river} and ΔA_i^{canal} respectively, where $A_{i_{other}}$ and $A_{i_{local}}$ denote the accessibility due to the remote and the local contribution, respectively.

$$\Delta A_i^{river} = \frac{A_{i_{other}}^{river} - A_{i_{other}}^{road}}{A_{i_{other}}^{road}}, \qquad \Delta A_i^{canal} = \frac{A_{i_{other}}^{canal} - A_{i_{other}}^{river}}{A_{i_{other}}^{river}}, \tag{3-6}$$

$$Where\ \ A_{i_{other}} = \sum_{j \neq i} P_j \cdot \exp\left(-0.21 D_{ji}\right), \text{and,} \tag{3-7}$$

$$\text{since } D_{ii} = 0, \tag{3-8}$$

$$A_{i_{local}} = P_i \cdot \exp(-\beta \cdot D_{ii}) = P_i\,. \tag{3-9}$$

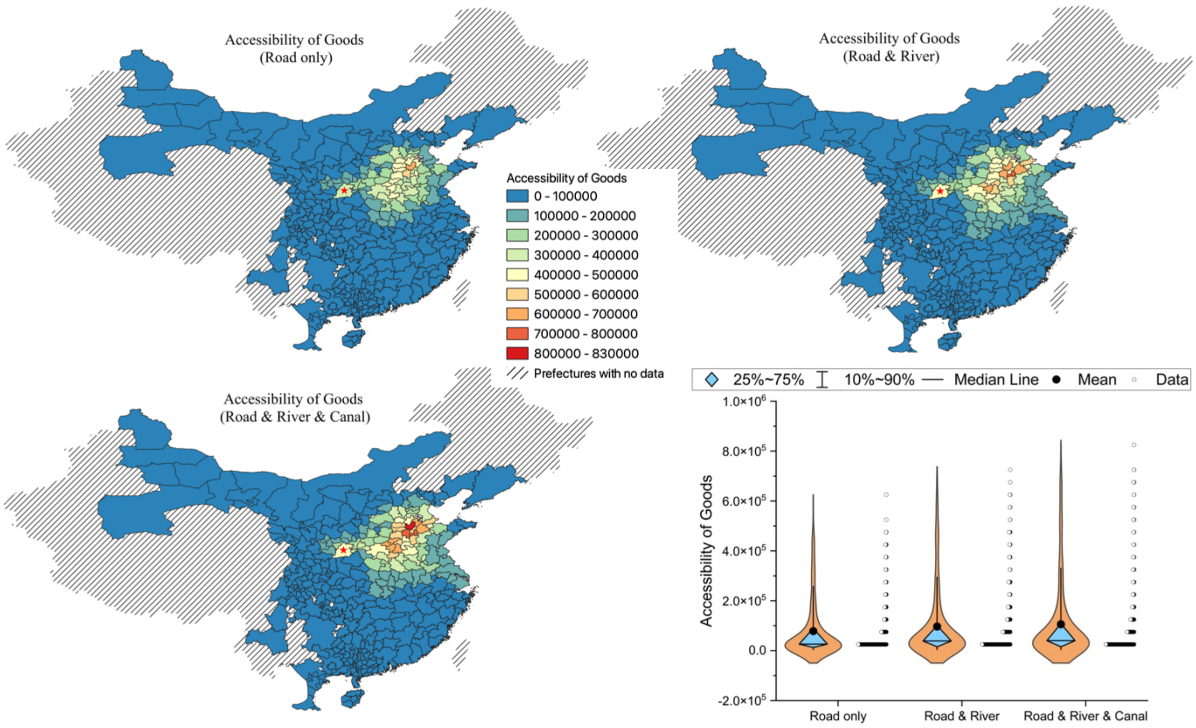


Figure 3-5 Accessibility of Goods based on Different Infrastructure (Year 609)

From the results of Figures 3-4 and 3-5, it can be observed that generally, the rivers have a limited improvement value on Accessibility of Information. The fastest Speed of information flow on roads by horse, which is 35km/day, is already fast enough compared to the travel speed on water (15~75 km/day). Especially for the prefectures in the north, where the density of the road system is very high. The addition of rivers and canals is just like the addition of another road, whose influence is relatively small. Nevertheless, for the prefectures in the south, where road density is relatively low, even a small increase is double its accessibility value. As shown in Figure 3-6, the rivers brought a 30%~90% incensement to most of them.

As for the Accessibility of Goods, rivers are crucial for most prefectures due to the speed gap between ships and wagons. This kind of incensement is obvious for southern prefectures, as shown in Figure 3-6, most southern prefectures increase 2 to 5 times. The most significant increase up to 17.5 times. As for the northern prefectures, there is also a considerable increase.

As for the function of the Grand Canal, there is almost no impact on the Accessibility of Information. Nevertheless, the Grand Canal brought a considerable increase to prefectures along it. Especially for prefectures on the northeast around Beijing. Those prefectures doubled or tripled their Accessibility of

Goods. This result also can explain why the north end of the Grand Canal is Beijing. The middle end is the national capital, and the southern end is the political and economic center of the south. However, the north end is not the regional center nor populous area. The emperor decided to build the Grand Canal to Beijing, aiming to support the war with Korea [63]. This can explain why only the prefectures around Beijing have a substantial increase due to the Grand Canal.

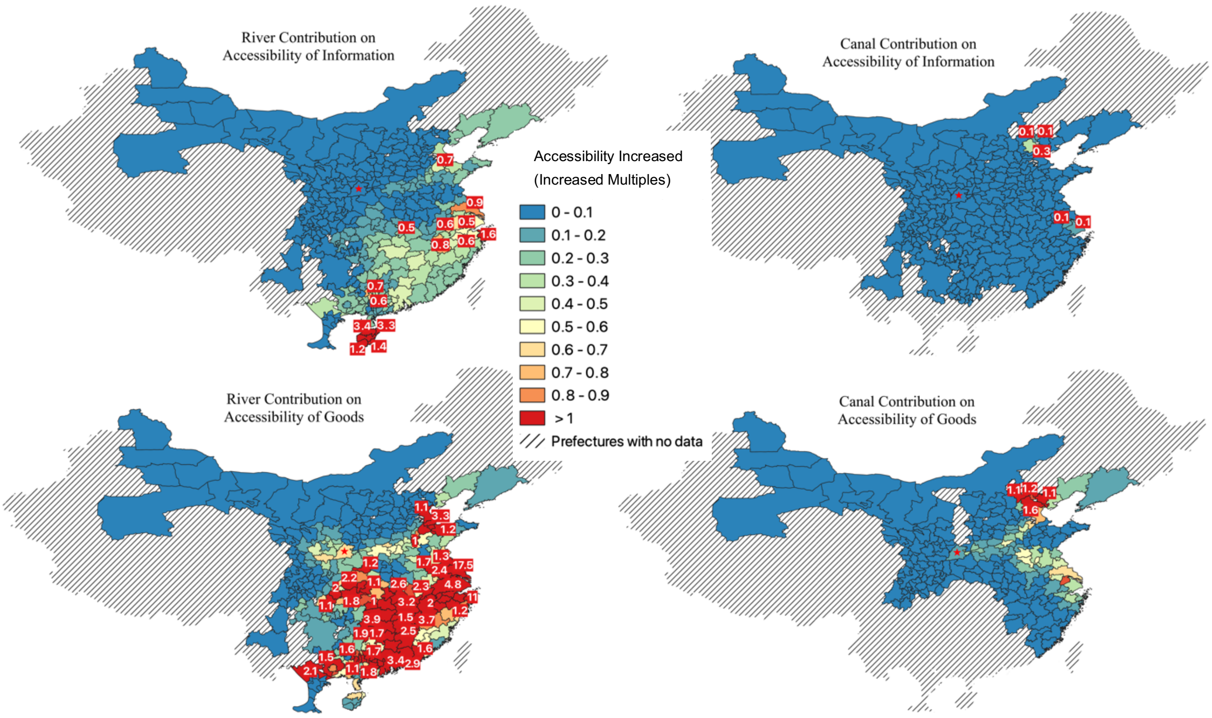


Figure 3-6 Accessibility Increase due to Rivers and the Grand Canal (Increased Multiples)

3.5 Accessibility along Different Periods

This section focuses on the accessibility changes through Years 609-813. The accessibility results are calculated based on five different population data sets: Years 609, 639, 740, 742, and 813. The Grand Canal was finished around the Year 608. Generally, the differences in the transportation system are are considered small. Thus, the calculation for those five years is based on the same transportation network. In order to include the period before the construction of the Grand Canal, it is assumed that there is no significant population change between Year 608 and

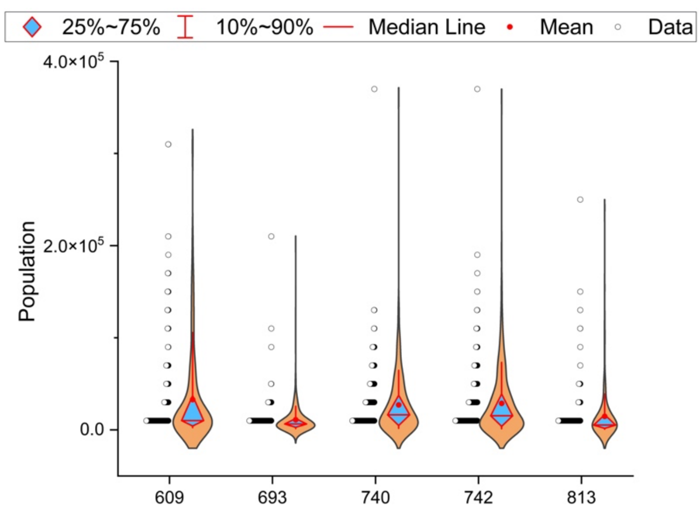


Figure 3-7 Prefectures Distributions on Population

Year 610. Those two years share the same population data set, but the former represent the time right before the construction of the Grand Canal, and the latter represents the time after the construction. Therefore, there are six calculation results in total: Years 608, 610, 639, 740, 742, 813. Figure 3-8 are the result for Accessibility of Information, and Figure 3-9 are the results for Accessibility of Goods.

When calculation results in Figures 3-8 and 3-9 are compared with population data in Figure 3-1 and Figure 3-7, it is easy to conclude that the distribution of Accessibility has a vital characteristic of homogeny with the population distribution. However, accessibility values change in a more continuous way along the neighboring prefectures. This continuity is because the calculation for Accessibility is a weighted sum calculation defined in Section 3.3. This kind of sum calculation will wipe the population differences among neighboring prefectures. Accessibility values for both types (Information & Goods) share this characteristic. It is straightforward to know where the economic center is.

Secondly, it is clear that economic geography transformed from a monopole center in the north into multipole centers. New economic centers in the south and southwest emerge. Due to the massive migration triggered by the civil war in the chaos period: Years 610~639 and Years 742~813, Another two population clusters are formed in the south, whose center is Suzhou, and in the southwest, whose center is Chengdu. This kind of change is undeniable in the prefectural results in Figures 3-8 and 3-9, especially for the Accessibility of Goods in the Year 742.

On the other hand, the shape changes along different years in the distribution graphs of Figures 3-8 and 3-9 can also explain this characteristic. The shape of the distribution changes from a drop-shape into a gourd-shape. Even though most prefectures are still at the bottom and share low accessibility, some prefectures in the accessibility distribution are promoted; therefore, the distribution shape changes from drop to gourd. The prefectures causing this change are the two rising regional economic centers and their neighboring prefectures.

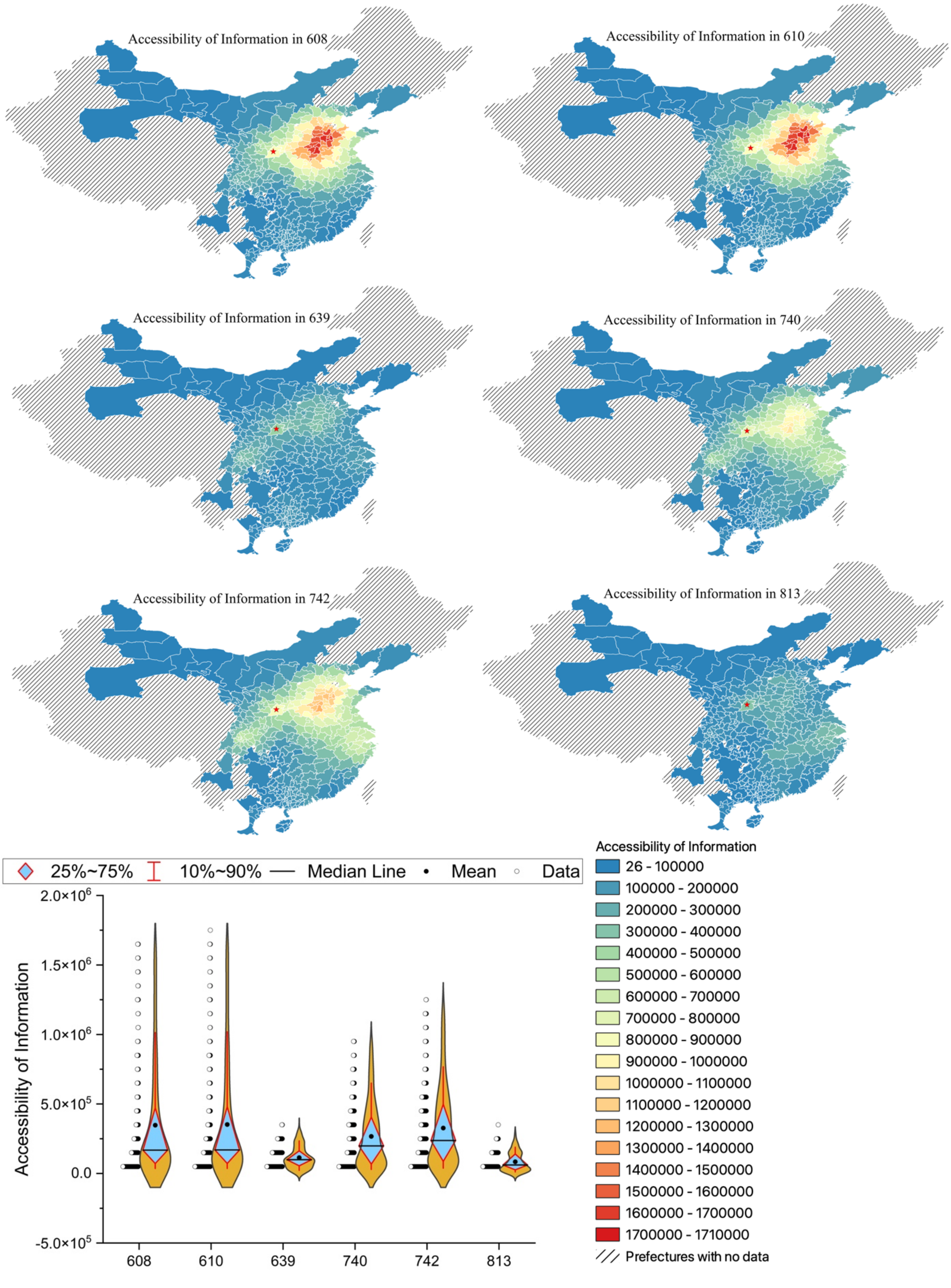


Figure 3-8 Accessibility of Information on Different Years

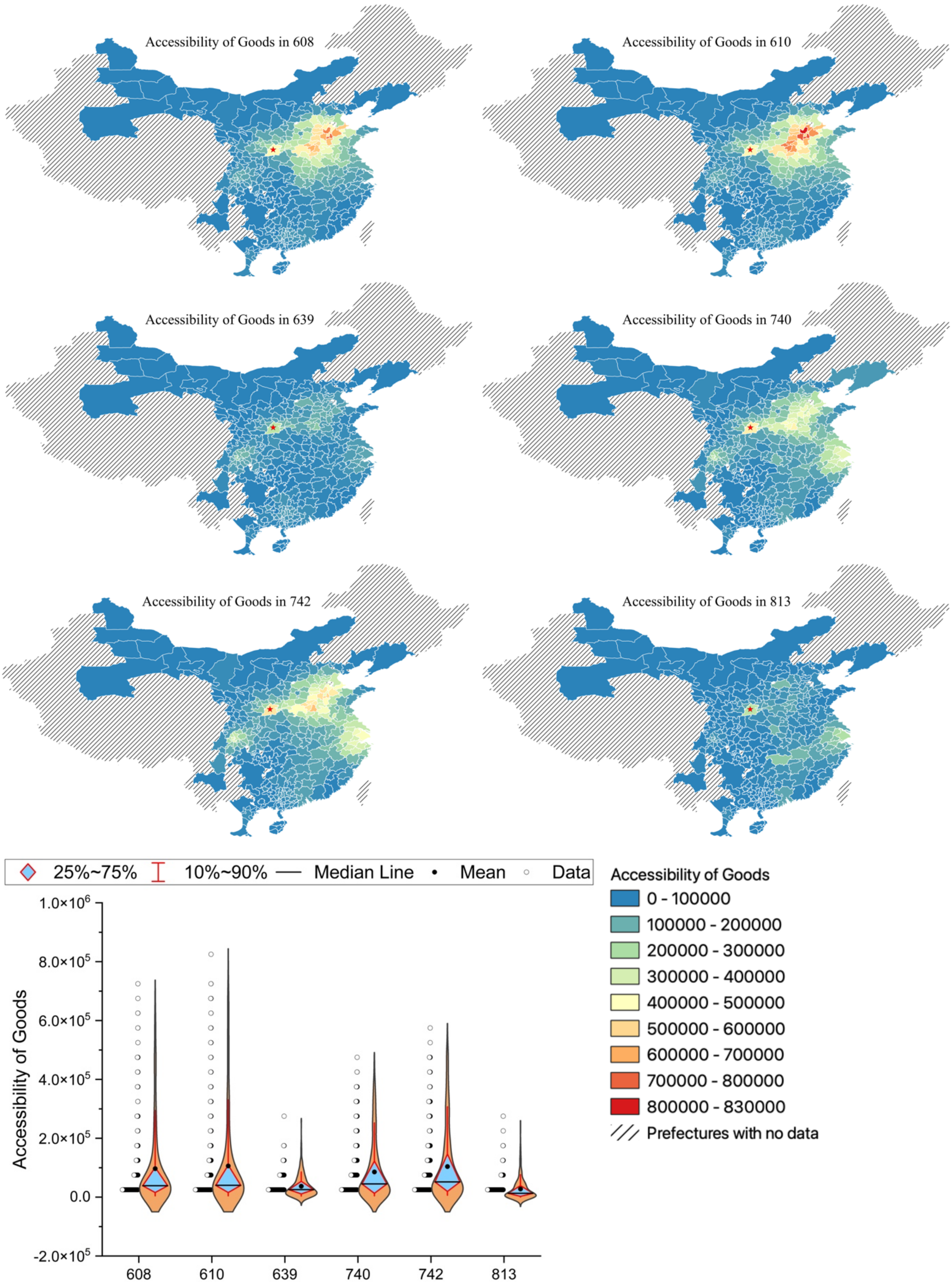


Figure 3-9 Accessibility of Goods on Different Years

3.6 Accessibility Distribution on the Individual Level

Unlike the analyses in Sections 3.4 and 3.5, which focus on accessibility distribution at the city level—where each data point corresponds to an entire city—this section examines accessibility from a population-centric perspective. Here, each data point represents a single individual, factoring in the city's population size to create a more granular view of accessibility. For example, if the city of Chang'an has a population of 10 million people and an accessibility value of 4 million units, the city-level accessibility distribution would include just one data point at 4 million units. In contrast, the population-level distribution for Chang'an would feature 10,000 data points (corresponding to its 10 million residents), each with the same accessibility value of 4 million units. This approach multiplies the original city data points by the corresponding population figures, thereby generating multiple population data points that carry the city's accessibility value.

It is known that only a few prefectures were enjoying a very high level of accessibility. Nevertheless, this does not mean that only a few people were enjoying high accessibility. Because the prefectures with high accessibility usually have a large population. Most prefectures having relatively low accessibility also have a smaller population. It is assumed that all citizens in the same prefecture or city enjoy the same level of accessibility of their prefecture or city. Therefore, the accessibility distribution on the prefectural level is quite different from the individual level. It is necessary to inquire about the differences.

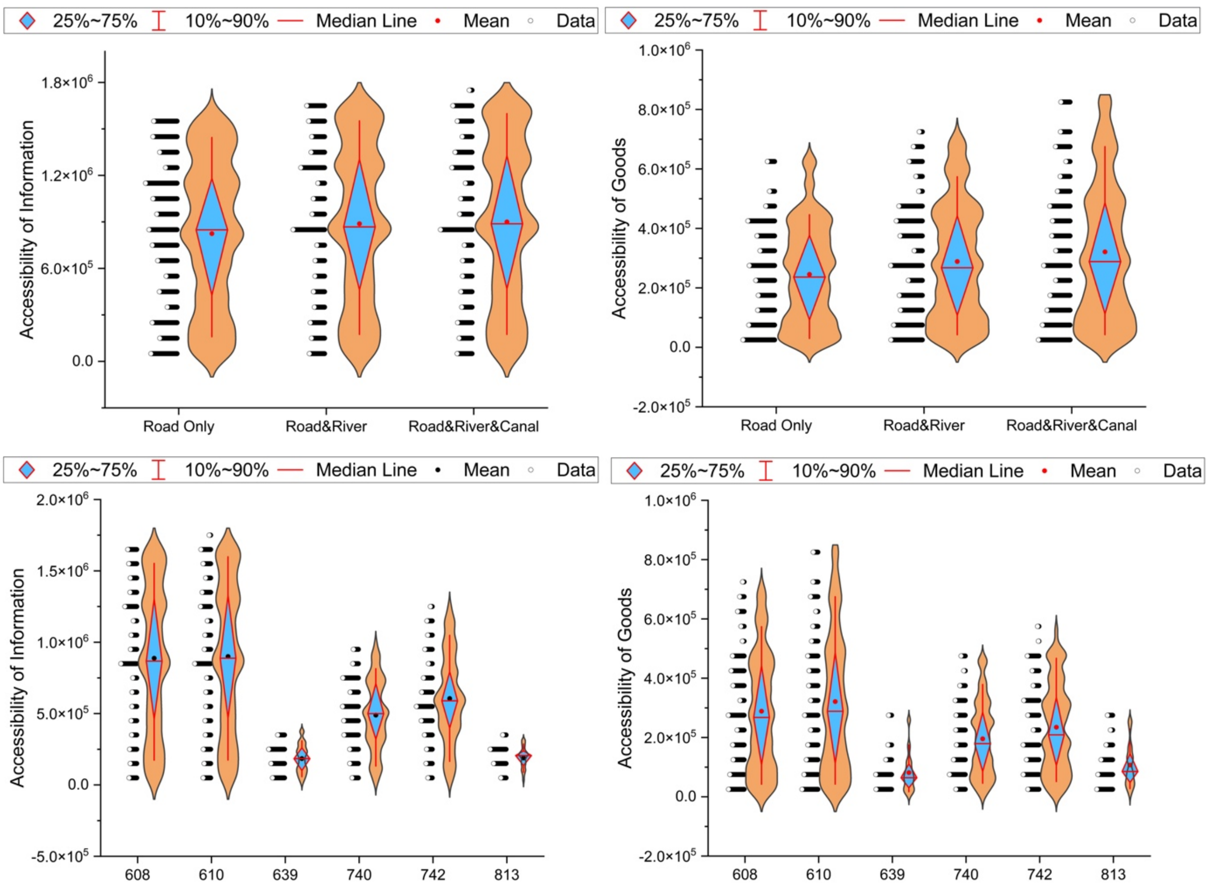


Figure 3-10 Accessibility of Different Years on Individual Level

Figure 3-10 shows the accessibility of different infrastructures on the individual level. Same with the analysis on the prefectural level in Section 3.4, the influence of rivers and canals on the Accessibility of Information is limited. The impact of rivers and canals on Accessibility of Goods is noticeable: They brought some people from a median level to a relatively high level of accessibility. This conclusion is reasonable because prefectures along rivers usually have a relatively larger population. Figure 3-11 show the Accessibility of different years on the individual level. Generally speaking, the population distribution along different accessibility values are relatively even.

3.7 Discussion: Evaluating the Impact of Infrastructure with Accessibility: The Case of the Grand Canal

The analytical exploration conducted in Section 3.2, which employed accessibility modeling for various infrastructures, reveals that the construction of the Grand Canal significantly enhanced accessibility for prefectures along its route, particularly in the northeastern regions surrounding Beijing. These areas experienced a remarkable two to threefold increase in their Accessibility of Goods, a metric indicative of the canal's transformative impact on regional commerce and connectivity.

This finding provides a nuanced understanding of the strategic placement of the Grand Canal, with its northern terminus in Beijing. While Beijing was not the regional center or a densely populated area at the time, the decision to extend the Grand Canal to this location was driven by strategic military considerations, specifically to support military campaigns against Korea. This strategic choice by the emperor led to a disproportionate increase in accessibility for prefectures near Beijing, underscoring the canal's role in shaping regional dynamics.

Furthermore, the methodology applied in this analysis offers a valuable framework for evaluating the impact of other historical infrastructures. By quantitatively assessing the changes in accessibility brought about by such infrastructures, we gain deeper insights into their role in historical urban and regional development. The Grand Canal's influence on the distribution of economic and political power, from the national capital at its midpoint to the southern political and economic hub, demonstrates the profound impact of transportation infrastructure on historical societal structures. This approach, therefore, presents a replicable model for assessing the long-term impacts of infrastructural developments across different historical contexts.

4. Studying Population Dynamics with Accessibility of Sui-Tang Age

Chapter 4 of this dissertation unfurls as a captivating exploration of the dance between transportation and population dynamics during the Chinese Sui-Tang era. Envision this chapter as a journey through the ebb and flow of ancient societies, where each step uncovers the subtle interplay of people, roads, and rivers in shaping the economic tapestry of the time.

We begin with a foray into the shifting sands of population changes, as portrayed in Section 4.1. Here, demographics are not mere numbers but the pulse of ancient economies, resonating with the rhythms of consumption and production. This section paints a vivid picture of the demographic landscape, setting the stage for an intricate narrative that weaves together historical factors, economic conditions, and social dynamics. It's akin to a historian and economist's joint expedition, decoding the past's societal patterns.

Next, in Section 4.2, our path takes us into the heart of the model developed for this study. Picture a craftsman meticulously shaping a tool – this section details the crafting of our model, its evaluation, and optimization. Here, methodologies and processes are not just technical terms but keys to unlocking the past. This part of our journey is fundamental, ensuring that our model resonates with the authenticity and intricacy of historical data.

Then, we delve into the essence of our findings in Section 4.3, where calculated parameters and accessibility come to the forefront. This section is like illuminating a dark room, revealing how accessibility was a silent yet powerful force in the economic and societal developments of the Sui-Tang era. It's here that our narrative delves deeper, drawing connections between the movement of people and goods and the larger historical canvas of development and change.

Through this chapter, our exploration is not just an academic exercise but a voyage back in time. We navigate through historical data, modeling techniques, and theoretical frameworks to piece together a story of how transportation infrastructure molded population dynamics and, in turn, the economic and social fabric of ancient China. This chapter, thus, stands as a testament to the interconnectedness of human societies and their means of connectivity across time and space.

4.1 Population Dynamics Analyze

As shown in Figure 3-1, the population's total number and distribution significantly change over time. There is no doubt that political reason is the leading cause of those changes. Generally, take the Year 609 as the start year. There are two decline periods and one recovery period in the middle. The following is a brief introduction of the political background over the study periods.

Table 4-1 Political Situation of Study Periods

Year/Period	Political Situation
609	Golden Age of the Sui Dynasty, the Grand Canal was just finished, but the empire began to collapse. Because the emperor started several wars with Korea, which was also one reason why the Grand Canal was built.
609~639	Period of endless civil rebellion and civil wars. Population dropped by more than 60%. Finally, the Tang Dynasty was established. The empire began to recover.
639~742	Golden Ages of Chinese History. Peace Period.
742~813	After a big rebellion war happened in year 755, the empire remained united nominally, but civil wars followed in the next 300 years.

The impact of chaotic events is reflected on the total population number and its distribution dynamics among different prefectures. There are some prefectures whose population keeps growing during the two chaotic periods. Because those prefectures were relatively peaceful, which helps them attract migrations from the war zone, and this migration process is directly affected by the transportation system. Based on this analysis, the first assumption is that politics and transportation are the two main reasons for the changes in ancient populations. Generally, a prefecture's chaotic events will decide the direction of its related migration, which determines whether the population will grow or decline. Transportation factors will decide the amount of its migration. It is easy to conclude that a place with better accessibility brings people more mobility to move in or out. This assumption is the necessary foundation for the developed model.

Based on the above assumption, the population changes should be possible to be predicted by two factors: chaotic events and Transportation. This also means that in practice, three values are needed for the calculation of the next period's population: Parameter for chaotic events, Accessibility, and Population Base. The accessibility value should represent the function of the transportation system on migration among prefectures. So, the accessibility contributed by other prefectures $A_{i_{other}}$ will be used, preferably the total accessibility. Its calculation is shown in Equation (3-7).

As another factor, the influence of chaotic events cannot be neglected. However, it is challenging to quantify its influence. It is possible to summarize the related data on wars, for example, when and where the war happened. The war's impact is still hard to quantify just based on those data. There are also other examples that massive people are deployed to the battlefield in Korea and dying there, making it impossible to get an accurate number representing its influence. Another strategy is taken into this study, which is to group prefectures based on specific standards and assuming they shared a similar political situation. The same parameter is defined for prefectures inside the same group. The standard adopted in this research is geography. Especially for wars, prominent geographical landmarks bring difficulties.

The first general classification is north and south. As shown in Figure 4-1, the prefectures located in the blue zone belong to the north, and the orange zone represents the south. This kind of division is based on the geographical line of the Qin-Ling Mountains and the Huai River. This division of northern China and southern China is still followed today. The study period – Tang Dynasty is the turning point of the Chinese Demographic. Due to the endless war in the north, many migrations move south, and the economic center began to shift to the south. This classification of north and south aims at capturing this massive migration movement.

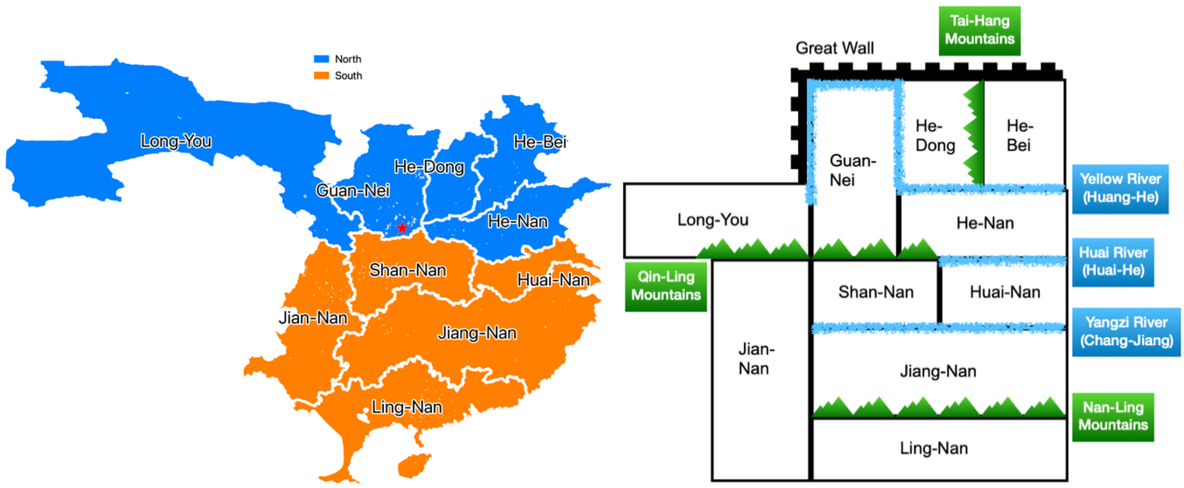


Figure 4-1 Provincial Division in Tang Dynasty

Anther classification with detail is based on the provincial division of the Tang Dynasty. Even it is known that there is migration moving from the north to the south. Nevertheless, the situation in different provinces is quite different. For example, the border provinces located away from the economic and political centers, such as Long-You and Ling-Nan, are rarely affected by this movement. As shown in Figure 4-1, the provinces' division is based on the geographical situation. The whole country is divided into ten provinces based on three major rivers and mountains, which grantee that every province is a relatively closed area. This closed area supports the assumption that prefectures inside the same province share a similar political situation.

4.2 Regression, Evaluation, and Optimization

Assume that chaotic events (wars and disasters) and transportation are the two main reasons for the ancient population changes. This study uses three values to analyze the population dynamics: Accessibilit y, Population Base, and Chaotic Events. Let t, i, and j denote the time period, prefecture, and province indices respectively. Let k denote the area (N = North, S = South) of China. We use the following notations in the regression analysis. See Table 4-2.

Table 4-2 Variables in the Regression Model

Variables	Meaning	Unit
$\Delta\rho_i^t$	Change of population density of a prefecture i from period t-1 to t.	Families per 10,000 km^2
α, α_k, α_j	Values indicating the accessibility effects for the whole country, area, and province levels, respectively.	
β, β_k, β_j	Values indicating the local effects for the whole country, area, and province levels, respectively.	
γ, γ_k, γ_j	Values indicating independent effects of chaotic events for the whole country, area, and province levels, respectively.	
$A_{i_{other}}$	Accessibility of prefecture i contributed by other prefectures, defined by $\sum_{j\neq i} P_j \cdot \exp(-0.21D_{ji})$.	Economic Opportunity represented by 1 family
A_i	Accessibility of prefecture i, defined by Equation (3-5).	

ρ_i^t	Population density of prefecture *i* in period *t*.	Families per 10,000 km^2
δ_i^k, δ_i^j	Dummy variables indicating whether a prefecture belongs to an area *k* and a province *j*, respectively.	1 = yes, 0 = no
c	Intercept (constant)	

Let us illustrate the regression models with a general model (4-1). The first term on the right indicates the influence of transportation due to other prefectures, reflecting the migration process. The second term indicates the influence due to local changes. The third part indicates the independent impact of chaotic events based on different groping level. A regression model depends on the variables. This study added the dummy variables of chaotic events gradually according to the level. As the result, Equations (4-2) to (4-9) in Table 4-3 show the regression models studied.

$$\Delta\rho_i^t = \text{Accessibility effects} + \text{Local effects} + \text{Effects due to Chaotic events} + \text{Constant}. \quad (4\text{-}1)$$

Table 4-3 Evaluated Regression Models

Dependent Variable	Accessibility Effects	Local Effects	Effects due to Chaotic events	Constant	Model
$\Delta\rho_i^t$	$\alpha A_{i_{other}}$	$\beta\rho_i^{t-1}$		c	(4-2)
$\Delta\rho_i^t$	$\alpha A_{i_{other}}$	$\beta\rho_i^{t-1}$	$\sum_{k=N,S}\gamma_k\delta_i^k$	c	(4-3)
$\Delta\rho_i^t$	$\sum_{k=N,S}\alpha_k\delta_i^k A_{i_{other}}$	$\sum_{k=N,S}\beta_k\delta_i^k\rho_i^{t-1}$	$\sum_{k=N,S}\gamma_k\delta_i^k$	c	(4-4)
$\Delta\rho_i^t$	$\sum_{k=N,S}\alpha_k\delta_i^k A_{i_{other}}$	$\sum_{k=N,S}\beta_k\delta_i^k\rho_i^{t-1}$		c	(4-5)
$\Delta\rho_i^t$	$\alpha A_{i_{other}}$	$\beta\rho_i^{t-1}$	$\sum_j\gamma_j\delta_i^j$	c	(4-6)
$\Delta\rho_i^t$	$\sum_j\alpha_j\delta_i^j A_{i_{other}}$	$\sum_j\beta_j\delta_i^j\rho_i^{t-1}$	$\sum_j\gamma_j\delta_i^j$	c	(4-7)
$\Delta\rho_i^t$	$\sum_j\alpha_j\delta_i^j A_{i_{other}}$	$\sum_j\beta_j\delta_i^j\rho_i^{t-1}$		c	(4-8)
$\Delta\rho_i^t$	$\sum_j\alpha_j\delta_i^j A_i$	$\sum_j\beta_j\delta_i^j\rho_i^{t-1}$		c	(4-9)

As shown in Tables 4-4~4-7, the regression analysis is conducted based on the population data on three periods: Years 609~639, 639~742, and 742~813. Because there is always missing population data on different periods. The analysis is only done for the prefectures whose population data for both the start and end years are available. The data points for the three periods are 232, 264, and 171. As shown in Tables 4-4~4-7, the corresponding parameters for Models 4-2 to 4-9 are calculated. Among those parameters, the red indicates parameters whose p-value is lower than 0.005, which means that its significance should be reconsidered.

Models 4-5 and 4-8 are relatively good models on the regional and provincial levels. An additional Model 4-2 is used for indicating the whole country. In all selected models, the independent variable γ is not considered. Moreover, the ten dummy variables on the provincial level are taken. The calculated parameters for accessibility effects α and local effects β can reflect the situation of migration and population loss, which will be explained in the next section.

Generally, as shown in Tables 4-4~4-7, the regression analysis on chaotic periods (Year 609~639, 742~813) is relatively ideal, which means the population dynamics during the civil wars can be simply attributed to two factors: refugee migration and death due to wars and disasters. The regression analysis on the peace period (Year 639~742) did not work. It suggests that more complex models may need to consider other factors except for chaotic events and transportation, such as the birth rate difference.

Table 4-4 Regression Analysis based on Model 4-8 and 4-9

Year	609~639 (232 Prefectures)				639~742 (264 Prefectures)				742~813 (171 Prefectures)			
Equation	4-8		4-9		4-8		4-9		4-8		4-9	
	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
$\alpha_{Long-You}$	-0.160	0.700	-0.160	0.700	0.180	0.874	0.180	0.874	0	--	0	--
$\alpha_{Guan-Nei}$	-0.206	0.001	-0.206	0.001	-0.084	0.470	-0.084	0.470	-0.491	<0.001	0.263	0.030
α_{He-Nan}	0.007	0.657	0.007	0.657	0.564	<0.001	0.564	<0.001	-0.326	<0.001	0.014	0.786
$\alpha_{He-Dong}$	-0.158	0.006	-0.158	0.006	0.204	0.329	0.204	0.329	-0.395	0.001	0.031	0.592
α_{He-Bei}	0.007	0.736	0.007	0.736	0.406	0.008	0.406	0.008	-0.190	<0.001	0.045	0.130
$\alpha_{Shan-Nan}$	0.092	0.356	0.092	0.356	0.005	0.985	0.005	0.985	0.099	0.678	0.225	0.004
$\alpha_{Huai-Nan}$	-0.054	0.528	-0.054	0.528	0.390	0.463	0.390	0.463	-0.030	0.924	-0.347	0.099
$\alpha_{Jiang-Nan}$	0.116	0.225	0.116	0.225	0.774	0.004	0.774	0.004	-0.095	0.197	0.058	0.102
$\alpha_{Jian-Nan}$	0.744	<0.001	0.744	<0.001	-0.056	0.713	-0.056	0.713	-0.270	0.013	-0.107	0.015
$\alpha_{Ling-Nan}$	0.075	0.455	0.075	0.455	-0.227	0.167	-0.227	0.167	-0.558	0.045	0.086	0.568
$\beta_{Long-You}$	-0.845	0.014	-0.725	0.251	-0.960	0.496	-1.094	0.573	0	--	0	--
$\beta_{Guan-Nei}$	-0.332	<0.001	-0.178	0.023	0.686	<0.001	0.749	<0.001	-0.043	0.502	-1.390	<0.001
β_{He-Nan}	-0.957	<0.001	-0.962	<0.001	0.587	0.120	0.166	0.709	-0.142	0.245	-0.934	<0.001
$\beta_{He-Dong}$	-0.533	<0.001	-0.416	<0.001	0.289	0.126	0.136	0.651	-0.163	0.320	-0.801	<0.001
β_{He-Bei}	-0.899	<0.001	-0.904	<0.001	1.356	<0.001	1.052	0.026	-0.671	<0.001	-0.991	<0.001
$\beta_{Shan-Nan}$	-1.036	<0.001	-1.105	<0.001	0.073	0.897	0.069	0.926	-0.880	0.004	-1.045	<0.001
$\beta_{Huai-Nan}$	-0.802	<0.001	-0.761	0.001	1.349	0.179	1.057	0.430	-0.787	0.306	0.503	0.332
$\beta_{Jiang-Nan}$	-0.372	0.231	-0.458	0.212	1.369	0.001	0.791	0.166	-0.337	0.018	-0.694	<0.001
$\beta_{Jian-Nan}$	-0.568	0.062	-1.124	0.010	0.144	0.374	0.186	0.463	-1.496	<0.001	-0.663	<0.001
$\beta_{Ling-Nan}$	-0.604	0.006	-0.659	0.010	-0.724	0.034	-0.555	0.174	-0.060	0.881	-0.871	0.022
c	3875	0.034	3875	0.034	11871	<0.001	11871	<0.001	10458	0.016	153.2	0.943
R^2 adjusted	0.953		0.953		0.570		0.570		0.768		0.941	

Note: Coefficients marked in red in Tables 4-4~4-8 have p-value lower than 0.005.

Table 4-5 Regression Analysis for Year 609~639 based on Model 4-2 to 4-7

<table>
<tr><th rowspan="2">Equation</th><th colspan="2">4-2</th><th colspan="2">4-3</th><th colspan="2">4-4</th><th colspan="2">4-5</th><th colspan="2">4-6</th><th colspan="2">4-7</th></tr>
<tr><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th></tr>
<tr><td>α</td><td>-0.077</td><td><0.001</td><td>-0.069</td><td><0.001</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">N/A</td><td>-0.030</td><td>0.079</td><td colspan="2" rowspan="2">N/A</td></tr>
<tr><td>β</td><td>-0.738</td><td><0.001</td><td>-0.712</td><td><0.001</td><td>-0.700</td><td><0.001</td></tr>
<tr><td>α_N</td><td colspan="2" rowspan="6">N/A</td><td colspan="2" rowspan="4">N/A</td><td>-0.075</td><td><0.001</td><td>-0.496</td><td><0.001</td><td colspan="2" rowspan="6">N/A</td><td colspan="2" rowspan="6">N/A</td></tr>
<tr><td>α_S</td><td>0.018</td><td>0.802</td><td>1.119</td><td><0.001</td></tr>
<tr><td>β_N</td><td>-0.687</td><td><0.001</td><td>-0.312</td><td><0.001</td></tr>
<tr><td>β_S</td><td>-0.953</td><td><0.001</td><td>-0.352</td><td><0.001</td></tr>
<tr><td>γ_N</td><td>-2458</td><td>0.287</td><td>-3908</td><td>0.127</td><td colspan="2" rowspan="2">N/A</td></tr>
<tr><td>γ_S</td><td>6822</td><td><0.001</td><td>8196</td><td><0.001</td></tr>
<tr><td>$\alpha_{Long-You}$</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="20">N/A</td><td>0.232</td><td>0.983</td></tr>
<tr><td>$\alpha_{Guan-Nei}$</td><td>-0.012</td><td>0.976</td></tr>
<tr><td>α_{He-Nan}</td><td>0.013</td><td>0.933</td></tr>
<tr><td>$\alpha_{He-Dong}$</td><td>-0.168</td><td>0.705</td></tr>
<tr><td>α_{He-Bei}</td><td>-0.010</td><td>0.962</td></tr>
<tr><td>$\alpha_{Shan-Nan}$</td><td>-0.162</td><td>0.920</td></tr>
<tr><td>$\alpha_{Huai-Nan}$</td><td>-0.109</td><td>0.920</td></tr>
<tr><td>$\alpha_{Jiang-Nan}$</td><td>0.098</td><td>0.795</td></tr>
<tr><td>$\alpha_{Jian-Nan}$</td><td>0.694</td><td>0.845</td></tr>
<tr><td>$\alpha_{Ling-Nan}$</td><td>-0.043</td><td>0.977</td></tr>
<tr><td>$\beta_{Long-You}$</td><td>-1.116</td><td>0.893</td></tr>
<tr><td>$\beta_{Guan-Nei}$</td><td>-0.368</td><td>0.795</td></tr>
<tr><td>β_{He-Nan}</td><td>-0.925</td><td>0.262</td></tr>
<tr><td>$\beta_{He-Dong}$</td><td>-0.481</td><td>0.745</td></tr>
<tr><td>β_{He-Bei}</td><td>-0.865</td><td>0.544</td></tr>
<tr><td>$\beta_{Shan-Nan}$</td><td>-0.973</td><td>0.254</td></tr>
<tr><td>$\beta_{Huai-Nan}$</td><td>-0.576</td><td>0.936</td></tr>
<tr><td>$\beta_{Jiang-Nan}$</td><td>-0.308</td><td>0.940</td></tr>
<tr><td>$\beta_{Jian-Nan}$</td><td>-0.327</td><td>0.950</td></tr>
<tr><td>$\beta_{Ling-Nan}$</td><td>-0.586</td><td>0.876</td></tr>
<tr><td>$\gamma_{Long-You}$</td><td>-3431</td><td>0.505</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{Guan-Nei}$</td><td>8183</td><td>0.075</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>γ_{He-Nan}</td><td>-23046</td><td><0.001</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{He-Dong}$</td><td>2220</td><td>0.672</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>γ_{He-Bei}</td><td>-17183</td><td>0.003</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{Shan-Nan}$</td><td>-261</td><td>0.939</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{Huai-Nan}$</td><td>-5427</td><td>0.259</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{Jiang-Nan}$</td><td>9686</td><td>0.005</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{Jian-Nan}$</td><td>26934</td><td><0.001</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>$\gamma_{Ling-Nan}$</td><td>4926</td><td>0.114</td><td>5.3e15</td><td>0.972</td></tr>
<tr><td>c</td><td>9883</td><td><0.001</td><td>4364</td><td>0.003</td><td>4288</td><td>0.004</td><td>-11257</td><td>0.03</td><td>2602</td><td>0.217</td><td>-5.3e15</td><td>0.972</td></tr>
<tr><td>R^2 adjusted</td><td colspan="2">0.884</td><td colspan="2">0.887</td><td colspan="2">0.889</td><td colspan="2">0.665</td><td colspan="2">0.906</td><td colspan="2">0.956</td></tr>
</table>

Table 4-6 Regression Analysis for Year 639~742 based on Model 4-2 to 4-7

Equation	4-2		4-3		4-4		4-5		4-6		4-7	
	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value	Coeff.	p-value
α	0.399	<0.001	0.327	<0.001	N/A		N/A		0.202	0.003	N/A	
β	0.472	<0.001	0.466	<0.001					0.550	<0.001		
α_N	N/A		N/A		0.387	<0.001	0.453	0.000	N/A		N/A	
α_S					0.173	0.236	0.096	0.462				
β_N					0.532	<0.001	0.552	0.000				
β_S					0.342	0.034	0.323	0.044				
γ_N			8.6e17	0.46	-7.3e17	0.517	N/A					
γ_S			8.6e17	0.46	-7.3e17	0.517						
$\alpha_{Long-You}$	N/A		N/A		N/A		N/A		N/A		0.747	0.493
$\alpha_{Guan-Nei}$											-0.061	0.634
α_{He-Nan}											0.023	0.860
$\alpha_{He-Dong}$											0.330	0.258
α_{He-Bei}											0.387	0.011
$\alpha_{Shan-Nan}$											-0.750	0.074
$\alpha_{Huai-Nan}$											0.362	0.605
$\alpha_{Jiang-Nan}$											0.870	<0.001
$\alpha_{Jian-Nan}$											0.242	0.169
$\alpha_{Ling-Nan}$											-0.068	0.734
$\beta_{Long-You}$											1.478	0.423
$\beta_{Guan-Nei}$											0.690	<0.001
β_{He-Nan}											0.062	0.857
$\beta_{He-Dong}$											0.307	0.074
β_{He-Bei}											1.309	0.001
$\beta_{Shan-Nan}$											0.268	0.597
$\beta_{Huai-Nan}$											1.341	0.140
$\beta_{Jiang-Nan}$											1.803	<0.001
$\beta_{Jian-Nan}$											0.220	0.135
$\beta_{Ling-Nan}$											-0.518	0.143
$\gamma_{Long-You}$									-10388	0.064	-7.4e16	0.749
$\gamma_{Guan-Nei}$									-7701	0.148	-7.4e16	0.749
γ_{He-Nan}									37399	<0.001	-7.4e16	0.749
$\gamma_{He-Dong}$									-7154	0.221	-7.4e16	0.749
γ_{He-Bei}									28321	<0.001	-7.4e16	0.749
$\gamma_{Shan-Nan}$									-5951	0.157	-7.4e16	0.749
$\gamma_{Huai-Nan}$									10843	0.082	-7.4e16	0.749
$\gamma_{Jiang-Nan}$									17223	<0.001	-7.4e16	0.749
$\gamma_{Jian-Nan}$									-28400	<0.001	-7.4e16	0.749
$\gamma_{Ling-Nan}$									-22418	<0.001	-7.4e16	0.749
c	6668	0.023	-8.6e17	0.46	-7.3e17	0.517	11077	<0.001	11773	<0.001	7.4e16	0.749
R^2 adjusted	0.241		0.286		0.292		0.292		0.539		0.656	

Table 4-7 Regression Analysis for Year 742~813 based on Model 4-2 to 4-7

<table>
<tr><th rowspan="2">Equation</th><th colspan="2">4-2</th><th colspan="2">4-3</th><th colspan="2">4-4</th><th colspan="2">4-5</th><th colspan="2">4-6</th><th colspan="2">4-7</th></tr>
<tr><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th><th>Coeff.</th><th>p-value</th></tr>
<tr><td>α</td><td>-0.29</td><td><0.001</td><td>-0.299</td><td><0.001</td><td colspan="2" rowspan="2">N/A</td><td colspan="2" rowspan="2">N/A</td><td>-0.285</td><td><0.001</td><td colspan="2" rowspan="2">N/A</td></tr>
<tr><td>β</td><td>-0.273</td><td><0.001</td><td>-0.277</td><td><0.001</td><td>-0.290</td><td><0.001</td></tr>
<tr><td>α_N</td><td colspan="2" rowspan="6">N/A</td><td colspan="2" rowspan="4">N/A</td><td>-0.321</td><td><0.001</td><td>-0.335</td><td><0.001</td><td colspan="2" rowspan="6">N/A</td><td colspan="2" rowspan="6">N/A</td></tr>
<tr><td>α_S</td><td>-0.110</td><td>0.181</td><td>-0.104</td><td>0.204</td></tr>
<tr><td>β_N</td><td>-0.153</td><td>0.042</td><td>-0.166</td><td>0.020</td></tr>
<tr><td>β_S</td><td>-0.740</td><td><0.001</td><td>-0.729</td><td><0.001</td></tr>
<tr><td>γ_N</td><td>4234</td><td>0.409</td><td>-1497</td><td>0.826</td><td colspan="2" rowspan="2">N/A</td></tr>
<tr><td>γ_S</td><td>-216.3</td><td>0.948</td><td>5209</td><td>0.308</td></tr>
<tr><td>$\alpha_{Long-You}$</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="30">N/A</td><td colspan="2" rowspan="20">N/A</td><td>0</td><td>--</td></tr>
<tr><td>$\alpha_{Guan-Nei}$</td><td>-0.425</td><td><0.001</td></tr>
<tr><td>α_{He-Nan}</td><td>-0.353</td><td><0.001</td></tr>
<tr><td>$\alpha_{He-Dong}$</td><td>-0.397</td><td>0.009</td></tr>
<tr><td>α_{He-Bei}</td><td>-0.208</td><td>0.001</td></tr>
<tr><td>$\alpha_{Shan-Nan}$</td><td>0.511</td><td>0.352</td></tr>
<tr><td>$\alpha_{Huai-Nan}$</td><td>0.181</td><td>0.681</td></tr>
<tr><td>$\alpha_{Jiang-Nan}$</td><td>-0.095</td><td>0.198</td></tr>
<tr><td>$\alpha_{Jian-Nan}$</td><td>-0.456</td><td>0.001</td></tr>
<tr><td>$\alpha_{Ling-Nan}$</td><td>-0.277</td><td>0.515</td></tr>
<tr><td>$\beta_{Long-You}$</td><td>0</td><td>--</td></tr>
<tr><td>$\beta_{Guan-Nei}$</td><td>-0.028</td><td>0.664</td></tr>
<tr><td>β_{He-Nan}</td><td>-0.187</td><td>0.178</td></tr>
<tr><td>$\beta_{He-Dong}$</td><td>-0.164</td><td>0.323</td></tr>
<tr><td>β_{He-Bei}</td><td>-0.707</td><td><0.001</td></tr>
<tr><td>$\beta_{Shan-Nan}$</td><td>-0.843</td><td>0.006</td></tr>
<tr><td>$\beta_{Huai-Nan}$</td><td>-0.297</td><td>0.776</td></tr>
<tr><td>$\beta_{Jiang-Nan}$</td><td>-0.288</td><td>0.057</td></tr>
<tr><td>$\beta_{Jian-Nan}$</td><td>-1.507</td><td><0.001</td></tr>
<tr><td>$\beta_{Ling-Nan}$</td><td>0.092</td><td>0.834</td></tr>
<tr><td>$\gamma_{Long-You}$</td><td>0</td><td>--</td><td>0</td><td>--</td></tr>
<tr><td>$\gamma_{Guan-Nei}$</td><td>-464</td><td>0.963</td><td>-6850</td><td>0.620</td></tr>
<tr><td>γ_{He-Nan}</td><td>14451</td><td>0.185</td><td>17146</td><td>0.355</td></tr>
<tr><td>$\gamma_{He-Dong}$</td><td>3439</td><td>0.705</td><td>4742</td><td>0.736</td></tr>
<tr><td>γ_{He-Bei}</td><td>-3858</td><td>0.723</td><td>13758</td><td>0.455</td></tr>
<tr><td>$\gamma_{Shan-Nan}$</td><td>6696</td><td>0.506</td><td>-19380</td><td>0.467</td></tr>
<tr><td>$\gamma_{Huai-Nan}$</td><td>8508</td><td>0.535</td><td>-26137</td><td>0.517</td></tr>
<tr><td>$\gamma_{Jiang-Nan}$</td><td>18341</td><td>0.003</td><td>-113</td><td>0.990</td></tr>
<tr><td>$\gamma_{Jian-Nan}$</td><td>-43629</td><td><0.001</td><td>30300</td><td>0.012</td></tr>
<tr><td>$\gamma_{Ling-Nan}$</td><td>215</td><td>0.981</td><td>-7407</td><td>0.607</td></tr>
<tr><td>c</td><td>4331</td><td>0.383</td><td>4018</td><td>0.298</td><td>3712</td><td>0.33</td><td>7142</td><td>0.157</td><td>3698</td><td>0.471</td><td>6058</td><td>0.356</td></tr>
<tr><td>R^2 adjusted</td><td colspan="2">0.473</td><td colspan="2">0.471</td><td colspan="2">0.504</td><td colspan="2">0.506</td><td colspan="2">0.559</td><td colspan="2">0.769</td></tr>
</table>

4.3 Observation and Conclusion

Table 4-8 Calculated Parameters in the Selected Models and War Data.

Year		609~639 (232 Prefectures)				639~742 (264 Prefectures)			742~813 (171 Prefectures)			
Province		Acces. α	Local β	War	R^2 a	Acces. α	Local β	R^2 a.	Acces. α	Local β	War	R^2 a.
Whole Nation		-0.077	-0.738	94	0.884	0.399	0.472	0.241	-0.29	-0.273	57	0.473
Northern All		-0.496	-0.312	76	0.665	0.453	0.552	0.292	-0.335	-0.166	44	0.506
Southern All		1.119	-0.352	18		0.096	0.323		-0.104	-0.729	13	
North	Long-You	-0.160	-0.725	5	0.953	0.180	-1.094	0.570	0	0	8	0.768
	Guan-Nei	-0.206	-0.178	11		-0.084	0.749		0.263	-1.390	12	
	He-Nan	0.007	-0.962	31		0.564	0.166		0.014	-0.934	12	
	He-Dong	-0.158	-0.416	15		0.204	0.136		0.031	-0.801	5	
	He-Bei	0.007	-0.904	14		0.406	1.052		0.045	-0.991	7	
South	Shan-Nan	0.092	-1.105	2		0.005	0.069		0.225	-1.045	1	
	Huai-Nan	-0.054	-0.761	5		0.390	1.057		-0.347	0.503	1	
	Jiang-Nan	0.116	-0.458	6		0.774	0.791		0.058	-0.694	2	
	Jian-Nan	0.744	-1.124	1		-0.056	0.186		-0.107	-0.663	7	
	Ling-Nan	0.075	-0.659	4		-0.227	-0.555		0.086	-0.871	2	

The regression analysis parameters can explain the real situation of migration and other population dynamics in history. In order to certify the correctness of calculated parameters. The related data of war number is also utilized. The number of wars in the chaos periods in different provinces is documented based on the book "*Detailed Chronology of Wars in Every Chinese Dynasty*" [61]. The number of wars can reflect but cannot be equivalent to the real influence of chaotic events because there is no way to precisely quantify different wars' influence. The comparison between the war number and calculated parameters can be taken as a verification.

The outcomes shown in Table 4-8 are based on three models: the whole nation part is the result on model 4-2, the regional part (Northern/Southern All) is the result on model 4-5, and the provincial part is the result on model 4-8.

In the chaotic period from Year 609 to 639, based on the calculated parameters, it is clear that the general migration is moving from the north to the south. Migration movement is evident in several provinces from Guan-nei, He-dong, to Jian-nan. Based on historian research [62], it is known that Jian-nan Province receipted the most refugees from the north. Based on the war data, it is known that the Jian-nan province is the most peaceful province at that time.

In the recovery period from Year 639 to 742, the population is growing in every province. Except that, there is also migration flowing into He-nan, He-bei, and Jiang-nan. Those three provinces are the war zone in the last periods and the political and economic center enjoying the highest Accessibility. Therefore, the migration includes the refugees back home, and people flow into the political and economic center.

In the last chaotic period, the rebellion civil war focuses on He-nan, He-bei, and the capital (Guan-nei). The population loss in those provinces is apparent. The migration to Shan-nan and Guan-nei is evident also. The Shan-nan province is located in the south, which is seldom disrupted by the war and naturally attracts the refugees. As for Guan-nei Province, where even the capital is located, most prefectures away from the capital can be assumed peace, especially the northern prefectures close to the borders. It is hard for some refugees in the north to go to southern provinces because they need to go through the war zone. Many of them may go north to the border prefectures in Guan-nei provinces.

In general, it is convincing that transportation, combining with the factors indicating chaotic events, can be taken as the primary drive of population dynamics, especially for ancient times. The population changes can be divided as accessibility effects related to migration and local effects, indicating direct population loss or growth happened locally. As for the accessibility effects, it can be observed that the chaotic events will decide the direction of migration, and the accessibility value affects the size of migration.

Therefore, we suggest that there are some general implications which might be consistent throughout history. This research shows that the existing political atmosphere determines whether accessibility works in favor or against the regions. There are similar situations in the modern society today. Growing concern surrounding the existence of 'straw effects' is evident in recent studies that reveal how improved road network accessibility causes lower economic productivity in lagging areas by increasing the level of local dependency on major metropolitan areas [64].

4.4 Discussion: The Role of Accessibility in Accelerating Population Flow

Drawing upon the research presented in Chapter 4, this section of the dissertation highlights the critical interconnection between accessibility and population dynamics. Historically, pivotal events like wars or epidemics have been primary drivers of population movement, determining the patterns of migration and settlement. These events often dictated the flow of populations, directing either an influx or exodus of people in various regions.

However, the findings of this research illuminate a crucial aspect: the role of transportation accessibility in acting as a catalyst for these population movements. It is evident that enhancements in transportation infrastructure and connectivity significantly expedite the process of population flow. Improved transport links not only facilitate easier movement but also amplify the rate at which demographic shifts occur following major events.

This insight reveals that while historical events such as conflicts or health crises may set the initial course for population migration, the pace and extent of these movements are heavily influenced by the level of transportation accessibility. Such an understanding underscores the importance of transport infrastructure in shaping demographic patterns and suggests that advancements in accessibility can have profound implications for population distribution and urban development.

Therefore, this section posits that transportation accessibility plays a more significant role in demographic changes than previously recognized, acting not just as a facilitator but also as an accelerator of population movements. This perspective offers a new lens through which to view historical population dynamics, emphasizing the transformative impact of transportation infrastructure on societal evolution

5. Accessibility of Other Ancient Periods

Chapter 5 of our historical odyssey expands the realm of our accessibility modeling to encompass other illustrious epochs of ancient China: the Han, Song, and Ming dynasties. Envision this chapter as a time-traveling expedition, each stop offering a unique vista into the evolution of transportation through these pivotal periods of Chinese history.

The journey begins in Section 5.1, where we set the stage by delving into the historical significance of the Han, Song, and Ming eras. Imagine standing at the crossroads of time, witnessing the transformation of transportation infrastructures and practices. This section isn't just a narrative of changes; it's a tribute to the ingenuity and innovation of each era, highlighting how these periods each added a unique brushstroke to the evolving canvas of Chinese transportation.

Transitioning to Section 5.2, our focus shifts to the arduous yet fascinating task of reconstructing the transportation networks of these distinct periods. Picture a team of historians and data scientists, piecing together ancient maps and texts, digitally reviving long-lost roads, waterways, and pathways. This section is akin to an archaeological dig, but instead of unearthing relics, we're uncovering routes and connections that once defined the lifelines of ancient China.

In Section 5.3, we delve into the heart of our analysis, examining the accessibility models crafted for these dynasties. Here, our narrative takes a profound turn, as we uncover a pivotal economic shift from the north to the south over these periods. This section is not just about data and models; it's a revelation of how transportation shaped the economic heartbeat of a civilization, influencing trade, migration, and societal evolution.

This chapter, therefore, is more than just an extension of our modeling efforts. It's a journey through the corridors of time, where each dynasty's transportation story is meticulously woven into a broader tapestry, revealing a dynamic and interconnected portrait of historical change and continuity in China. Through this exploration, we gain not just insights into the past but also a deeper understanding of the forces that have shaped the transportation landscapes of today and possibly, of the future.

5.1 Significance of Studied Periods

This chapter explores the rationale behind extending accessibility simulations to the Han, Song, and Ming dynasties, following the initial analysis of the Tang Dynasty. It emphasizes the significance of these periods in the evolution of China's transportation infrastructure, justifying the omission of earlier dynasties due to a lack of demographic data and the exclusion of the later Qing Dynasty due to transformative Western influences during the Industrial Revolution.

This study seeks to understand the decision to model accessibility patterns in the Han, Song, and Ming dynasties, after establishing a methodology in the Tang Dynasty context. It posits that these eras are pivotal in the progression of transportation infrastructure and demographic movements, which are fundamental to the historical development of China.

By examining the Han, Song, and Ming dynasties, this chapter underscores the historical significance of transportation development and its socio-economic impacts. Each dynasty represents a unique period in China's transition from traditional to more sophisticated transportation networks, offering a comprehensive view of the historical trajectory.

A comparative approach is employed, wherein each dynasty's transportation infrastructure is modeled using the same methodological framework established for the Tang Dynasty. The analysis is grounded in historical records, with a focus on the evolution of transportation systems and their implications for population dynamics.

The simulation results reveal distinct patterns of transportation accessibility and their correlation with demographic movements across the Han, Song, and Ming dynasties. Each era showcases incremental advancements in transportation infrastructure, reflecting the broader trends in China's development.

The discussion section highlights the significance of modeling transportation accessibility in these dynasties. The Han Dynasty represents the foundation of China's imperial transportation system, the Song Dynasty showcases the burgeoning of commercial networks, and the Ming Dynasty exemplifies the consolidation of a centralized transportation policy. The paper discusses the omission of earlier dynasties due to data limitations and the Qing Dynasty due to the substantial Western impact on transportation technology, which marks a departure from traditional patterns.

5.1.1 Transportation in the Han Dynasty

The Han Dynasty's significance in the development of ancient Chinese transportation can be highlighted through several key aspects that underscore its foundational role in establishing a unified transportation network [65]:

1. Unification and Infrastructure: As the first long-lasting unified empire, the Han Dynasty was instrumental in creating a nationwide transportation network. This endeavor was crucial for maintaining the vast empire's cohesion and facilitating movement across its diverse regions.
2. Standardization of Transport: Building on the Qin Dynasty's policies, the Han administration standardized the width of cart axles, which was essential for the development of roads. This standardization allowed carts to travel efficiently throughout the empire, enhancing trade and military logistics.
3. Development of the Silk Road: The Han Dynasty is credited with establishing the Silk Road, which connected China to Central Asia, the Middle East, and beyond. This network was not only pivotal for trade but also for diplomatic and cultural exchanges, marking a significant milestone in global connectivity.
4. Post Stations and Communication: The establishment of post stations played a critical role in enhancing the Han Dynasty's administrative reach. These stations, which were positioned along key roadways and waterways, supported the rapid relay of horses and lodging for officials, facilitating timely official communications across the empire.

The Han Dynasty's comprehensive approach to transportation laid the foundation for China's future development. Its innovations in road and waterway construction, standardization of transport, and establishment of major trade routes like the Silk Road set patterns that would be followed and improved upon by subsequent dynasties. The Han Dynasty's lasting impact on transportation infrastructure made it a cornerstone of ancient Chinese transportation development, underscoring its paramount importance in the historical narrative.

5.1.2 Transportation in the Song Dynasty

The Song Dynasty is considered a highly significant era for studying the development of ancient Chinese transportation for several reasons [66]:

1. Technological Innovation and Waterways: The Song Dynasty is known for technological innovations, particularly in navigation and shipbuilding. This period saw the widespread use of the compass and improvements in ship design, which revolutionized maritime transportation. The Song government invested heavily in waterway transport, enhancing the Grand Canal and other water networks, which were vital for economic integration and the movement of massive amounts of goods and grains. These advancements positioned the Song Dynasty as a maritime power with an increased capacity for long-distance trade.
2. Commercialization and Urbanization: The Song era was characterized by a significant commercial expansion, leading to increased urbanization and the need for improved transportation systems. The demand for efficient movement of goods and people resulted in a more complex and extensive road system, which facilitated the growth of trade and markets, contributing to the economy's monetization.
3. Introduction of Paper Money: The introduction of paper money under the Song administration is another indicator of the sophisticated level of commerce and the necessity for efficient transportation systems to support this new economic activity. Paper money's circulation depended on a broad and secure network to facilitate trade across the empire.
4. Cultural and Intellectual Exchange: Improved transportation networks facilitated the exchange of not only goods but also ideas and culture, contributing to the flourishing of arts, literature, and philosophy during the Song Dynasty. The mobility of scholars, artists, and monks across the empire played a significant role in the spread of Neo-Confucianism and other intellectual movements.

The Song Dynasty's contribution to transportation development is a reflection of its broader innovative spirit, which encompassed economic, cultural, and technological aspects, making it a crucial period for understanding the evolution of ancient Chinese transportation systems.

5.1.3 Transportation in the Ming Dynasty

The Ming Dynasty is integral to the study of ancient Chinese transportation development due to several key factors [67]:

1. Expansion of the Grand Canal: The Ming Dynasty's expansion and renovation of the Grand Canal occurred during a pivotal shift from the dual capitals of Chang'an and Luoyang to the north-south capitals of Beijing and Nanjing. This period marked the political center's historic move to the northernmost point in Chinese history, while the economic center shifted entirely to the Jiangsu and Zhejiang regions. The separation of political and economic hubs placed unprecedented demands on the empire's transportation infrastructure, particularly on the Grand Canal. Its role became indispensable in bridging the north-south divide, ensuring the seamless transit of grain, military forces, and commercial goods. This infrastructural imperative was a direct response to the logistical challenges posed by the geographical separation of China's political authority and its economic heartland, making the Grand Canal not just a physical structure, but a vital artery of the Ming Dynasty's socio-economic organism.

2. Maritime Expeditions: The Ming Dynasty's maritime expeditions, led by the illustrious Admiral Zheng He, are not only celebrated for demonstrating the era's advanced shipbuilding and navigational prowess but also for their significant impact on domestic transportation infrastructure and the flow of goods. These voyages necessitated the development of robust supply chains and port facilities to support the large fleets, which in turn stimulated the improvement of roads and canals within China. The increase in maritime trade during this period brought about a surge in demand for the production and transportation of goods, influencing the entire economic landscape and integrating maritime commerce with inland transportation development. This integration marked a transformative period in China's history of global navigation and internal commerce.
3. Military Logistics: The strategic emphasis of the Ming Dynasty's transportation infrastructure was significantly influenced by the ongoing military pressure from the northern frontiers, where the threat from Mongol and Manchu forces persisted. The need for rapid and reliable troop movements to counter these threats made transportation a key military asset. This was further complicated by the economic center's shift to the south, which required the dynasty to maintain and improve long-distance routes for troop deployment from the populous and wealthy south to the contested northern borders. Thus, the Ming Dynasty's transportation strategies were heavily weighted toward ensuring military readiness and securing the nation's stability against northern incursions.
4. Documentation and Records: Among the studied dynastic periods of China, the Ming Dynasty stands closest to modernity, and as a result, the records from this era are relatively abundant and well-preserved. This richness in documentation provides a comprehensive picture of the period's transportation systems, offering scholars detailed insights into the logistics, administration, and everyday functioning of Ming transportation networks. Such extensive records serve as invaluable resources for contemporary research, allowing a clearer understanding of the historical context and the intricacies of transportation management in one of China's most pivotal eras.

In summary, the Ming Dynasty's transportation developments were instrumental in promoting economic growth, consolidating imperial control, and fostering cultural exchange. The dynasty's infrastructural achievements, particularly in road and canal construction, set lasting standards for efficiency and organization that would influence transportation systems in China and abroad.

5.2 Transportation Network Reconstruction

5.2.1 Spatial Differentiation of Study Area

As delineated in Table 5-1, 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 Figure 5-1, the blue squares overlaying the population points represent the normalized division of the study area.

Table 5-1 Historical Data Utilized in this Chapter.

Data Category	Details
Normalized Study Area	1777 normalized study area/squares.
Population	Population Distribution Data of Year 2, 742, 1102, 1522. [56][68][69][70].
Transportation	Roads in Han Dynasty [29]; Roads in Tang Dynasty [27]; Courier Routes in Ming Dynasty [69]; Natural Rivers [55]; The Grand Canal [56].
Velocity	Speed of different vehicles [58].
Geography	Digital Terrain Model of China. [57].

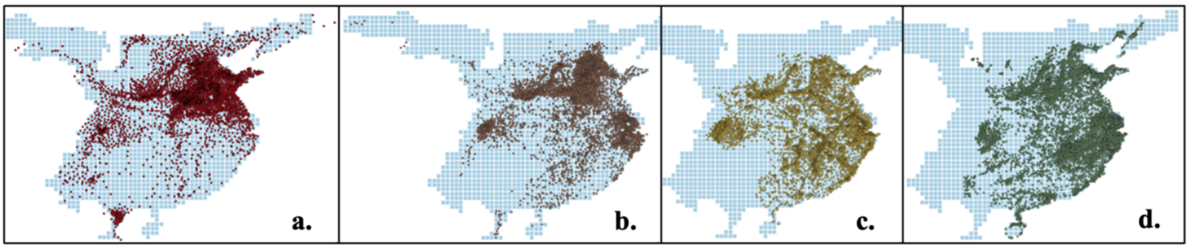


Figure 5-1 Population Distribution (1 point represents 10,000 people).
(a) 4673 points in Year 2 of the Han Dynasty; (b) 5320 points in Year 742 of the Tang Dynasty; (c) 5550 points in Year 1102 of the Song Dynasty; (d) 8813 points in Year 1522 of the Ming Dynasty.

5.2.2 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 Figure 5-1, the population distribution for the years 2, 742, 1102, and 1522 are procured [56][68][69][70]. 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.

5.2.3 Transportation

The transportation system encompasses natural routes, roads, and rivers/canals. As illustrated in Figure 5-2-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 ensure 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 is shown in Table 5-2, which is generally the same as the modeling of the Tang dynasty. Only the velocity of natural routes and courier routes is added.

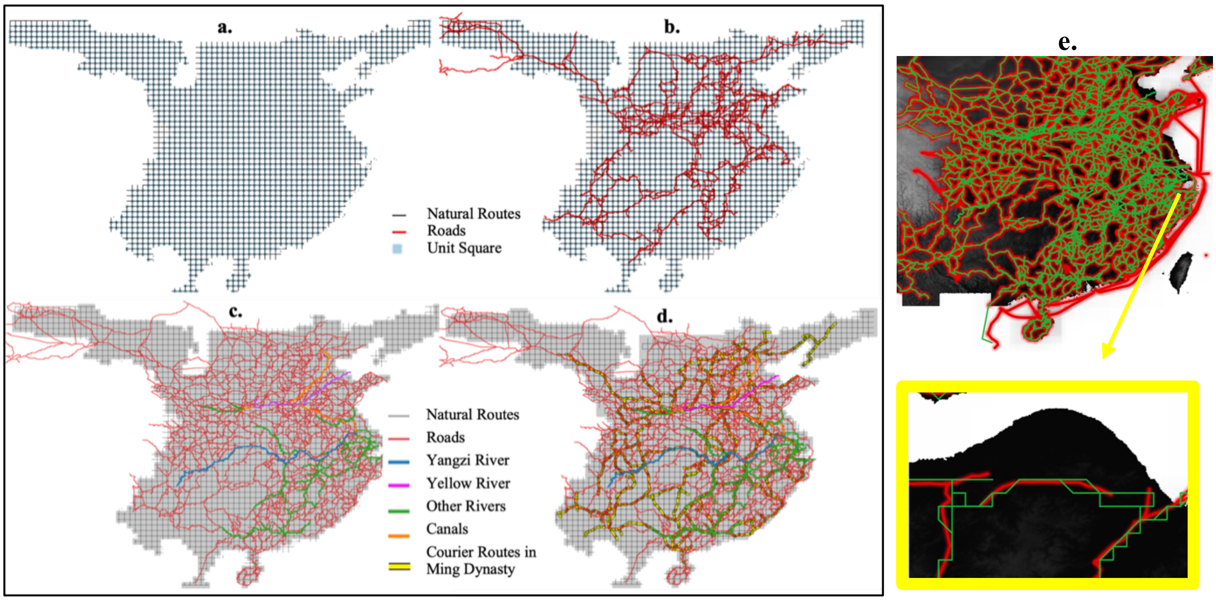


Figure 5-2 Transportation System for Years 2, 742 & 1102, and 1522.
(a) Natural routes connecting all unit squares; (b) Transportation system for Han Dynasty (Year 2);
(c) Transportation system for Tang and Song Dynasty (Year 742&1102);
(d) Transportation system for Ming Dynasty (Year 1522);
(e) Adjusted (green) and Original Routes (red) around Ning-Bo City.

Chen Cheing-siang 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 Figure 5-2-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 Figure 5-2-c, the road system data was compiled by Yen and digitized by Chu. Yen's seminal work, "*Mapping Research on Transportation of Tang Dynasty*"[27], 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 [34] 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 [32]. 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.

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 [69]'s courier routes from the Ming Dynasty depicted in Figure 5-2-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 historical 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 Figure5-2-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. The accessibility model remains the same as the modelling of Tang dynasty. The details can be checked in Chapter 3.

Table 5-2 Speed of Ancient Vehicles (Unit: kilometers/day; Lyu, 2015) [58].

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

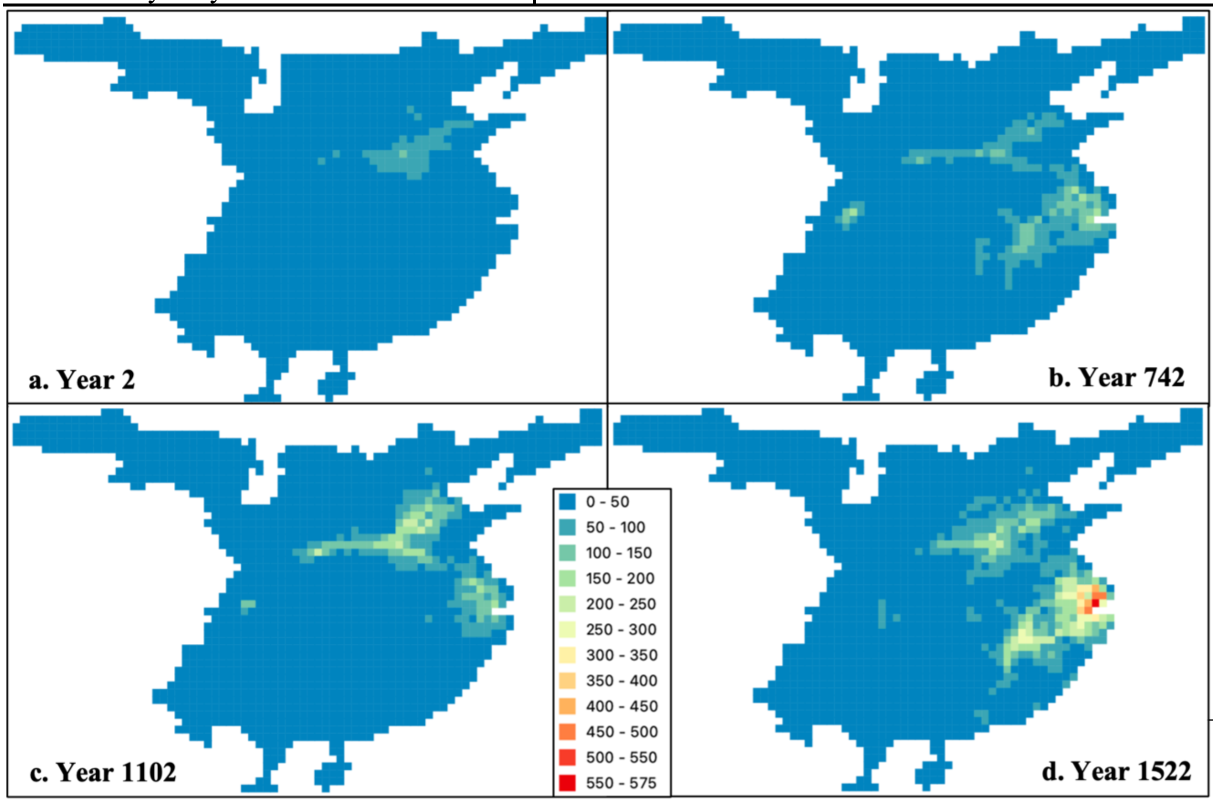


Figure 5-3 Accessibility Values for Years 2, 742, 1102, and 1522.
(Units: economic opportunities contributed by 10,000 people)

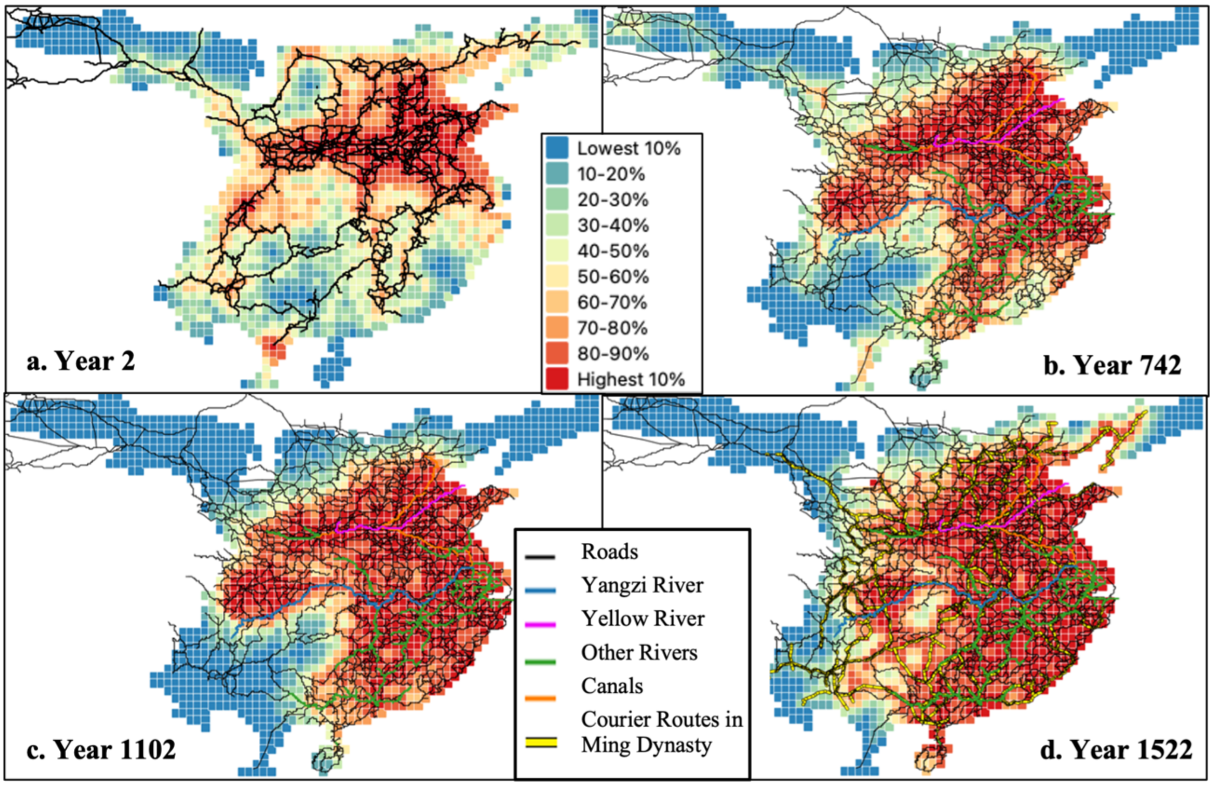


Figure 5-4 Grouping by Accessibility Values and Corresponding Transportation System.

5.3 Accessibility Results

Using the methodologies and functions outlined in Sections 5.2 and Chapter 3, we computed the accessibility values for the years 2, 742, 1102, and 1522. Figure 5-3 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 Figure 5-4, 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.

The average accessibility value for units situated in various provinces is calculated, according to the provincial division of the Tang dynasty. The right of Figure 4-1 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. As depicted in Figure 5-5, 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.

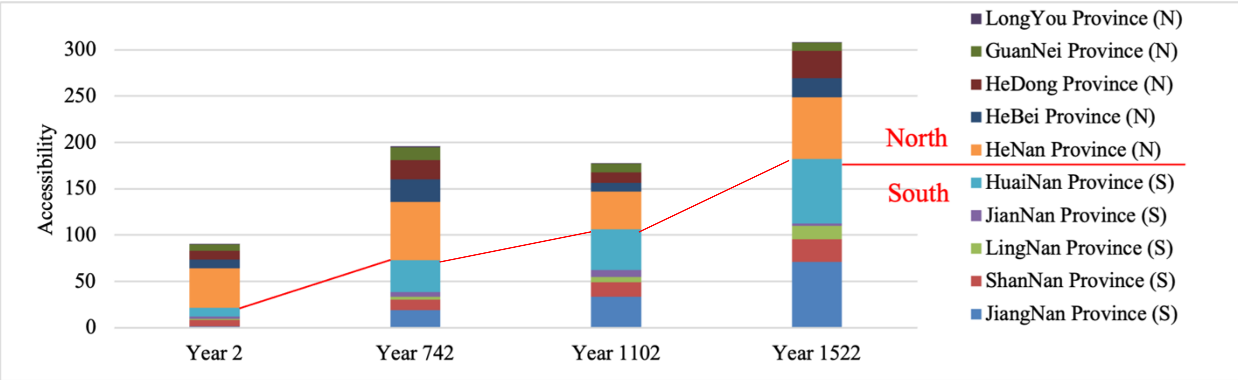


Figure 5-5 Average Accessibility Value for Different Provinces.

5.4 Discussion: Accessibility as an Indicator of Historical Trends

In Section 5.3, a comprehensive analysis was conducted utilizing the methodologies detailed in Sections 5.2 and Chapter 3 to calculate accessibility values for various timeframes: 2, 742, 1102, and 1522 CE. This analysis, graphically represented in Figure 5-3, unveils a significant initial high accessibility in northern prefectures, followed by the gradual emergence of a new center of high accessibility in the southern prefectures, particularly around the Yangtze River Delta. This shift mirrors historical narratives indicating a southward migration of the economic epicenter during the Tang dynasty.

The role of transportation infrastructure in facilitating this shift in accessibility is evident. As delineated in Figure 5-4, the factors contributing to improved accessibility varied across different historical periods. The Han dynasty's extensive road network, the river and canal systems prominent during the Tang and Song dynasties, and the courier routes established in the Ming dynasty each played a pivotal role in enhancing accessibility for their respective regions.

Further, this study delves into the average accessibility values across various provinces, as per the Tang dynasty's provincial divisions. These divisions, as illustrated on the right side of Figure 4-1, were strategically based on geographical features such as major rivers and mountain ranges, resulting in ten provinces that each formed a relatively isolated area. Remarkably, some of these provincial divisions persist in contemporary times. The analysis, as portrayed in Figure 5-5, indicates a growing dominance in total accessibility by the southern provinces over time, reflecting and potentially contributing to the historical shift of the economic center from Henan Province in the north to Jiangnan Province in the south.

These findings underscore accessibility's effectiveness as a metric for capturing and understanding historical trends, particularly in the context of China's dynamic economic and infrastructural evolution. The use of accessibility as an analytical lens provides a nuanced understanding of the interplay between transportation infrastructure and regional economic shifts, thereby offering a robust tool for historical analysis.

6. Studying Social Links with Accessibility Across Ancient China

Chapter 6 of our scholarly journey delves into the intricate tapestry of social networks and accessibility in ancient China, particularly focusing on the elite who often dictated the course of transregional economic interactions. This chapter is akin to navigating a complex network of roads and relationships, each turn revealing how the privileged few shaped the societal structures of their time through their extensive travels and connections.

We embark on this exploration in Section 6.1, which illuminates the pivotal role of social networks among the elite in ancient societies. This section paints a vivid picture of how these networks were not just conduits for personal connections but also played instrumental roles in shaping the economic and political landscapes. It sets the stage for a deeper understanding of the significance of these networks in historical research, akin to uncovering the hidden levers that moved ancient societies.

In Section 6.2, we delve into the core of our analysis: the primary database utilized for social network analysis. Here, we meticulously gather and process historical data, laying the groundwork for our exploration. This section is much like assembling a puzzle, where each piece of data, each methodology, contributes to forming a clearer picture of the ancient social fabric.

Section 6.3 takes us through a journey across different eras of Chinese history, examining the dynamics of social connections. We traverse through the Tang, Song, and Ming dynasties, unraveling how these networks evolved and impacted society over time. This part of the chapter is like traveling through a time-lapse, witnessing the transformation of social ties and their implications across centuries.

In Section 6.4, we introduce a Modified Gravity Model paired with an accessibility model, tools that allow us to quantify and visualize the social ties between cities. This section highlights how transportation infrastructure and travel time were consistent influencers of social connections, offering a novel lens to view the historical interplay between movement and relationships.

Moving to Section 6.5, our narrative takes a turn towards the realm of machine learning, addressing the dynamics that the Modified Gravity Model alone can't encapsulate. Here, we uncover the "self-reinforcement effect," especially prevalent in interactions between populous cities, thereby offering new perspectives on the dynamics of social networks.

In Section 6.6, our accessibility model comes to the forefront, shedding light on the varying degrees of societal openness to long-distance travel across different eras. This model is like a key, unlocking insights into how such openness, or the lack thereof, influenced the political and economic systems of the times.

Finally, Section 6.7 wraps up our chapter with a summary of our key findings and their implications. This concluding section encapsulates our journey, highlighting how our exploration into accessibility and social networks provides a nuanced understanding of the interconnectedness between transportation, social engagement, and broader societal dynamics in ancient China. It's a reflection of our scholarly voyage, piecing together the puzzle of how the elite's movements and connections molded the fabric of ancient societies.

6.1 What Social Network Reveals?

This section explores how the social networks of ancient upper-class individuals can reveal patterns of interregional communication and travel. Given that long-distance travel in ancient agricultural societies was predominantly a privilege of the elite [71], due to its associated costs and dangers, examining the social interactions of this class provides insights into the broader economic and social interconnections between regions.

In ancient agricultural societies, travel was an arduous and costly endeavor, typically reserved for the privileged few. This paper discusses how the social networks of the elite class—comprising government officials, traders, and landlords—were an indicator of interregional communication and the flow of ideas and resources across distances that were rarely traversed by the common populace.

Travel in ancient times was hindered by high costs, significant dangers, and the immense effort required. For the majority, who were farmers, travel was not viable due to the time cost and the absence of any compelling need or desire, as the concept of tourism emerged much later with the industrial revolution. The paper examines the circumstances that led to the rarity of long-distance travel among commoners, contrasting it with the motivations and capabilities of the elite.

The elite's access to resources allowed them to engage in long-distance travel for political, economic, and sometimes personal reasons. Their movements created a network of social and economic connections [72] that linked cities and regions in ways that were impossible for the lower classes. The emergence of professions catering to the travel needs of the elite, such as servants, cooks, chaperones, and guides, is discussed as evidence of the extent of elite travel and its influence on society and the economy.

The long-distance social links of the affluent classes serve as a reflection of the underlying economic and social interconnections between regions [73]. These networks often determine the flow of goods, information, and cultural practices. Social network analysis provides a methodology to infer patterns of travel and communication in ancient times. By mapping the connections of the elite, researchers can gain insights into the factors that facilitated or hindered travel and interaction across regions. The social networks of ancient society's upper echelons are a mirror of the broader dynamics of interregional communication. These networks were a byproduct of the economic and political activities that necessitated and facilitated long-distance travel, providing a framework for understanding how ancient societies were interconnected.

6.2 Chinese Biographical Database (CBDB)

Embedded within the expansive realms of digital humanities is the China Biographical Database (CBDB) [74], a freely accessible, relational compendium encompassing biographical details of approximately 531,898 individuals who shaped the historical tapestry of China from the 7th to the 19th centuries. This segment of the doctoral thesis delineates the inception, evolution, and scholarly application of the CBDB.

Conceived from the scholarly endeavors of Robert M. Hartwell, the CBDB has burgeoned into an indispensable digital repository for sinologists. With an aim to meticulously curate an exhaustive biographical corpus from China's extensive historiographical annals, the CBDB emerges as an unparalleled tool for researchers' intent on statistical, social network, and spatial analyses of historical data. Under the auspices of the Fairbank Center for Chinese Studies at Harvard University, the Institute of History and Philology at Academia Sinica, and the Center for Research on Ancient Chinese History at Peking University, the CBDB represents a synergy of academic excellence. This trilateral collaboration aspires to incessantly augment the database, enhancing it with rich biographical entries across Chinese dynasties, thus ensuring its continuity and relevance.

The CBDB presents a structured collection of historical data concerning Chinese individuals. This extensive repository is a gateway to exploring ancient lives and societal patterns. Beyond serving as a repository of individual life stories, the CBDB shines as an instrument for collective biographical analysis—or prosopography—which scrutinizes the shared characteristics within historical cohorts through systematic inquiries into their personal histories. This involves cross-referencing a multitude of personal data points to identify patterns and correlations within and across societal behaviors.

In addition, CBDB facilitates the examination of historical social structures through Social Network Analysis (SNA), a method long utilized in the social sciences and adapted by historians to the study of past societies. This approach assesses the personal connections that shaped individual and community life, underscoring the diversity of social and economic support networks.

The CBDB is poised to transform the study of vast populations, moving beyond small, well-defined groups to analyze patterns within the broader social fabric of China's history. It encapsulates diverse aspects of life, from familial connections and marriage alliances to educational and professional affiliations, enabling researchers to formulate and investigate an array of questions about social dynamics across time and regions.

Using the CBDB Database, Wang (2022) [75] made a statistical analysis demonstrating that a politician's support for state-building increased with the geographic size of his kinship network during the Northern Song Dynasty. Hsu (2018) [76] reconstructed the network of antiquity collectors from the 1090s to the 1120s and offered a micro-examination of this critical period of the development of collecting antiquities. Yan (2018) [77] provided an empirical exploration of the aspects of the whole political network in the Song Dynasty, the status of the core figures and the party structure, and the evolution of the time sequence diagram in different historical periods to compare and explain several historical problems and viewpoints.

Recent scholarship utilizing the CBDB has predominantly concentrated on the realms of political history and literary studies, employing the rich tapestry of ancient social networks documented within. Investigations that intertwine these social networks with the historical intricacies of transportation networks remain scarce. This doctoral research endeavors to bridge this gap, exploring the interplay between social connections and the evolution of transportation systems throughout history.

6.3 Connection Networks Dynamics

6.3.1 From Individual's Social Network to Cities' Connection Network

In the CBDB, most individuals are attributed with a unique index year and index place. The index year, serving as an artificial variable for analyses is derived from the presumed birth year. CBDB further strives to link each person with an index place. Similar to index years, place associations in CBDB are allocated according to accessible data, albeit frequently incomplete. As such, CBDB employs a hierarchy of place association categories to determine an individual's index place. It primarily utilizes the "basic affiliation", given its availability. This database also comprises the social relationships between individuals, as informed by historical records. It gathers diverse types of social relationships, encompassing family, friends, academia, politics, and writings, among others. The historical records primarily retained pertain to influential individuals in higher social strata and their associates.

For the social links, this study initially substituted individual nodes within the social network with city nodes, signifying their index locations. This substitution resulted in a social network that represented the social connections among cities, effectively mirroring the social links within their populations. This city-based social connection network is henceforth referred to as the "connection network" to differentiate it from the social networks of individuals.

A total of 90,426 social connections, excluding familial relationships, involving 36,993 individuals were retrieved from the database. However, only 55,899 of these social links have sufficient data regarding place and time information. Among these, 12,402 are multiple links (self-loops), characterized by having the same origin and end at the prefecture node. The remaining 43,497 simple links represent cross-regional connections during the ancient period.

6.3.2 Basic Information on Dynamic Social Networks along History

Each individual in the database is associated with an indexed year, usually the birth year. This helps us to define a dynamic social network. Let us assume that each individual lives for 70 years and a social link exists only for two individuals aged from 20 to 70. Therefore, each link has its active time characterized by a start year when both connected parties aged more than 20 and an end year marked by the death of one of the linked individuals. Hence, this is a dynamic social network. Beginning from year 590, this study studied it in every 10 years' gap (i.e., Years 590, 600, 610, and so on) till year 1900. For each year studied, a "snapshot" of the dynamic network is obtained by collecting all social links that were active at that year. As illustrated in Figure 6.1, comprehensive data was gathered for each designated year, encompassing the number of nodes and links, the quantity of loops and non-loop links, as well as metrics like average degree, network diameter, and network density.

As depicted in Figure 6.1, the x-axis represents the studied years, while the y-axis corresponds to various calculated values, presented in different subfigures. The differently colored zones within the figure denote distinct dynasties. Observing the link numbers in subfigures 6.1-(a) to 6.1-(c), three prominent peaks are discernible, corresponding to the Tang, Song, and Ming Dynasties. The quantity of loop links is markedly smaller than that of non-loop links, constituting less than 25% of the total. Figure 6.1-(d) illustrates the average degree of social networks, which fluctuates between 5 and 299 across different historical periods. Subfigure 6.1-(e) reveals the number of prefectures (nodes) within the social networks. Given that 351 prefectures are under consideration, it can be noted that in most periods, more than 10% of the prefectures are included in the social network, reaching up to more than 50% during peak periods. The network diameter describes the greatest distance (measured in the shortest paths) between any two nodes within the network. In layman's terms, it is the maximum number of links that must be traversed to travel from one node to any other within the network, following the shortest available path. As displayed in Figure 6.1-(f), the network diameter is typically around 4, reflecting a relatively tightly knit connection pattern among the nodes. Figure 6.1-(g) shows the network density, which quantifies the proportion of potential connections that are actual connections.

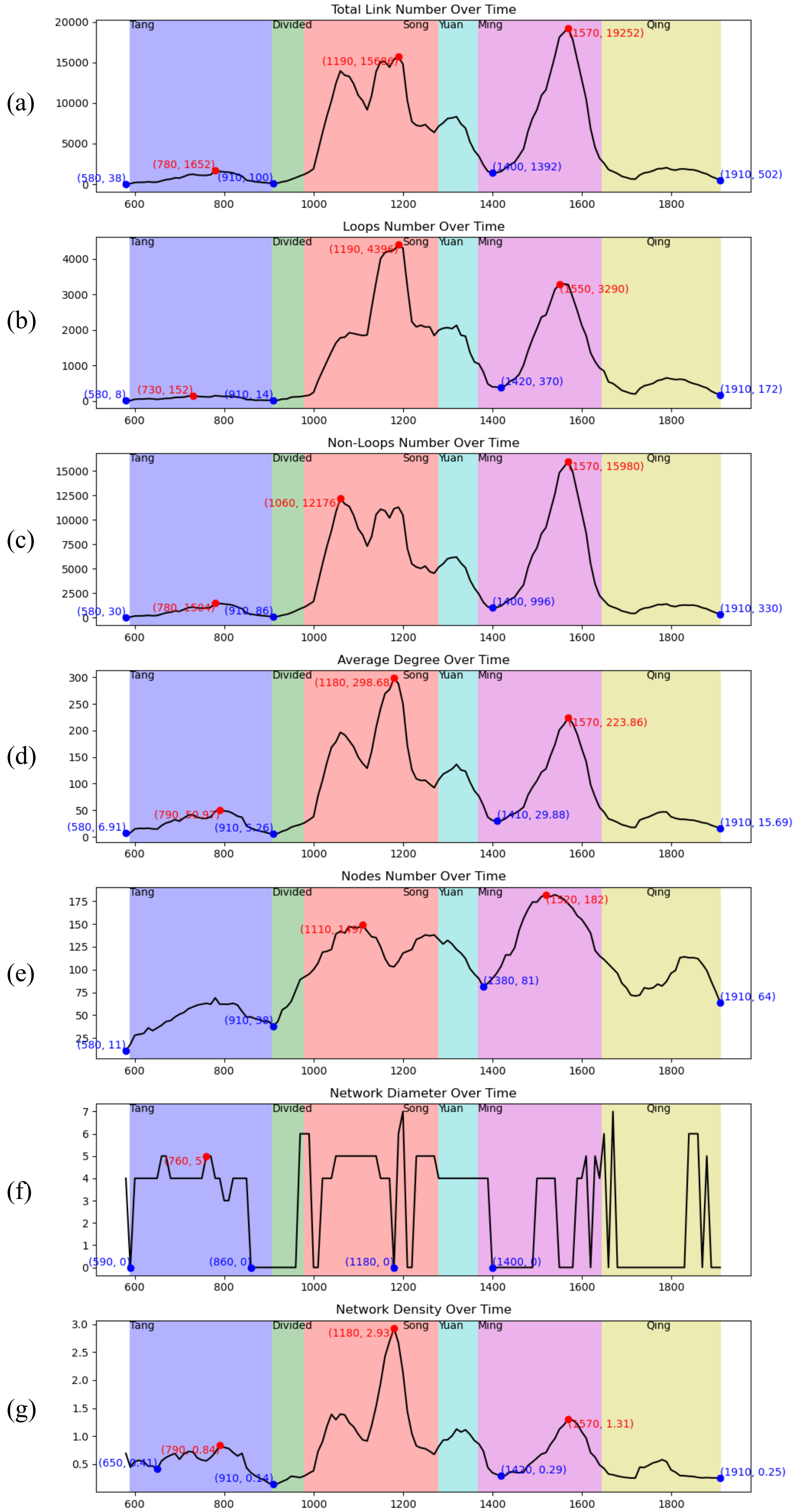


Figure 6-1 Basic Information of the Social Networks Along History.

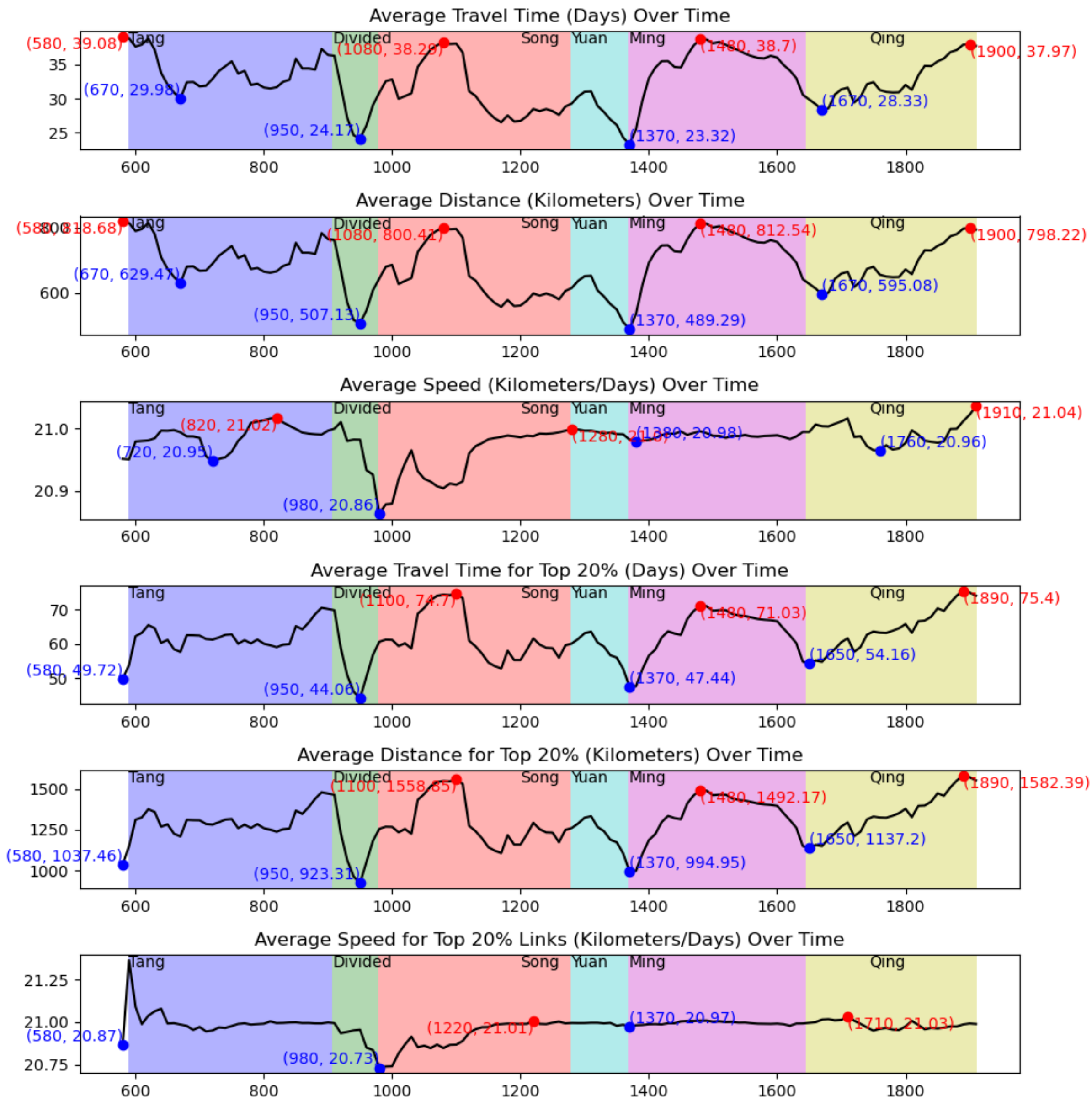


Figure 6-2 Travel Cost of Social Connections along History.

6.3.3 Travel Time Cost of Social Connections Along History

Combined with the transportation network, the travel time cost for each social link can be calculated. From this, the city-based social connection network can reflect the capacity or intention to communicate across geographical boundaries. To quantify the evolution of this ability over time, we analyzed the average geographical distance (measured along the shortest routes between the origin and end nodes), travel times, and travel speeds for the studied years. To minimize the impact of social connection loops, we also considered only the links ranking within the top 20% of the longest group.

As depicted in Figure 6-2, during chaotic eras—especially the periods marked by regime change—there is a noticeable downward trend in both the travel distance and time for both the average value and the top 20% of links' value. This decrease implies that people likely curtailed their long-distance travels during tumultuous periods, leading to a consequent reduction in the scope of social connections. The fluctuations in average speed are negligible, with variations less than 1 in 20, demonstrating that changes in speed were not a significant factor in these observed trends.

6.3.4 Social Hubs along History

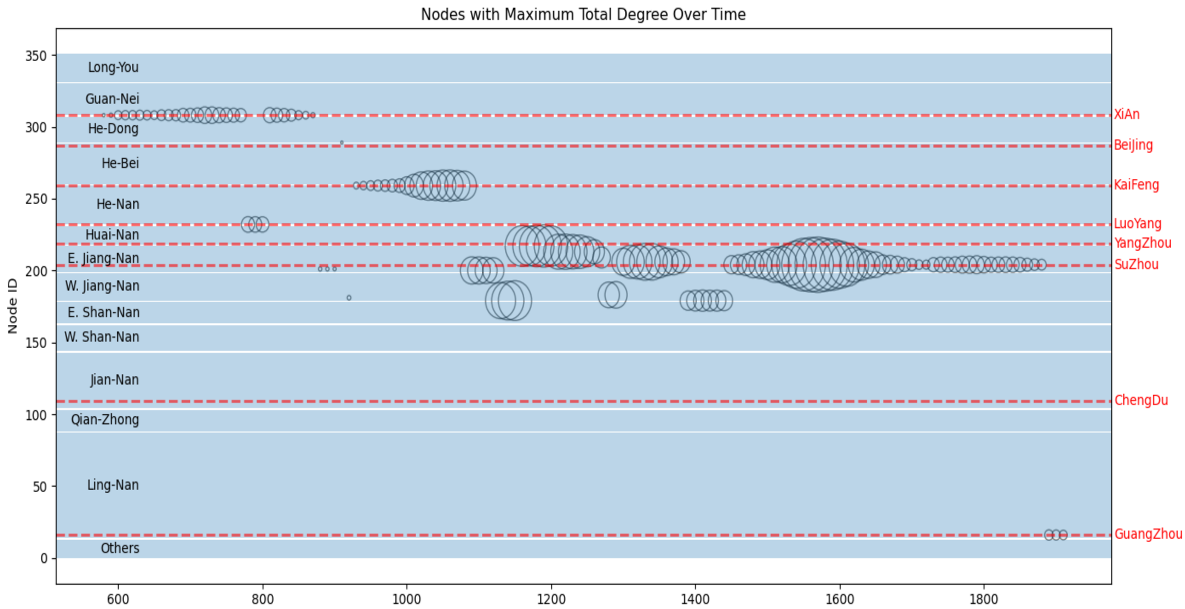


Figure 6-3 Prefectures with Maximum Degree along History.

In the study of social networks, the scale-free property [78] is likely to be pronounced. Therefore, the social hubs within the network would be highly significant. The social hub notes for the studied network are illustrated in Figure 6-3, where the prefectures with the maximum degree are listed. The x-axis represents the studied year, and the y-axis denotes the ID of the prefectures, with the size of the circles reflecting the degree number of the highlighted prefectures. The locations and IDs of these prefectures are shown in Figure 6-4.

Several essential cities are marked in Figures 6-3 and 6-4, including Xi'an, Luoyang, Kaifeng, and Beijing, which served as the capitals of various dynasties from the years 590 to 1900. Yangzhou, Suzhou, and Hangzhou are representative prefectures around the Yangzi River Delta, a region that has been the most prosperous since the Tang dynasty. Chengdu and Guangzhou are central to two other population clusters throughout history.

Figure 6-3 reveals a critical turning point around the year 1100. Before this point, the social hubs were consistently the capitals of the ruling dynasties. For example, Xian was the social hub during the Tang dynasty, and Kaifeng fulfilled this role during the Northern Song dynasty. After the year 1100, cities such as Yangzhou, Suzhou, and Hangzhou, situated around the Yangzi River Delta, began to have the highest degree numbers. This shift coincides closely with the fall of the Northern Song dynasty in 1127, when the dynasty lost control of northern China and moved the capital from Kaifeng to Hangzhou. Although China was reunited in 1279, with the central government again establishing the capital in the north, the social hub remained in the Yangzi River Delta region. This pattern highlights the intricate relationship between political power, economic prosperity, and the geography of social connections in ancient China. The detailed programming of the network analysis is attached in Appendix 1.

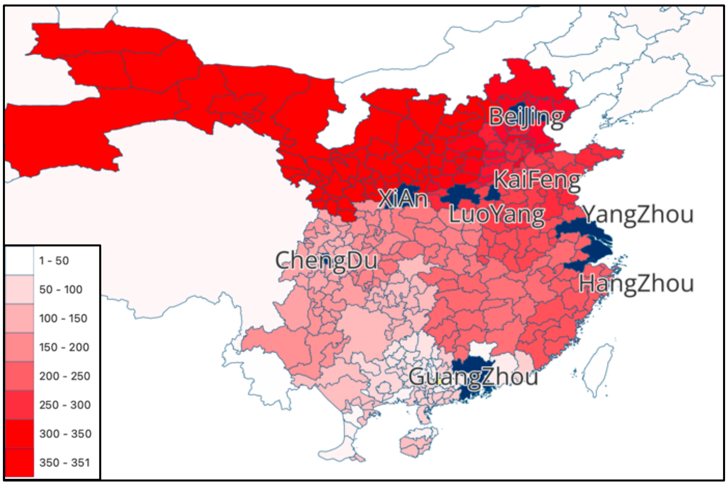


Figure 6-4 Prefectures with Their ID.

6.3.5 Social Networks for Regression Analysis

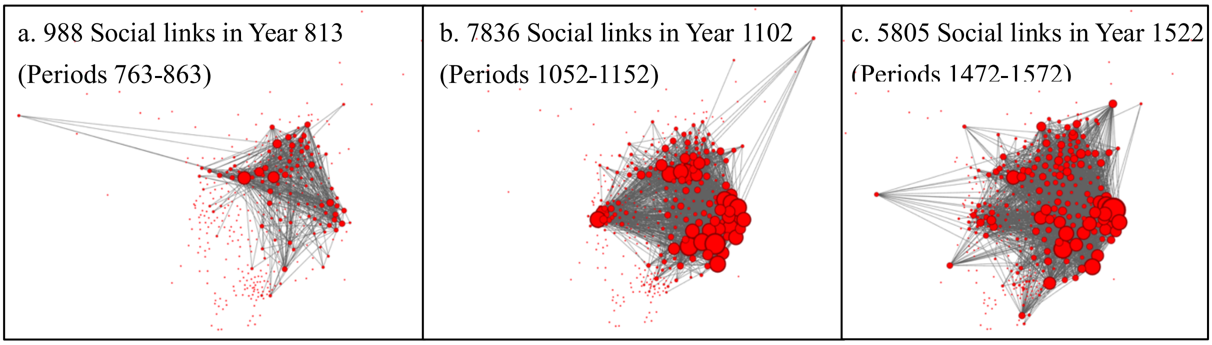


Figure 6-5 Social Links for Studied Periods.

As explained before, each link in the social network has a lifespan marked by the beginning year when both linked individuals are over 20 years old and an end year when one of the linked individuals passes away. To depict the connection scenario for a specific year, the study selected all social links that existed within a 100-year span, encompassing 50 years before and after the studied year (e.g., for Year 813, we collected all links that existed from Year 763 to Year 863). This approach is essential for analysis, as selecting data from a single year would result in an insufficient amount of data for meaningful analysis. Of course, an appropriate interval for study needs careful consideration. Too short a span may not provide enough data, while too long a span may dilute the relevance of the analysis to the specified year. This research chose a 100-year interval, centered on the target year, primarily because, in ancient times, people's social age was generally considered to span from 20 to 70 years—a 50-year period. By indirectly ensuring that the selection of 50 years before and after the target year encompasses individuals active within the social network during the study year, the approach guarantees that the individuals involved in the social network are alive, not deceased, and are of an age to actively participate in the social network, thus not too young or unborn. This methodology ensures a comprehensive and representative analysis of the social network connections relevant to the specified mid-century timeframe.

The author took all social links that existed within a 100-year span to depict the connection scenario for the mid-century. As demonstrated in Figure 6-5, different connection networks are used to represent the examined years of 813, 1102, and 1522. The node size corresponds to the total degree number within the connection network. The number of social links between pairs of cities and the total degree number is then utilized for the regression analysis in the next section.

In this study, the urban centers, namely the nodes within the connectivity network, are identified based on the prefectural divisions during the Tang Dynasty. Additionally, an alternative approach to node division was explored, utilizing a standardized area unit division characterized by square segments each measuring 50 km in length. This method of division was also applied in Chapter 5, where it was used for modeling accessibility across various dynasties. However, it was observed that the performance of the Modified Gravity Model was suboptimal when applied to this standard area unit division framework. For a detailed exposition of the network process and the associated analysis under this division method, Appendix 2 is attached in this thesis.

6.4 Modified Gravity Model and Transportation Deterrence

The proposition of intercity social connections serves as a potential indicator for travel time deterrence. Consequently, a Modified Gravity Model, as delineated in Equations (6.1) and (6.3), is posited by researchers to elucidate the social attraction interplay between two cities. The research pivots on $D_{ij,\tau}$, the total number of social links for a city pair, i and j. The hypothesis suggests that this variable is directly proportional to the cities' population and inversely proportional to travel time deterrence. In this context, travel time between two cities is employed as the negative indicator.

Linear regression analyses are executed through Equations (6.2) and (6.4). A distinguishing factor between the two Modified Gravity Models is the population parameter configuration. Equations (6.1) and (6.2) assign diverse parameters for relatively larger and smaller population values, implying that cities of varying sizes could have distinct impacts on the generation of new links or manifest diverse social network characteristics. Conversely, Equations (6.3) and (6.4) maintain uniform parameters for both population values within the city pair. As exhibited in Table 6-1, the proposed pair of Modified Gravity Models are employed across three distinct periods.

$$(\textbf{Model 1})\ \dot{D}_{i,j,\tau} = e^{c}\,\frac{\left(\hat{P}_{i,j,\tau}\right)^{\hat{\alpha}}\left(\check{P}_{i,j,\tau}\right)^{\check{\alpha}}}{\left(T_{i,j,\tau}\right)^{\beta}}, \tag{6.1}$$

which is equivalent to

$$ln\ (\dot{D}_{i,j,\tau}) = \hat{\alpha}\ ln\left(\hat{P}_{i,j,\tau}\right) + \check{\alpha}\ ln\left(\check{P}_{i,j,\tau}\right) - \beta\ ln\left(T_{i,j,\tau}\right) + c. \tag{6.2}$$

$$(\textbf{Model 2})\ \ddot{D}_{i,j,\tau} = e^{c}\,\frac{\left(P_{i,\tau}\cdot P_{j,\tau}\right)^{\alpha}}{\left(T_{i,j,\tau}\right)^{\beta}}, \tag{6.3}$$

which is equivalent to

$$ln\,(\ddot{D}_{i,j,\tau}) = \alpha\, ln\left(P_{i,\tau} \cdot P_{j,\tau}\right) - \beta\, ln\left(T_{i,j,\tau}\right) + c. \tag{6.4}$$

Let us define

$$G_{i,j,\tau} = \frac{\hat{P}_{i,j,\tau} - \breve{P}_{i,j,\tau}}{\hat{P}_{i,j,\tau}}. \tag{6.5}$$

In the above, we use the next notations:

i, j : City ID number (see Figure 6-4);

τ : Time period ($\tau = 1, 2, 3$, denoting Years 813, 1102, and 1522, respectively);

$D_{i,j,\tau}$: Number of social links in the database between cities i and j in the period τ;

$\dot{D}_{i,j,\tau}, \ddot{D}_{i,j,\tau}$: Estimated numbers of social links by Models 1 and 2, respectively;

$P_{i,\tau}, P_{j,\tau}$: Populations of cities i and j in the period τ;

Note: population used for Year 813 is family number. Others are population numbers.

$\hat{P}_{i,j,\tau}, \breve{P}_{i,j,\tau}$: The larger and smaller population between $P_{i,\tau}, P_{j,\tau}$, i.e.,

$\hat{P}_{i,j,\tau} = \max\{P_{i,\tau}, P_{j,\tau}\},\ \breve{P}_{i,j,\tau} = \min\{P_{i,\tau}, P_{j,\tau}\}$.

$T_{i,j,\tau}$: Average travel days needed for trips from city i to j and j to i in the period τ,

$\alpha, \hat{\alpha}, \breve{\alpha}$: Regression variables indicating the contribution of population in regression,

β : Regression variables indicating the contribution of travel time in regression,

c : Constant regression variables.

$G_{i,j,\tau}$: Population gap indicator defined between cities i and j in the period τ.

Table 6-1 Regression Details and Results for the Modified Gravity Model

Details			Model 1 (Equation 6-2)					Model 2 (Equation 6-4)			
Year	City Pairs #	Social Links #	R^2	$\hat{\alpha}$	$\breve{\alpha}$	β	$-c$	R^2	α	β	$-c$
813	243	988	0.182	0.268**	0.116*	0.206**	9.51**	0.170	0.187**	0.190**	9.34**
1102	1376	7836	0.177	0.190**	0.476**	0.237**	15.6**	0.168	0.331**	0.257**	16.3**
1522	1535	5805	0.216	0.326**	0.166**	0.220**	13.8**	0.207	0.231**	0.187**	13.4**

Note: ** P-value <0.01, Significant at 1% level; * P-value <0.05, Significant at 5% level.

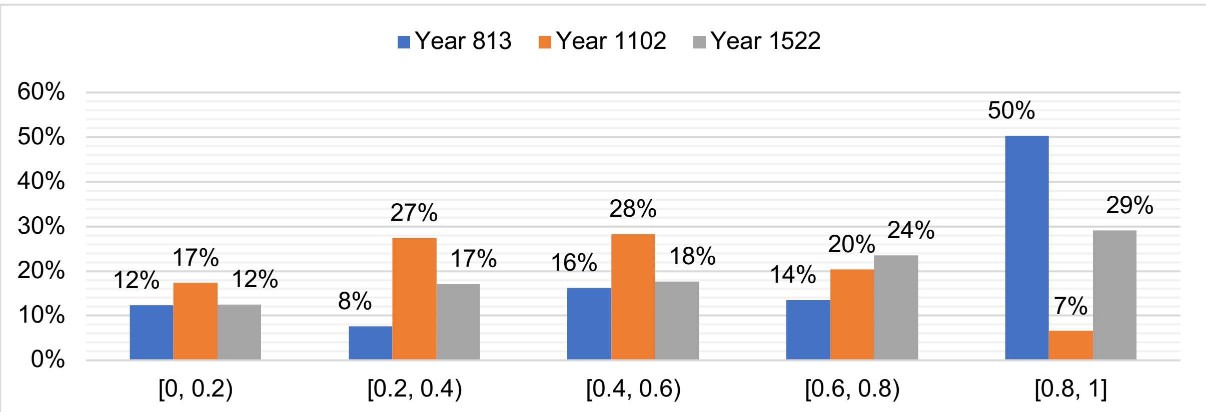


Figure 6-6 Share of the city pairs on different range of $G_{i,j,\tau}$

(X: ranges of the population gap indicator $G_{i,j,\tau}$, Y: share of social links located in the range)

Derived from regression analyses, the initial observation indicates that the travel time deterrence parameter, β, ranges from 0.19 to 0.26. Given the absence of significant infrastructure development and transportation innovation during the investigated periods, these findings suggest that the influence of travel time deterrence remained relatively consistent in antiquity, averaging around 0.21. This underscores the potential of transportation infrastructure to foster historically pervasive social networks. The accessibility calculation model mapping the social interconnectedness of each city was developed in Section 3.3, employing the constant travel time deterrence.

An additional compelling discovery pertains to the values of $\hat{\alpha}$ and $\breve{\alpha}$, which are associated with the Assortativity and Disassortativity of social networks in relation to population. An assortative network, in our context, establishes connections between two cities of comparable population sizes, while a disassortative network tends to do the opposite.

As evidenced in Figure 6-5, the capital city, with its significantly large population, dominated the social network in 813 and 1522, thereby contributing to a relatively high $\hat{\alpha}$ value. In contrast, in 1102, a plethora of cities boasted similar population sizes and demonstrated numerous social ties amongst themselves, leading to an elevated $\breve{\alpha}$ of 0.467. It should be stressed, however, that this does not imply cities with smaller populations had more connections, considering their foundational population remained limited contributing to the final degree results. Rather, city pairs with relatively close large population counts tended to have more ties.

The population disparity indicator, $G_{i,j,\tau}$, as defined in Equation (6.5), is employed to depict the Population Assortativity and Disassortativity across the three analyzed social networks. As Figure 7-6 demonstrates, over 50% of the social connections in 813 and 29% in 1522 fell within the [0.8, 1] bracket. This signifies a city with a large population linked to another city whose population was less than 20% of its population. Thus, the social networks from these two periods represent typical population disassortative networks. Conversely, in 1102, a mere 7% of the social networks fell within the [0.8, 1] range, implying that most social links were between cities with relatively similar population sizes.

$$
\begin{aligned}
\dot{D}_{ij,\tau} &= e^{c}\,\frac{\left(\hat{P}_{i,j,\tau}\right)^{\hat{\alpha}}\left(\breve{P}_{i,j,\tau}\right)^{\breve{\alpha}}}{\left(T_{i,j,\tau}\right)^{\beta}} \\
&= e^{c}\,\frac{\left(\hat{P}_{i,j,\tau}\right)^{\hat{\alpha}}\left(\left(1-G_{ij,\tau}\right)\hat{P}_{i,j,\tau}\right)^{\breve{\alpha}}}{\left(T_{i,j,\tau}\right)^{\beta}} \\
&= \left(1-G_{i,j,\tau}\right)^{\breve{\alpha}}\times e^{c}\,\frac{\left(\hat{P}_{i,j,\tau}\right)^{(\hat{\alpha}+\breve{\alpha})}}{\left(T_{i,j,\tau}\right)^{\beta}}.
\end{aligned} \tag{6.6}
$$

The interrelation of $\hat{\alpha}$ and $\breve{\alpha}$ can be elucidated with greater precision by invoking Equation (6.6). We postulate that $c'\,\frac{\left(\hat{P}_{i,j,\tau}\right)^{(\hat{\alpha}+\breve{\alpha})}}{\left(T_{i,j,\tau}\right)^{\beta}}$ remains constant. The function $G_{i,j,\tau}$, constrained to the interval [0, 1], quantifies the disparity between $\hat{P}_{i,j,\tau}$ and $\breve{P}_{i,j,\tau}$, with $\breve{\alpha}$ mirroring the divergence between $\hat{\alpha}$ and $\breve{\alpha}$. Based on the empirical regression outcomes depicted in Table 7-1, we suppose the apex for $(\hat{\alpha}+\breve{\alpha})$ is 0.666, dictating the selection of $\breve{\alpha}$'s domain as [0, 0.666]. Figure 7-7 delineates that a diminutive $G_{i,j,\tau}$ signifies a negligible variance between $\hat{P}_{i,j,\tau}$ and $\breve{P}_{i,j,\tau}$, rendering disparate values of $\breve{\alpha}$ inconsequential, as they converge upon a similar yield. Conversely, a pronounced $G_{i,j,\tau}$ intimates a substantial rift between $\hat{P}_{i,j,\tau}$ and $\check{P}_{i,j,\tau}$, necessitating a lesser $\breve{\alpha}$ to engender an augmented $\dot{D}_{i,j,\tau}$, hence, $\hat{\alpha}$ ought to be magnified. In essence, when the discrepancy between $\hat{P}_{i,j,\tau}$ and $\check{P}_{i,j,\tau}$ is stark, the genesis of links between two urban entities is predominantly contingent upon $\hat{P}_{i,j,\tau}$, the populace magnitude of the more substantial city.

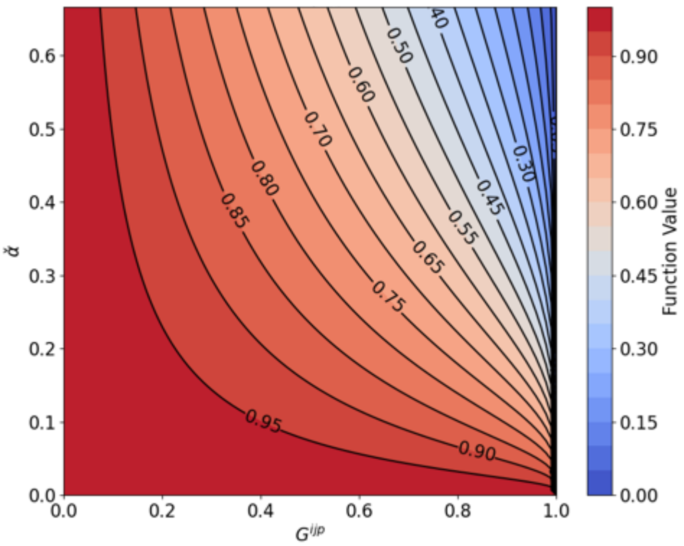


Figure 6-7 Function Value of $\left(1 - G_{i,j,\tau}\right)^{\breve{\alpha}}$

6.5 Enhancing the Modified Gravity Model with Machine Learning

The Modified Gravity Model, while offering a cogent framework for elucidating the formation of social connections during ancient China, exhibits suboptimal simulation efficacy. As evidenced in Table 6-1, the R^2 values for Modified Gravity Models across various historical periods hover around 0.2. This substantial divergence between observed degrees and the model's predictions underscores the model's limitations in capturing certain underlying dynamics in the formation of social networks. A salient oversight of the Modified Gravity Model is its inability to encapsulate the self-reinforcing nature [79] inherent in social networks, a trait not typically observed in transportation networks. Social networks exhibit a propensity for densification over time, whereby individuals with pre-existing cross-regional social ties are more inclined to develop additional such connections. To substantiate this hypothesis and enhance the Modified Gravity Model's robustness, we integrate machine learning methodologies, aiming to refine and augment the model's predictive capacity.

In the following models, as shown in Equation (6.7), we define $R_{i,j,\tau}$ as the indicator for the difference between the predicted value and actual value. A bigger $R_{i,j,\tau}$ which is larger than one indicates the Modified Gravity Model underestimates the social connection for cities *i, j*. A smaller value less than one indicates the Modified Gravity Model overestimates the social connection. In Table 6-2, we incorporated the estimated values from the Modified Gravity Model as well as other variables, such as population, accessibility, and travel time between the cities under study, as explanatory variables to model the actual number of social connections. To this end, we employed four distinct regression models: Linear Regression (LR), Decision Tree (DT), Random Forest (RF), and Gradient Boosting Decision Tree (GBRT) [80]. Critical parameters for these models, including maximum depth for the Decision Tree, the number of estimators for the Random Forest, and both the learning rate and number of estimators for the Gradient Boosting Decision Tree, were optimized to enhance the modeling process. The 5-fold cross validation is also applied for the modelling. For further details on the algorithm and additional results not presented here, refer to Appendix 3, where the comprehensive machine learning modeling process is elucidated.

$$R_{i,j,\tau} = \frac{D_{i,j,\tau}}{\dot{D}_{i,j,\tau}} \tag{6.7}$$

denote the ratio between the actual number and prediction of the social links in Equation (6-1) for the cities *i, j* in the period τ, where $D_{ij,\tau}$ is the actual number of the social links between cities *i* and *j* in the period τ, and $\dot{D}_{ij,\tau}$ is the predicted value of the Modified Gravity Model.

Table 6-2 Explanatory and Response Variables for Machine Learning Modeling.

Variable Type	Note	Meaning
Response Variable	$R_{ij,\tau}$	The ratio between the actual number and prediction of the social links between the cities *i, j* at time τ
Explanatory Variables	$\hat{P}_{i,j,\tau}$	The bigger population value between cities *i, j* at time τ; $\hat{P}_{i,j,\tau} = \max\{P_{i,\tau}, P_{j,\tau}\}$
	$\check{P}_{i,j,\tau}$	The smaller population value between cities *i, j* at time τ; $\check{P}_{i,j,\tau} = \min\{P_{i,\tau}, P_{j,\tau}\}$
	$T_{i,j,\tau}$	Average travel days needed for trips from city *i* to *j* and *j* to *i* at time τ
	$\hat{A}_{i,j,\tau}$	The bigger accessibility value between cities *i, j* at time τ; $\hat{A}_{i,j,\tau} = \max\{A_{i,\tau}, A_{j,\tau}\}$
	$\check{A}_{i,j,\tau}$	The smaller accessibility value between cities *i, j* at time τ; $\hat{A}_{i,j,\tau} = \max\{A_{i,\tau}, A_{j,\tau}\}$

Note: the accessibility data used here are all remote contributions of all other cities to the accessibility of city i, $A_{i_{other}}$.

Table 6-3 Performance (R^2 and MSE) for Different Machine Learning Models on Test Datasets.

Datasets (Year)	Data Points #	R^2				MSE			
		LR	DT	RF	GBRT	LR	DT	RF	GBRT
813	243	-0.534	-1.484	-0.256	-0.878	1.200	1.942	0.982	1.468
1102	1376	0.009	0.170	0.226	0.297	9.065	7.589	7.075	6.431
1522	1535	0.077	0.198	0.409	0.403	2.977	2.587	1.905	1.925

Figure 6-8 SHAP Summary Plot for GBRT Model of Dataset 1102.

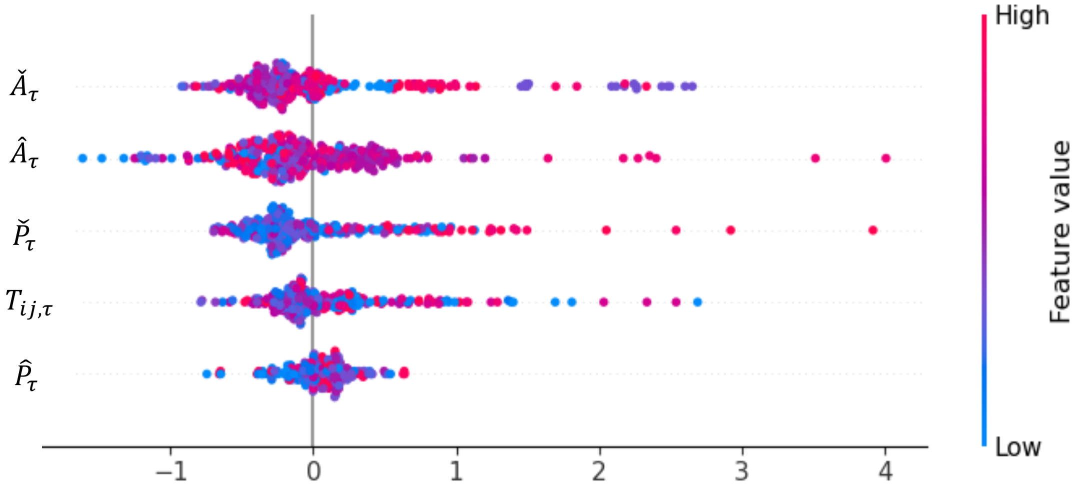


Figure 6-9 SHAP Summary Plot for RF Model of Dataset 1522.

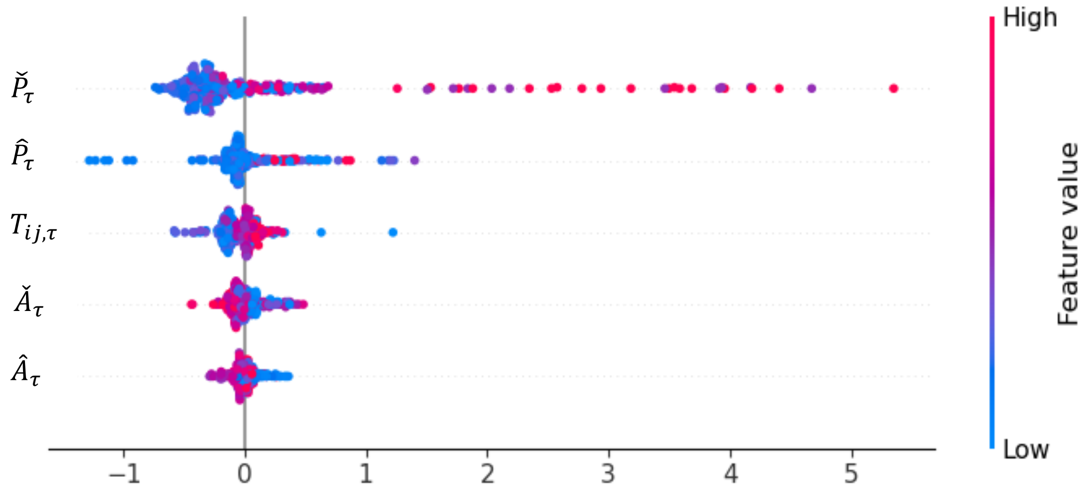


Figure 6-10 SHAP Value (Y) for $\check{A}_{i,j,\tau}$ (X) and $\hat{A}_{i,j,\tau}$ (Color Bar) in GBRT Model of Dataset 1102.

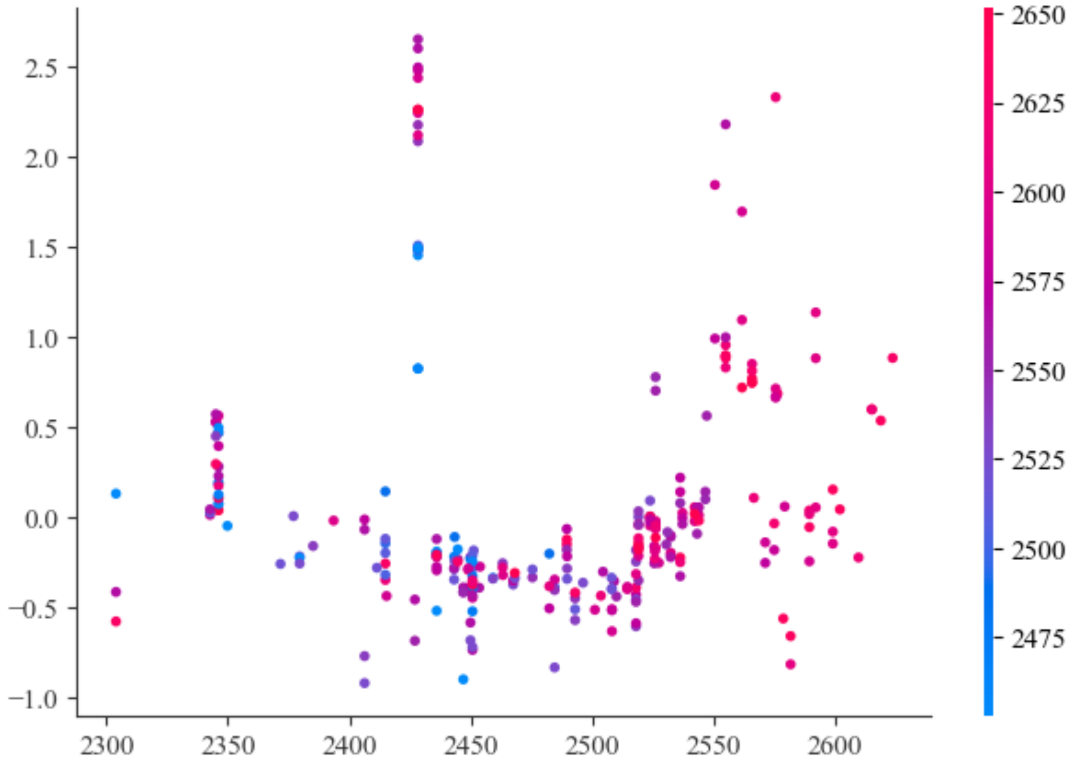
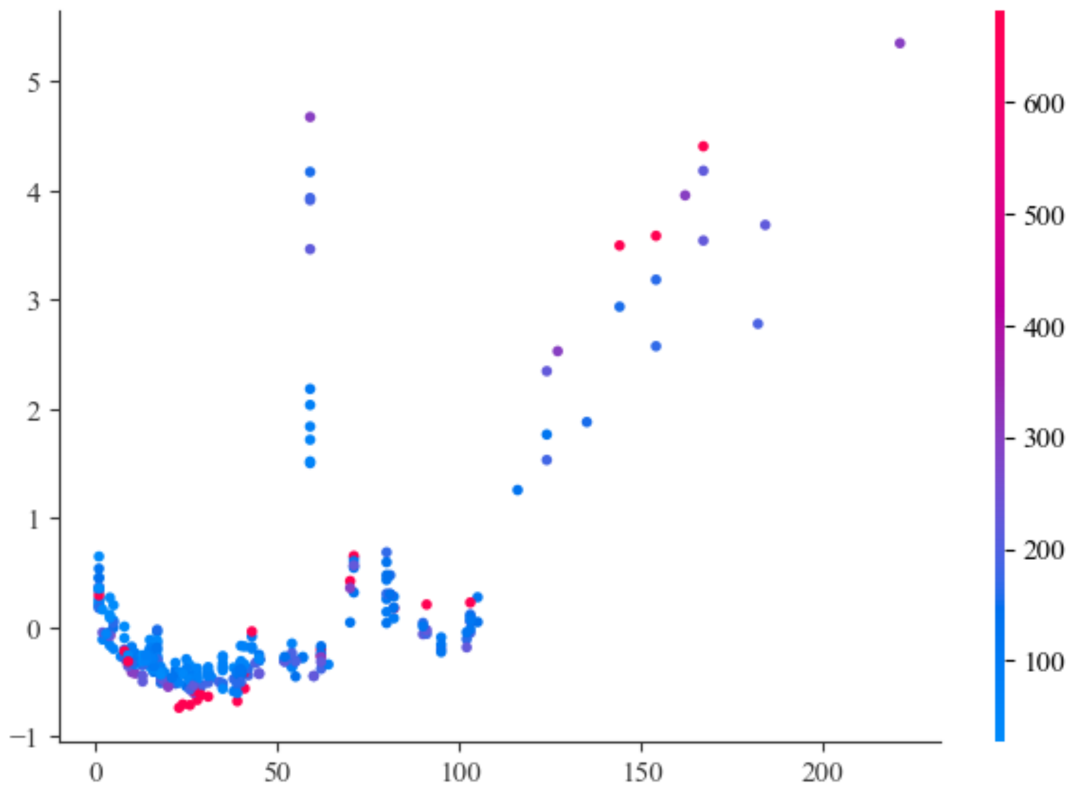


Figure 6-11 SHAP Value (Y) for $\check{P}_{i,j,\tau}$ (X) and $\hat{P}_{i,j,\tau}$ (Color Bar) in RF Model of Dataset 1522.



As illustrated in Table 6-3, the performance of machine learning models on the dataset from the year 813 exhibits significant shortcomings in its test dataset. This could potentially stem from inadequate training data. In contrast, the datasets from 1102 and 1522 show commendable performance. For these datasets, optimal parameters and models have been meticulously selected. The highest R^2 values achieved are approximately 0.3 for the 1102 dataset and 0.4 for the 1522 dataset.

We then delve into two pivotal visual tools for interpreting these machine learning models: the SHAP summary plot and the SHAP dependence plot. The SHAP summary plot offers an exhaustive overview of each feature's impact on the model output. Points on this plot represent the Shapley values for features and instances, where the horizontal axis reflects the effect's magnitude, and the vertical axis displays the distribution of effects across all features. This reveals the most influential features and their directional impact. Figures 6-8 and 6-9 highlight that accessibility values are the most influential for the 1102 dataset, while population values take precedence for the 1522 dataset. Intriguingly, smaller cities appear to exert greater influence than larger ones.

The SHAP dependence plot, conversely, investigates the interaction between one or two features and the model's predictions. This plot is essential for highlighting how variations in specific features impact the model's output, especially noting any non-linear dependencies or interactions. Figures 6-10 and 6-11 elucidate the influence of the top two features on the model's predictions. Each point represents a specific data point, with the Y-axis showing the SHAP value and the X-axis displaying the value of the top influential feature. The color denotes the value of the second most influential feature.

For the 1102 dataset, it's evident that a smaller city's accessibility value significantly influences the output. A lower accessibility value correlates with a negative output, suggesting the Modified Gravity Model might overestimate social links. Conversely, a higher accessibility value results in a positive output, indicating a potential underestimation of social links. The 1522 dataset exhibits a similar trend, with population values as the critical factor: smaller populations correlate with negative outputs (overestimation of social links), and larger populations with positive outputs (underestimation).

This discrepancy could be interpreted as a manifestation of the self-reinforcement effect discussed earlier. When smaller cities have higher accessibility or population, the formation of social linkages does not strictly adhere to the gravity theory; instead, the social linkage is reinforced. Given that our Modified Gravity Model did not account for the accessibility model's influence, introducing accessibility into the Modified Gravity Model could potentially bridge the gap between the model's estimates and the actual values of social linkages.

6.6 Accessibility-based Model

While the Modified Gravity Model serves its purpose for pairs of cities, it falls short in illustrating the national scenario comprehensively. As an alternative, this study proposes a new model to portray a city's social interconnectedness and its transportation accessibility. This innovative model aims to measure every city's relation with all other cities within the national framework, thus the computed parameter can provide insightful data about the national situation. Since accessibility is taken as the transportation contributor. Factors other than transportation also impact social connections, which can be studied based on the regression parameters of the accessibility-based model. For example, in distinct eras, political influences may alter the social acceptance of long-distance travel. In the proposed model, the regression parameter can illustrate the societal disposition or political acceptance towards extensive travel.

We propose that the social connectedness of a city correlates with its population and accessibility. We used $R_{i,\tau}$, as defined in Equation (6.7), to signify the social interconnectedness of a certain city i. This ratio value was selected based on the premise that even with varying data completeness across different periods, the distribution of the relative degree for different cities remains clear. It is expected that a city with a larger population and accessibility would have a higher probability of contributing a greater degree to total links, indicating a higher $R_{i,\tau}$. Here, population symbolizes a city's capacity to draw other cities and establish social connections, while accessibility reflects its convenience within the national transportation network or the ease of resource acquisition from diverse locations. We included an interaction term in Equation (6.8), considering the clear correlation between the two elements. The most significant term is likely the stronger determinant of social interconnectedness. To simplify comparisons across the three periods studied, only the interaction term was retained in Equation (6.9). The long-travel deterrence factor, β, is hypothesized to be 0.21 for the regression, based on the results of the Modified Gravity Model proposed in the Section 6.4.

The model discussed here is a straightforward linear regression model, which should be considered simpler compared to the previously mentioned Modified Gravity Model. This simplicity might not capture the full logic behind the formation of social networks in ancient societies. However, as shown in Tables 6-4 and 6-5, the model demonstrates moderately reliable simulation results, with R^2 values ranging between 0.23 and 0.67. This indicates that, despite its simplicity, the model can still provide a regression parameter that offers valuable insights. Therefore, we chose to adopt this model due to its ability to generate relatively reliable parameters with less complexity, making it a practical tool for analyzing the social connectedness of cities. This decision underscores the balance between model complexity and the need for manageable, interpretable results in social science research.

For a meaningful comparison across the three periods, population data units must be consistent. We converted the population data for the year 813 from family number to population number. Drawing from Yang's (1979) [81] study, the average population per family in the Tang Dynasty (which includes the year 813) was 5.72. We used this average value to establish a uniform unit of population.

$$R_{i,\tau}= \frac{D_{i,\tau}}{\sum D_{j,\tau}}. \tag{6.7}$$

$$\dot{R}_{i,\tau}= \theta P_{i,\tau}+ \delta A_{i,\tau,other}+\gamma\, P_{i,\tau}\cdot A_{i,\tau,other}+c. \tag{6.8}$$

$$\ddot{R}_{i,\tau}= \gamma\, P_{i,\tau}\cdot A_{i,\tau,other}+c. \tag{6.9}$$

In the above formulas, we use the next notations.

$R_{i,\tau}$: The ratio of the social degree number of city i to all links for the period τ,

$\dot{R}_{i,\tau}, \ddot{R}_{i,\tau}$: Estimated $R_{i,\tau}$ in different models,

$D_{i,\tau}$: The social degree number of city i for the period τ,

$P_{i,\tau}$: Population of city i for the period τ,

Note: population used for year 813 is family number. Others are population numbers.

$A_{i,\tau,other}$: Accessibility of the city i (only remote contributions made by all other cities) for the period τ.

Table 6-4 Regression Results based on Equation (6.8).

Year	City #	Social links #	R^2	$\theta[10^{-8}]$	$\delta[10^{-10}]$	$\gamma[10^{-7}]$	C
813	62	988	0.454	122**	417**	0**	-0.27**
1102	153	7836	0.237	-14	-7.19	6.41	0.018
1522	172	5805	0.668	-1.42	-1.69	0.75	0.005

Note: ** P-value <0.01, Significant at 1% level; * P-value <0.05, Significant at 5% level.

Table 6-5 Regression Results on Equation (6.9).

Year	City #	Social links #	R^2	$\gamma[10^{-8}]$	C
813	62	988	0.296	0**	0.003
1102	153	7836	0.228	8.55**	0.0004
1522	172	5805	0.666	3.85**	-0.0004

Note: ** P-value <0.01, Significant at 1% level; * P-value <0.05, Significant at 5% level.

As shown in Table 6-2, the interaction term yields a positive, albeit insignificant, contribution in the years 1102 and 1522, contrasting with a negative contribution in 813. Furthermore, in 813, both population and accessibility emerge as significant factors, conforming to anticipated positive parameters. Given the substantial magnitude of the interaction term, it may be inferred that the influence of accessibility and population on social connectivity is not as pronounced in 813 as it is in the latter two periods. Referencing the calculated γ value from Table 7-3, the investigators might infer that 1102 within the Song dynasty exhibited the greatest γ, signifying this era possessed the optimal "social atmosphere" or "political tolerance" for extensive travel, succeeded by the year 1522 within the Ming dynasty and finally the year 813 within the Tang dynasty. This analysis aligns with historical documentation.

This can be rationalized as follows: ancient societies, dictated by a small-scale peasant economy, witnessed the administration of all dynasties following a policy of "prioritizing agriculture and limiting commerce". On the one hand, the ancient businessmen were humiliated by restricting their food, clothing, housing, and transportation; on the other hand, they were trapped by imposing high taxes on them. Preceding the Tang Dynasty, commercial growth was sluggish, resulting in commercial taxes contributing a modest share to national finance. However, during the Tang and Song Dynasties, the commodity economy flourished, and commercial tax revenues saw substantial increments. The governance of this period enhanced management and control of commercial tax collection by amending commercial legislation. Of the eras studied, the Song dynasty, epitomized by the year 1102, exhibited the most advanced commercial economy [82], leading to the most considerable demand for long-distance travel. Interestingly, the Song dynasty is the only Chinese dynasty where commercial tax revenues surpassed those from agriculture [83]. Accordingly, it's logical that the Tang dynasty, exemplified by the year 813, demonstrated the least demand for long-distance travel, as the national system had only recently been established after the completion of the Grand Canal in 610. The Ming dynasty reinforced the policy of "prioritizing agriculture and limiting commerce". The Ming government even closed sea trade routes due to the incursions and disturbances caused by Japanese pirates. As estimated by Liu [84], the Ming dynasty's long-distance trade volume equates to a mere 24.2% of that of the Song dynasty. Consequently, it can be posited that the relationship between accessibility, population, and social connection is less substantial than in the Song dynasty.

6.7 Discussion: Transportation and Ancient Social Networks

6.7.1 Social Connection Formation: Integrating the Modified Gravity Model and Self-Reinforcement Dynamics

This section, building upon the discussions in Sections 6.4 and 6.5, centers on the application of the Modified Gravity Model to discern the intricate relationship between transportation networks and the formation of social connections. The Modified Gravity Model, a pivotal element in my thesis, has proven to be a robust tool in most urban contexts, demonstrating a clear direct correlation between a city's population size and the extent of its social connections. It also inversely correlates these social connections with the geographical distance between cities, thereby highlighting the impact of physical proximity on social interactions.

However, a critical limitation of the Modified Gravity Model is its inability to account for the self-reinforcement effect, particularly noticeable in interactions between cities with larger populations. This phenomenon is characterized by a tendency that stronger social ties are easier to be developed when both cities have a larger population base or enjoy a good accessibility. This aspect of social connectivity is not adequately captured by the traditional parameters of the Modified Gravity Model.

To address this gap, advanced machine learning techniques were employed, offering a more nuanced understanding of social network dynamics. These sophisticated models reveal that the Modified Gravity Model tends to underestimate the intensity of social connections between large population centers, primarily due to its oversight of the potent self-reinforcement effect inherent in these interactions.

This insight into the limitations of the Modified Gravity Model underscores the need for incorporating more complex mechanisms, like self-reinforcement, into our understanding of social networks. The application of machine learning models thus not only complements the Modified Gravity Model but also enhances our ability to capture the multifaceted nature of social connections, especially in the context of large urban centers where traditional models fall short. This approach offers a more comprehensive and accurate representation of the dynamics shaping social networks in the context of transportation and urbanization.

6.7.2 Constant Travel Deterrence Along Ancient History

The findings of my research, particularly within the framework of the Modified Gravity Model, consistently identify travel time as a significant deterrent to movement and interaction throughout history. This correlation aligns with the comprehensive analysis presented in my thesis (refer to Table 6.1), where marked improvements in travel speed are discernible only with the advent of modern vehicular technology.

Intriguingly, during ancient times, the parameters denoting travel deterrence remained constant across various dynasties. This parameter in the Modified Gravity Model, which correlates with that used in the accessibility modeling detailed in Section 3.3, is derived from studies conducted on Switzerland's historical transportation systems. The consistency of this parameter across different time periods not only substantiates the accessibility model employed in earlier chapters of my thesis but also provides a methodological foundation for deriving transportation deterrence parameters from historically recorded social network data.

This aspect of the study underscores the profound influence that historical transportation infrastructure exerted on the formation and maintenance of social networks. Prior to the introduction of modern transportation technologies, the challenges and limitations posed by travel time significantly shaped the nature and extent of social interactions.

The transition to modern transportation systems has drastically changed this dynamic. As highlighted by Axhausen [85], the proliferation of advanced transportation means has facilitated the development of more geographically dispersed social networks. This shift has been instrumental in altering the dynamics of social networks, catalyzing the formation of new connections and enabling the maintenance of long-distance relationships more feasibly.

Thus, this section of the thesis sheds light on the pivotal role of transportation in shaping social connectivity throughout history. The evolution from constant travel deterrence parameters in ancient times to the diversified, technology-enhanced travel of today highlights a fundamental shift in social network dynamics, emphasizing the interdependent relationship between transportation technology and social structures.

6.7.3 Social Acceptance for Long Distance Travel Raveled by Accessibility-based Model

The accessibility model employed in this research offers insightful revelations into the multifaceted influences on long-distance travel behaviors and the consequent formation of social networks. This model, through its generalized social deterrence parameter, provides a unique analytical approach to compare historical periods, thereby uncovering the enduring impact of other factors except travel time on societal dynamics.

Crucially, the model illuminates how political policies, economic structures, and the degree of commercial development have historically shaped attitudes and practices surrounding long-distance travel. These factors, often deeply intertwined with the socio-cultural fabric of a society, play a significant role in determining the feasibility and desirability of long-distance interactions and movements.

In sum, the accessibility model, with its emphasis on the social deterrence parameter, provides a comprehensive framework to understand how historical societies perceived and engaged with the concept of long-distance travel. This understanding is crucial in contextualizing the evolution of social networks and their dependency on the transportation modalities available in different historical periods.

7. Historical Accessibility Database of Ancient China

Chapter 7 unveils the 'Historical Accessibility' database, a profound assemblage of data on ancient Chinese society. The creation of this database is the culmination of meticulous data collection and analysis, offering a trove of insights into the transportation networks, accessibility, and socio-cultural dynamics across various Chinese dynasties. It stands as a cornerstone for future historical research, providing a detailed lens for scholars to examine and comprehend the past.

The introduction to the database in Section 7.1 gives a bird's-eye view of its contents, encapsulating the breadth of data collected — from the intricacies of transportation infrastructures to the nuances of socio-cultural elements across different eras. This part aims to spotlight the depth and expansiveness of the database, underscoring its potential utility in diverse historical inquiries.

Sections 7.2 to 7.5 unfold four application cases that delve into the relationship between accessibility and distinct facets of ancient Chinese society. Each segment hones in on a particular application, dissecting how accessibility shaped or interlinked with varied socio-historical phenomena. These portions collectively do not just demonstrate the versatile applications of the 'Historical Accessibility' database but also its significance in deepening the comprehension of ancient societal structures.

Through a series of case studies, this chapter casts light on the multifaceted influences of transportation and accessibility on historical occurrences, social frameworks, and cultural evolution, painting a complex portrait of the interdependencies that have steered the course of history.

7.1 General Contents

7.1.1 General Information and Significance

The construction of the "Historical Accessibility Database" is one of the most significant outcomes of this research. This database, a product of extensive doctoral research, is a comprehensive compilation of data that spans several crucial periods in Chinese history. It provides a unique lens to understand various aspects of ancient Chinese society, ranging from transportation to social interactions. The significance of this research work can be verified in the following aspects:

1. Multidisciplinary Integration: This database stands as a testament to the integration of historical, geographical, engineering, and sociological research. It provides a holistic view of ancient Chinese society, integrating physical aspects of transportation with human elements like social interactions and cultural dissemination. With its diverse data range, the 'Historical Accessibility' database is a valuable resource for scholars across various disciplines, including history, geography, sociology,

and data science. It encourages interdisciplinary collaboration in exploring ancient Chinese society.

2. Catalyst for Future Research on Temporal Analysis and Comparison: By making this database publicly accessible to scholars, it acts as a catalyst for future research endeavors. It opens new avenues for inquiry and can lead to groundbreaking discoveries about the intricate workings of ancient Chinese society. By spanning multiple dynasties, the database allows for comparative studies across different periods in Chinese history. Researchers can trace the evolution of infrastructure, societal norms, and cultural trends, offering insights into the dynamics of change over centuries.
3. Data Resource for Historical Model Building: The database's comprehensive data sets serve as a foundation for constructing historical models. These models can simulate various scenarios, providing a deeper understanding of the implications of transportation and social networks in historical contexts.

The 'Historical Accessibility' database is a monumental contribution to the field of historical research. It offers an unprecedented opportunity to delve into the complexities of ancient China through a data-driven lens. Its comprehensive nature and the potential for interdisciplinary research make it a valuable tool for scholars worldwide. This database not only enhances our understanding of the past but also sets a precedent for future historical data compilations and research methodologies.

This database is available on the platform of the WorldMap Community (Harvard University) in ArcGIS Online. Harvard WorldMap [86] began in 2008 to lower barriers for scholars to create, analyze, and share geospatial information. To continue the legacy and further expand opportunities for collaboration, the project has been moved to ArcGIS Online.

7.1.2 Database Content

Table 7-1 Overview of the Database Contents.

<table>
<tr><th>Data</th><th>Type</th><th>Language</th><th>Original Source</th><th>Author' Work</th></tr>
<tr><td>Historical Transport Network of Ancient China (Han, Tang, Ming)</td><td rowspan="3">Shape file</td><td rowspan="3">English</td><td colspan="2">See Sections 3.1, 3.2, 5.2.</td></tr>
<tr><td>Accessibility, Population of Unit Square Area (50*50km, 1777 Unites)</td><td colspan="2">See Sections 3.3, 3.5, Appendix 2.</td></tr>
<tr><td>Accessibility and Population of Prefecture in Sui-Tang Age</td><td colspan="2">See Sections 3.3, 3.5, 5.3.</td></tr>
<tr><td>Social Connection Network Across Ancient China</td><td>Grehi file</td><td>English, Chinese</td><td colspan="2">See Sections 6.2, 6.3.</td></tr>
<tr><td>War Data of Tang and Song Dynasty (Chinese)</td><td rowspan="3">Excel Table</td><td rowspan="3">Chinese</td><td>Wring Group of Military History [61]</td><td rowspan="3">Digitaliz-ation, key informat-ion collation</td></tr>
<tr><td>Detailed Info for Recorded “Jinshi” of Tang Dynasty (Chinese)</td><td>Tao Y. [87]</td></tr>
<tr><td>Exiled Officials of Tang Dynasty (Chinese)</td><td>Shang Y. [88]</td></tr>
<tr><td>Algorithms for Network Analysis and Machine Learning Models in this thesis</td><td>Algor ithms</td><td>English</td><td colspan="2">See Sections 6.3, 6.5, Appendix 1, 3.</td></tr>
</table>

As shown in Table 7-1, this database presents a comprehensive collection of datasets that serve as a significant resource for studying the historical transport network and social dynamics of Ancient China during the Han, Tang, and Ming dynasties. The data is organized in various formats conducive to scholarly research and analysis.

1. Historical Transport Network of Ancient China (Han, Tang, Ming).

This dataset is encapsulated in a Shapefile format, offering a detailed representation of the transportation routes of Ancient China. It is extensively documented in Sections 3.1, 3.2, and 5.2 of the data source and processing procedure. The data, provided in English, enables a deeper understanding of the connectivity and infrastructure that underpinned the ancient civilizations.

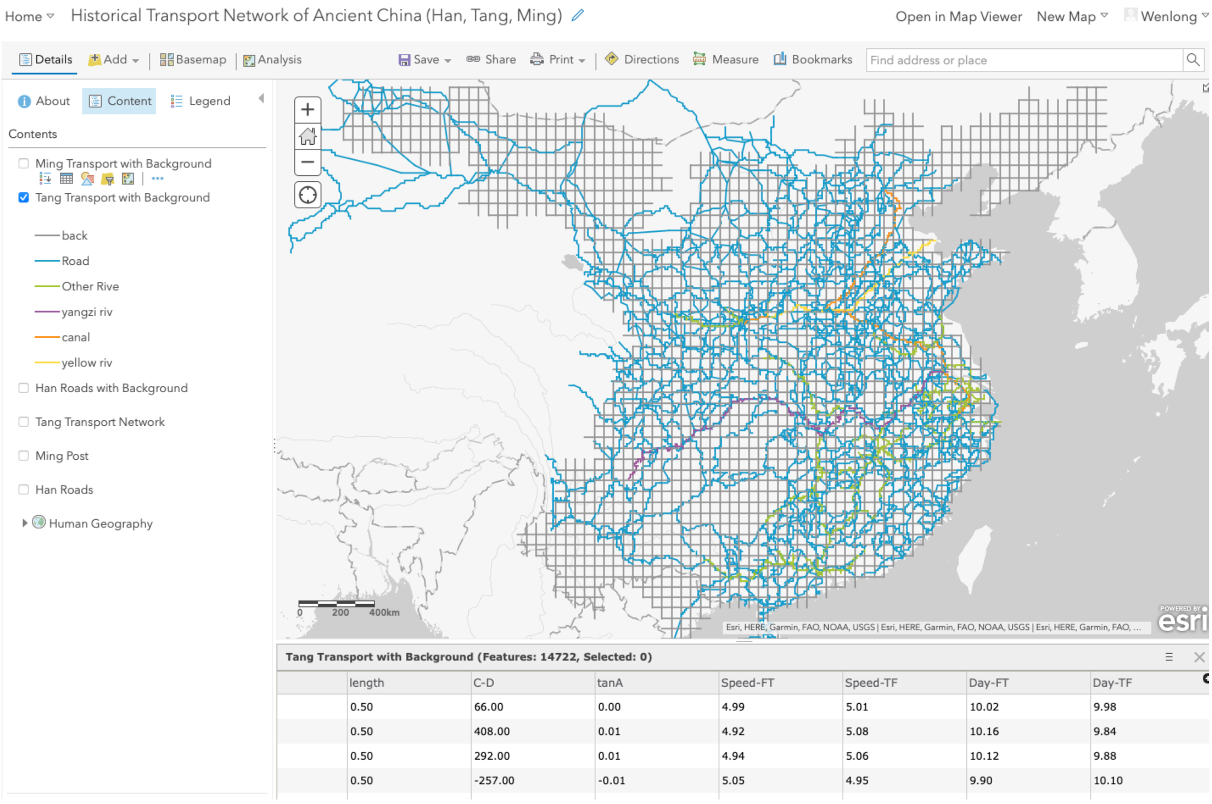


Figure 7-1 Operator Interface of Dataset “Historical Transport Network of Ancient China”.

As shown in Figure 7-1, transport networks are collected, including the location, climb, descent, slope, and estimated travel time information. A basic background grid road is applied to simulate the natural paths. The river, canal, and post routes are considered as routes with different travel speeds. For every section of the transportation routes, the following features can be found in the feature table:

- **ID:** transportation network segment label.
- **Type:** Transportation network type; where “0,1,2,3” are land trunk lines, “Grand Cana” is the Grand Canal, “Yangzi” is the mainstream of the Yangtze River, “yellow riv” is the lower reaches of the Yellow River, and “Other Rive” is the tributaries of the Yangtze River, Yellow River, and other rivers; the main type definition here is It is related to the definition of speed assignment later.
- **Horse/D+:** The time required for information flow to pass through this transportation network along the defined positive direction, in days; calculated based on the speed of fast horses on land and cargo-free waterways recorded in "Tang Huidian".

- **Wagon/D+:** The time required for cargo flow to pass through this transportation network along the defined positive direction, in days; calculated based on the speed of land carriage freight and waterway freight recorded in "Tang Huidian".
- **Horse/D-, Wagon/D-:** the time taken in the defined opposite direction; the speed change due to the direction of the land road is calculated based on the following slope-related fields. For the specific calculation formula, please refer to Formula 4 in the attached paper P150; the waterway is based on "Tang Huidian" "It is calculated based on the downstream and upstream speeds recorded in ".

The following fields are related to slope calculation and are only applicable to land trunk lines:

- **L/m:** The length of the transportation network, in meters.
- **Climb:** The height that this network cable climbs along the defined positive direction, in meters.
- **Decent:** The height that this network cable descends along the defined positive direction, in meters.
- **C-D:** Climb height minus descent height.
- **SinA:** Approximate slope, which is the ratio of difference to the length.

2. Accessibility, Population of Unit Square Area (50*50km, 1777 Units).

A meticulously structured dataset, it maps the accessibility and demographic distribution across Ancient China. Researchers can refer to Sections 3.3 and 3.5 for the accessibility calculation details and Appendix 2 for the unit area division. As shown in Figure 7-2, the accessibility and population of every square area (50*50km) covering Ancient China Proper for Years 2, 742, 1102, and 1522 are available.

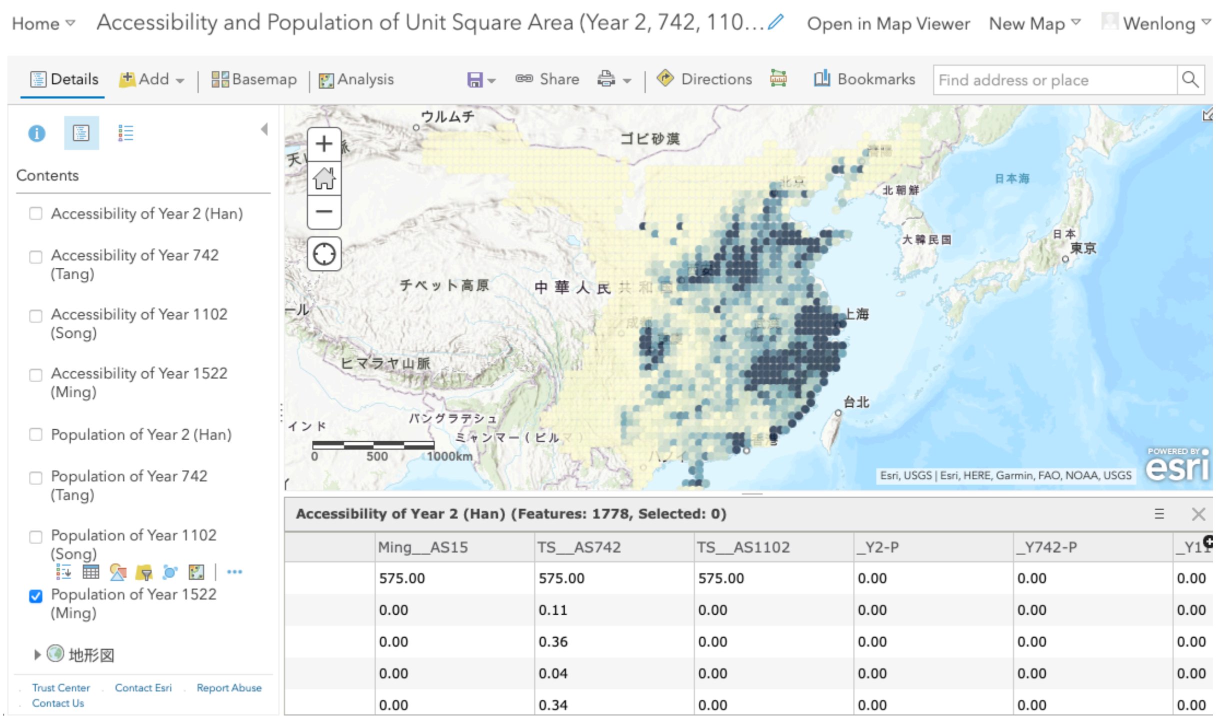
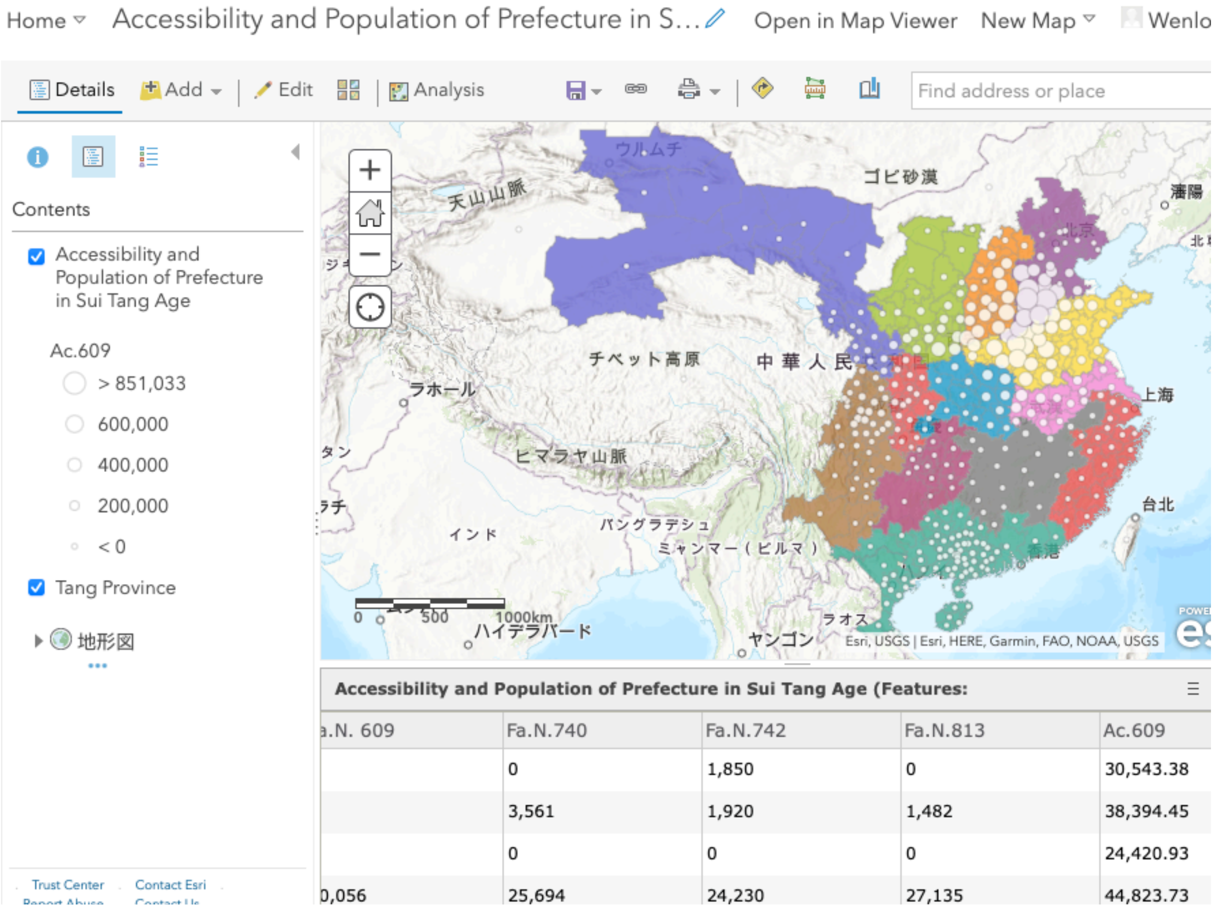


Figure 7-2 Operator Interface of Dataset “Accessibility, Population of Unit Square Area”.

3. Accessibility and Population of Prefecture in Sui-Tang Age.

As shown in Figure 7-3, this dataset complements the prior dataset by focusing on the Sui-Tang era, offering granular insights into the demographic and accessibility distribution for every prefecture in the Sui-Tang Age, including years 609, 639, 740, 742, and 813. Researchers can refer to Sections 3.3, 3.5, and 5.3 for further insights into the methodologies and implications of these data points.



a.N. 609	Fa.N.740	Fa.N.742	Fa.N.813	Ac.609
	0	1,850	0	30,543.38
	3,561	1,920	1,482	38,394.45
	0	0	0	24,420.93
0,056	25,694	24,230	27,135	44,823.73

Figure 7-3 Operator Interface of Dataset “Accessibility, Population of Prefectures in Sui-Tang Age”.

4. Social Connection Network Across Ancient China.

The Social Connection Network is offered in a Gephi file format, which is suitable for network analysis. The original data source and the possessing procedures are detailed in Sections 6.2 and 6.3. This dataset is pivotal for understanding the social fabric and interaction patterns of historical Chinese society. The social connection network includes 351 city nodes and 55,899 edges, transformed based on the social networks between 36,994 individuals from the 200s to 1900s. As shown in Figure 7-4, every node presents a city based on the administrative division of the Tang dynasty. The nodes’ size represents their degree within the social connection network.

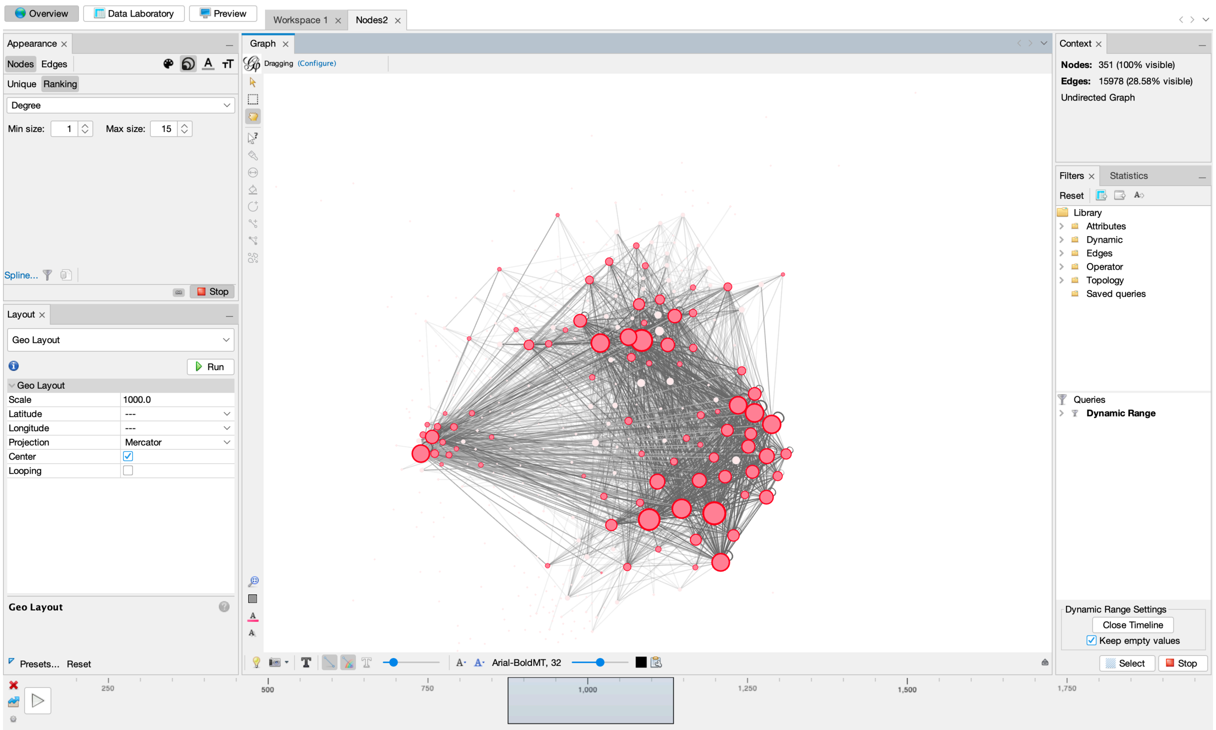


Figure 7-4 Operator Interface of Dataset “Social Connection Network across Ancient China” in Gephi.

5. War Data of Tang and Song Dynasty (In Chinese).

This dataset, offered in an Excel Table and authored in Chinese, is an extensive digital compilation by the author. It encompasses a digital recording and detailed aggregation of pivotal information on 407 military conflicts that transpired between 754 and 1102 during the Tang and Song dynasties.

The contents of the dataset are meticulously organized to present a clear historical record. Each entry delineates the year of the war, along with its name, which is listed according to the terms used by both involved parties and the location of the battlefields. This approach ensures a comprehensive understanding of the historical context and nomenclature of each conflict.

The data further includes the geographical scope of the wars by listing the affected provinces, providing a spatial dimension to the analysis of warfare's impact on the region. To facilitate cross-referencing with demographic and accessibility data, each affected province is assigned an identification number that corresponds to Dataset "Accessibility and Population of Prefecture in Sui-Tang Age." This linkage creates an opportunity for researchers to conduct in-depth studies into the socio-economic consequences of the wars on the local populations and infrastructure.

The source of this rich historical dataset is the authoritative work by the Writing Group of Chinese Military History titled "*Detailed Chronology of Wars in Every Chinese Dynasty* [61]," published in 2002 by the PLA Press in Beijing. The dataset not only serves as a crucial resource for military historians but also provides valuable insights for scholars interested in the broader socio-political fabric of the Tang and Song periods. Through its systematic presentation of warfare data, the dataset facilitates a nuanced understanding of the dynastic conflicts and their lasting effects on Chinese history.

6. Detailed Info for Recorded “Jinshi” of Tang Dynasty (In Chinese).

This dataset is an exhaustive compilation that profiles the "Jinshi," the elite scholars who triumphed in the highest imperial examinations during the Tang Dynasty, a period extending from 622 to 906. This data is fundamental for academic inquiries into the educational achievements and the subsequent bureaucratic contributions of these scholars. The dataset enumerates 1,548 individuals who succeeded as Jinshi. It meticulously records each individual's name, the year they passed the examination, and the reigning emperor at that time. Additionally, the dataset provides a personal dimension by including each official's hometown, which adds depth to the socio-cultural analysis.

Beyond personal details, the dataset aligns each individual with their corresponding prefectures and provinces, complete with identification numbers that correspond to Dataset "Accessibility and Population of Prefecture in Sui-Tang Age." This correlation allows for multifaceted research, bridging the geographical and demographic aspects of the period with the educational background of the officials.

Furthermore, the dataset chronicles the government positions these Jinshi held post-examination, shedding light on the career trajectories of the intellectual elite and their roles in the governance of the Tang Dynasty. This aspect of the data is invaluable for understanding the correlation between academic merit and governmental authority in ancient China.

The dataset draws from "*Records of Jinshi in Tang Dynasty* [87]," published by Tao Yi in 2010 through Anhui University Press. The work is a vital resource for those studying the intricate layers of the Tang Dynasty's educational and administrative systems. It enables scholars to trace the imprint of the Jinshi on the bureaucratic landscape of one of history's most influential civilizations.

7. Exiled Officials of the Tang Dynasty (In Chinese).

This dataset offers a unique window into the lives of officials who were exiled during the Tang Dynasty, a practice that held significant political and social consequences during the period spanning from 618 to 980. The dataset is an invaluable tool for understanding the punitive measures of exile and their effects on the governance structures of the time.

The dataset documents the number of officials exiled to 300 prefectures, detailing the scope and distribution of these exiles across the empire. Each entry specifies the number of exiled officials, the age of the emperor during which the exile took place, and the corresponding provinces and prefectures to which these officials were sent. This level of detail permits a comprehensive study of the exile patterns and their regional implications.

Through its detailed enumeration, the dataset allows researchers to analyze the prevalence of exile as a political tool, as well as its geographic spread and intensity. The inclusion of provincial and prefectural data provides a platform for researchers to investigate the administrative divisions most affected by this practice, potentially influencing the local administration and power dynamics of the Tang Dynasty.

This dataset is extracted from "*A Study on the Literature of Expelling Ministers and Relegating Officials in the Tang and Five Dynasties* [88]" by Shang Yongliang, published in 2007 by Wuhan University Press. The book is a scholarly resource that delves into the literature surrounding the exile of ministers and officials, highlighting the Tang Dynasty's use of banishment as a means of political control and its long-term implications for Chinese political history.

Collectively, these datasets encapsulate a wealth of information crucial for historians, social scientists, and scholars interested in the transport networks, population dynamics, social connections, military history, and educational examinations of Ancient China. The database stands as a testament to the intricate history of one of the world's oldest continuous civilizations and provides a platform for multifaceted historical analysis. The following sections demonstrate some application cases regarding the database.

8. Algorithms for Network Analysis and Machine Learning Models in this thesis.

This dataset, integral to the research on Algorithms for Network Analysis and Machine Learning Models within the context of ancient Chinese social structures, encompasses both the foundational data and the algorithms elaborated upon in Sections 6.3 and 6.5 of this thesis. The comprehensive specifics of this dataset are meticulously catalogued in Appendices 1 and 3, providing a robust foundation for subsequent analyses. Appendix 1 is dedicated to the exploration of network analysis techniques, specifically applied to decipher the dynamics of social connectivity throughout ancient China. This analysis is pivotal for understanding the intricate web of social relations that underpinned ancient Chinese society. In contrast, Appendix 3 delves into the assortment of machine learning models that have been meticulously developed to refine and enhance the Modified Gravity Model. This endeavor aims to furnish a deeper and more nuanced comprehension of the mechanisms driving the formation of social links, thereby offering invaluable insights into the structural underpinnings of social networks in historical contexts. Through the judicious application of these models, the research seeks to bridge the gap between theoretical frameworks and the empirical realities of ancient social networks, thereby contributing to a more sophisticated understanding of historical social dynamics.

7.2 Application Case 1: The Civil Service Examinations and Accessibility

The Tang Dynasty (618–907 AD) is celebrated as a golden age in Chinese history, characterized by cultural flourishes, economic prosperity, and bureaucratic refinement. A cornerstone of this era was the establishment and maturation of the imperial examination system, known as the 'Keju' system. This system heralded a new era of meritocratic bureaucracy by recruiting government officials through a rigorous examination process. Within this section, we delve deeper into the relationship between civil service examination successes and transportation accessibility, underpinned by data analytics covering 855 out of the 6688 documented 'Jinshi' over a span of 289 years.

The dynasty witnessed the 'Keju' system's systematic and consistent implementation. It became an avenue for social mobility, reshaping the bureaucratic and societal landscapes. The An Lushan Rebellion (755–763 AD) marked a pivotal juncture, leading to a decentralization of power and temporary cessation of the 'Keju' system. For the purposes of our analysis, the year 742 AD encapsulates the pre-rebellion epoch, reflecting the zenith of the 'Kaiyuan' reign—a time of unparalleled prosperity. In contrast, the year 813 AD is utilized for post-rebellion examination, given its reliable population data, which is integral for assessing accessibility.

The core analysis of the section are two visual representations: Figure 7-5, "Number of 'Jinshi' Civil Servants and Accessibility in Two Periods," and Figure 7-6, "Cities with Strong Correlation and Cities with High Political Significance." Figure 7-5 elucidates the correlation between cities' accessibility (x-axis) and the number of 'Jinshi' (y-axis) across two distinct eras, corroborating the positive relationship posited in the original chapter. Notably, cities marked within the blue regions exhibit a pronounced positive correlation, thereby meriting their demarcation on the map as shown in Figure 7-6. This second figure also highlights seven cities of substantial political significance: the two capitals and five cities associated with the major noble families of the Tang period (known as the "Five Surnames and Seven Families" [89]).

A remarkable pattern emerges from Figure 7-6. During the first period (618-756), there is a significant overlap between cities with a strong positive correlation and the seven politically significant cities. However, in the second period (756-907), the strong correlation is not only consistent with these seven cities but also expands to include certain southern cities. Given that the Tang Dynasty was the first to implement the 'Keju' system in a prolonged and systematic manner, these findings suggest that the early phases of the examination system were concentrated in the primary political cities. Subsequently, the system appears to have gradually proliferated throughout the empire.

This extended analysis demonstrates that transportation accessibility was more than a logistical convenience; it was a critical element in fostering the academic and bureaucratic elite essential for the empire's governance. The ability to travel and access educational resources was integral to a candidate's success in the imperial examinations. The spread of the 'Keju' system beyond the political centers into the southern cities indicates an expansion of bureaucratic opportunities throughout the Tang Dynasty.

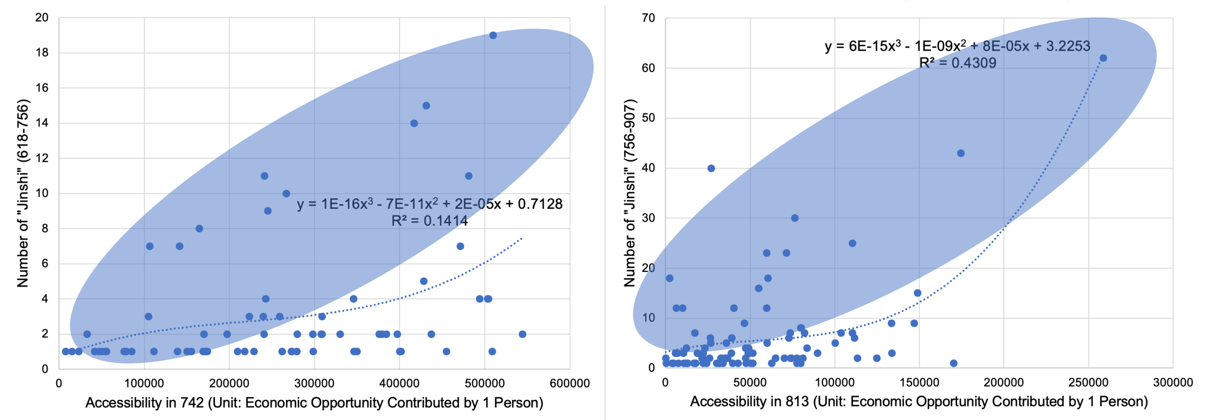


Figure 7-5 Number of “Jinshi” Civil Servants and Accessibility in Two Periods (Plotted by the author).

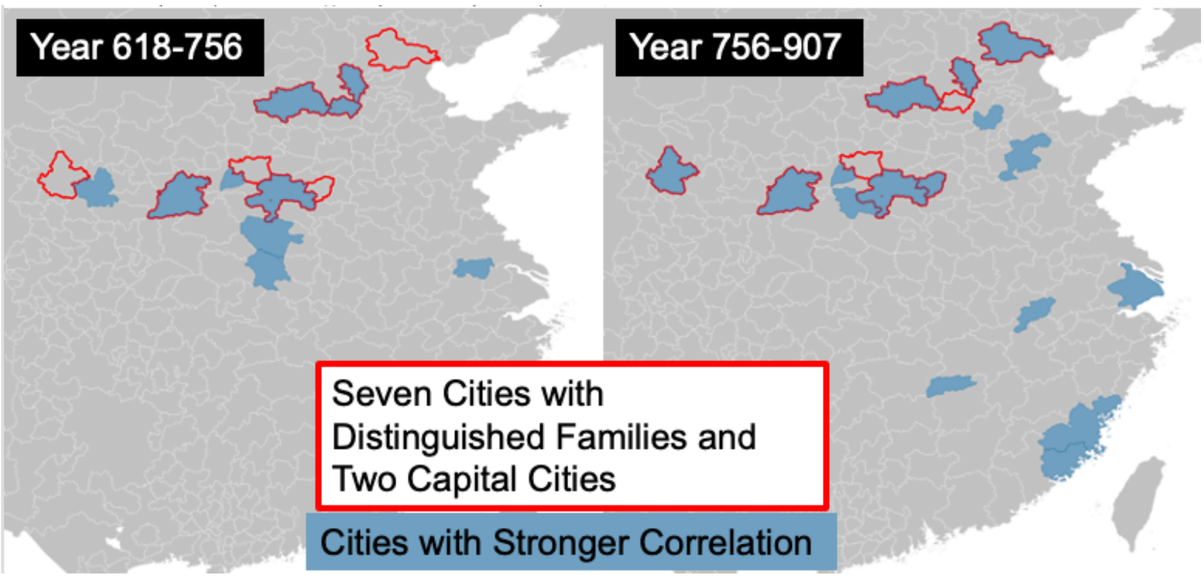


Figure 7-6 Cities with Strong Correlation and Cities with High Political Significance (Drawn by the author).

This section enhances our understanding of the geographical and political nuances influencing the 'Keju' system. It paints a picture of a dynamic administrative evolution, reflecting broader socio-economic trends and shifts within the Tang Dynasty. This evolution underscores the system's inherent flexibility and capacity to adapt to the empire's changing needs and challenges.

7.3 Application Case 2: Exile and Accessibility

The Tang Dynasty, renowned for its cultural and political grandeur, also witnessed the sophisticated administrative practice of official exile. The dispersion of exiled officials across the empire presents an opportunity to examine the interplay between transportation accessibility and the placement of these individuals. This section investigates the patterns of official exile in relation to transportation accessibility, with an emphasis on the significance of the An Lushan Rebellion as a dividing line in the dynasty's administrative control.

Understanding the dynamics of official exile during the Tang Dynasty provides valuable insights into the political maneuvers of the central government. It reflects the considerations behind maintaining control over distant territories and the central authority's strategy in curbing the influence of exiled officials. By analyzing the locations to which these officials were sent, we can infer the role of transportation accessibility in the empire's geopolitical and administrative decision-making processes.

The An Lushan Rebellion significantly impacted the Tang Dynasty, leading to the loss of central control over several regions and the rise of military strongholds. This upheaval had implications for the exile of officials, as it likely influenced the government's decisions on the destinations of exiles. In this context, the pre-rebellion year of 742, marking the zenith of the 'Kaiyuan' era, and the post-rebellion year of 813, the only year with precise population data, were pivotal for assessing transportation accessibility.

In the pre-rebellion period, prefectures were grouped into 18 categories based on accessibility, with each group representing a range of 40,000 units. The first group had an accessibility range of 0–40,000, with a midpoint value of 20,000 used as the x-coordinate for the corresponding data point. The total number of exiled officials received by all prefectures within each group was used as the y-coordinate. A similar approach was used for the post-rebellion period, with groups based on increments of 15,000 units of accessibility.

Figure 7-7 indicate an inverse relationship between the number of exiled officials and transportation accessibility, with higher numbers of officials being sent to less accessible areas. The addition of a color-coded map in Figure 7-8 displaying the density of exiled officials across the Tang Dynasty's prefectures provides a vivid illustration of the geographic considerations behind these exilic decisions. The map's gradation from red to blue, signifying the number of exiled officials, shows a clear concentration in the southeast coastal regions, as opposed to the sparser northwest frontier. This pattern suggests that the central government's strategy in assigning exiles was not solely based on low accessibility conditions for punishment, but also on preventing escape or defection. The dispersion of officials appears to reflect a strategic placement that maximizes control and minimizes the risk of escape or collusion with foreign entities.

The analysis of the distribution patterns of exiled officials in the Tang Dynasty demonstrates that transportation accessibility was a crucial factor considered by the central government when determining exile locations. The data shows a significant number of officials were exiled to regions with lesser accessibility, with a notable accumulation in the southeast. This pattern likely reflects strategic decisions to prevent risks associated with escape or foreign collusion, with an avoidance of the least accessible areas. This analysis provides a quantitative regression model to describe the relationship between exiled officials' number and accessibility, which can be used for future comparison study on different periods.

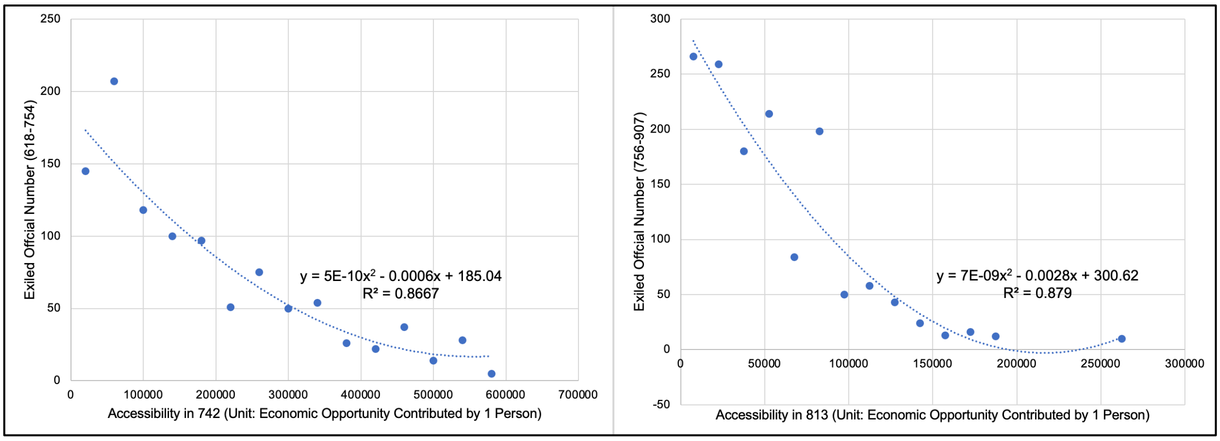


Figure 7-7 Exile Official Number and Accessibility in Two Periods (Plotted by the author).

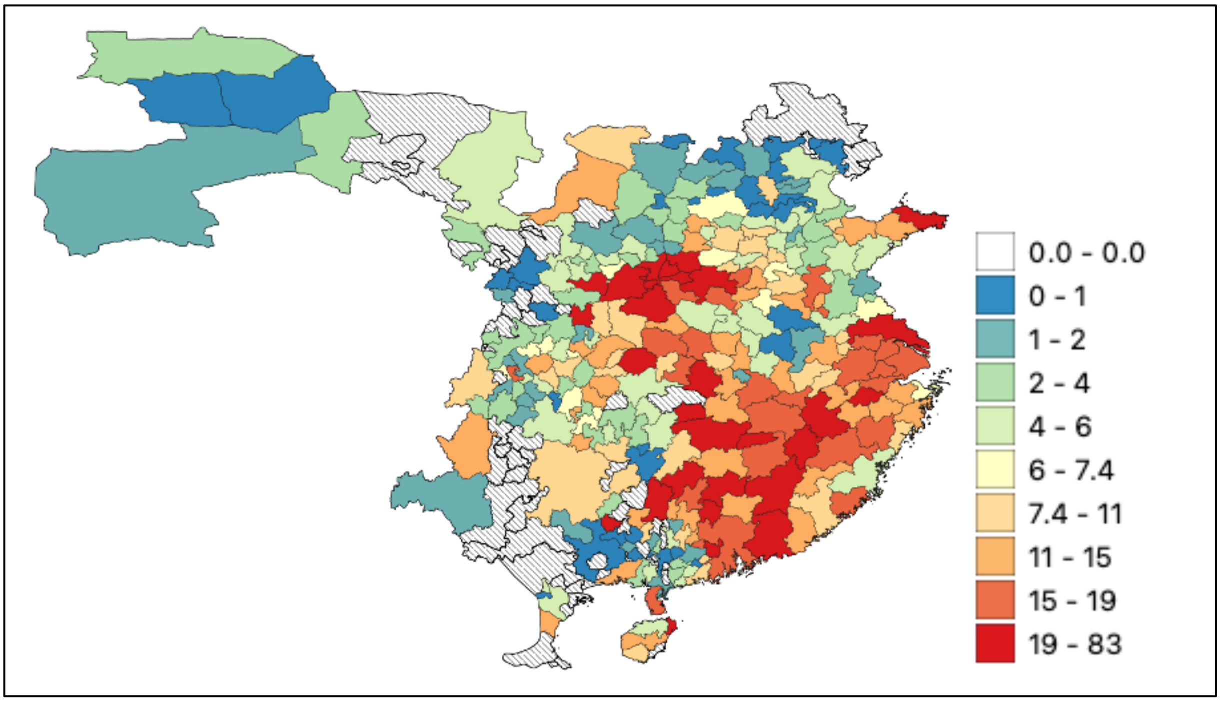


Figure 7-8 Exile Official Number of Different Prefectures in Tang Dynasty (Drawn by the author).

7.4 Application Case 3: Literature and Accessibility

This section explores the relationship between transportation accessibility and literary production in the Tang Dynasty, with a focus on the periods before and after 742 CE. Data from the Academia Sinica's geographic information system on the distribution of poets and their works is employed to analyze the average literary output relative to transportation accessibility. By excluding the capital Chang'an for its disproportionately high accessibility and literary production, the study aims to provide a clearer understanding of how infrastructural factors influenced cultural development.

The Tang Dynasty is renowned for its cultural richness and extensive literary production. This study examines the potential influence of transportation accessibility on the quantity of literary works produced during this era. It posits that greater accessibility could have facilitated the exchange of ideas and cultural interaction, thereby boosting literary activity. The data for this analysis is sourced from the Academia Sinica's Geographic Information System on the Distribution of Tang and Song Poetry Authors and Works [90], which provides a unique opportunity to quantitatively examine this historical period.

Previous research has established a correlation between economic prosperity, trade routes, and cultural activities, including literature. This study contributes to the discourse by specifically focusing on the role of transportation accessibility. Literature on the socio-economic conditions of the Tang Dynasty suggests that transportation played a critical role in administrative efficiency and cultural exchange, potentially impacting literary output.

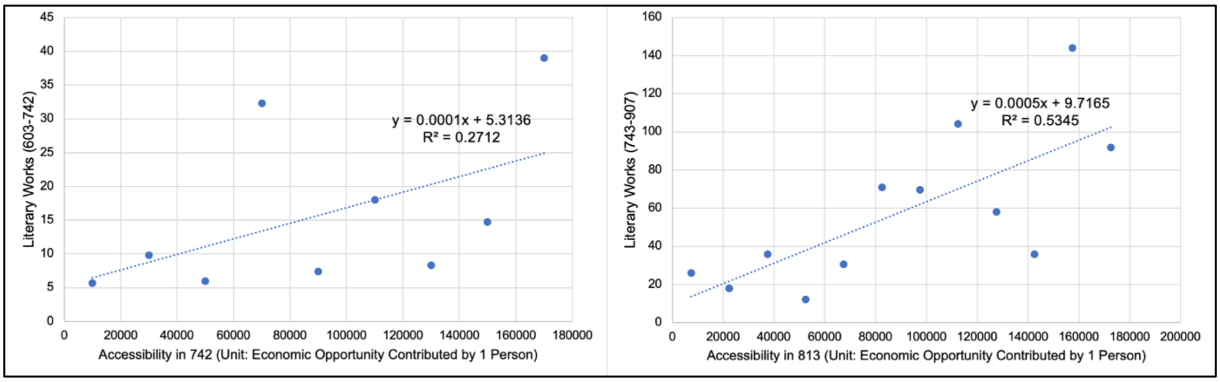


Figure 7-9 Literary Works of Different Prefectures and Accessibility in Tang Dynasty (Plotted by the author).

The study employs a quantitative analysis of transportation accessibility in relation to literary production across Tang Dynasty provinces and counties. Each data point represents the average for a group of jurisdictions within the empire. The regions are classified according to their transportation accessibility scores, segmented into 12 distinct groups at intervals of 20,000 units. The mid-point value of each interval serves as the representative accessibility score for that group, beginning at 10,000 for the lowest interval and increasing by 20,000 for each subsequent category. The x-value of each group's data point corresponds to this representative accessibility score. The y-value is the average number of literary works produced within the counties of that group during the target year. This methodology allows for an analysis of trends while controlling for variability within groups.

The analysis deliberately excludes data from the Tang capital, Chang'an, due to its anomalous status. With a literary output of 379 works during the zenith of the Tang period, and 2370 works in the subsequent era, Chang'an's figures dramatically exceeded those of other cities, with the second-highest producing city yielding only 47 and 612 literary works respectively in the same periods. Including Chang'an's data would distort the broader trends and obscure the patterns of interest in this study.

The scatter plots present a nuanced visual representation of the relationship between accessibility and literary production. The stratified data illustrates a general increase in literary output corresponding with higher accessibility scores across the Tang Dynasty's regions. Notably, the period before 742 CE shows a less pronounced correlation than the period after, suggesting that the influence of transportation accessibility on literary production may have become more significant over time.

While the correlation between accessibility and literary output is evident, the exclusion of Chang'an from the data set is a critical methodological decision. By removing the capital's outlier influence, with its extraordinarily high transportation accessibility score and unmatched literary production, the study avoids skewing the results. This allows for a more accurate examination of the underlying trends across the non-capital regions of the Tang Dynasty.

7.5 Application Case 4: Pandemic and Accessibility

This investigation explores the correlation between transportation accessibility and the frequency of significant epidemic outbreaks across the entirety of the Tang Dynasty. Two maps are analyzed: one depicting transportation accessibility, with varying shades of red indicating degrees of access, and another showing the frequency of epidemic disasters per prefecture as compiled by the Medical Geography Research Group at Central China Normal University [91].

The Tang Dynasty experienced considerable advancements in its transportation infrastructure, which facilitated the movement of populations and goods. This study aims to explore the potential impact of such developments on public health, specifically the frequency of epidemic outbreaks throughout the dynasty.

Historical patterns have demonstrated a link between trade routes and the spread of diseases. This paper builds upon existing research, applying it to the context of the Tang Dynasty, a period marked by significant infrastructural and demographic changes.

The study analyzes a transportation accessibility map from the year 742 CE and an epidemic frequency map, the latter of which records the total number of large-scale epidemic events throughout the Tang Dynasty. The epidemic map in Figure 7-11 is color-coded to reflect the number of occurrences, with the frequency ranging from one to four times.

A cross-analysis of the maps shows that areas with higher transportation accessibility often correlate with higher frequencies of epidemic events. This suggests that regions with more advanced transportation networks experienced more frequent epidemics across the dynasty's duration.

The observed correlation suggests that the density and efficiency of the transportation network could have played a role in the spread of epidemics. The data implies that areas with higher accessibility, serving as trade and administrative centers, were more exposed to the risk of recurring epidemic events.

Further scrutiny of Figure 7-11, "Pandemic Frequency of Different Prefectures in the Tang Dynasty," reveals intricate details about the geographical spread of epidemics. Notably, in the northern and southeastern cities, a high correlation between accessibility and epidemic frequency is evident, aligning with the historical centers of political and economic activity. These regions, being nexus points of trade and governance, likely had more robust data due to their significance and the consequent thorough record-keeping.

Conversely, for the southwestern regions and cities near Guangzhou in the south, despite their relatively high accessibility, the records show only sporadic instances of epidemic outbreaks. This pattern suggests a discrepancy that could be attributed to the political and economic focus shifting away from these areas. As the political heart was anchored in the northern cities and the economic center gravitated towards the southeast, other southern and southwestern cities, which were neither political nor economic hubs, may have had less comprehensive data collection on epidemic events. It is conjectured that these discrepancies may partly arise from a potential underreporting or lack of historical records due to the peripheral status of these locales within the empire's primary spheres of influence. Such gaps in the historical record present a nuanced challenge, reminding us that while data may suggest trends, it is also shaped by the contexts of its collection and preservation.

The section concludes that there is a historical association between transportation accessibility and the frequency of epidemic disasters in the Tang Dynasty. The findings underline the dual role of transportation infrastructure in promoting economic growth and potentially facilitating the spread of diseases. These insights contribute to a broader understanding of the impact of human mobility on public health over time.

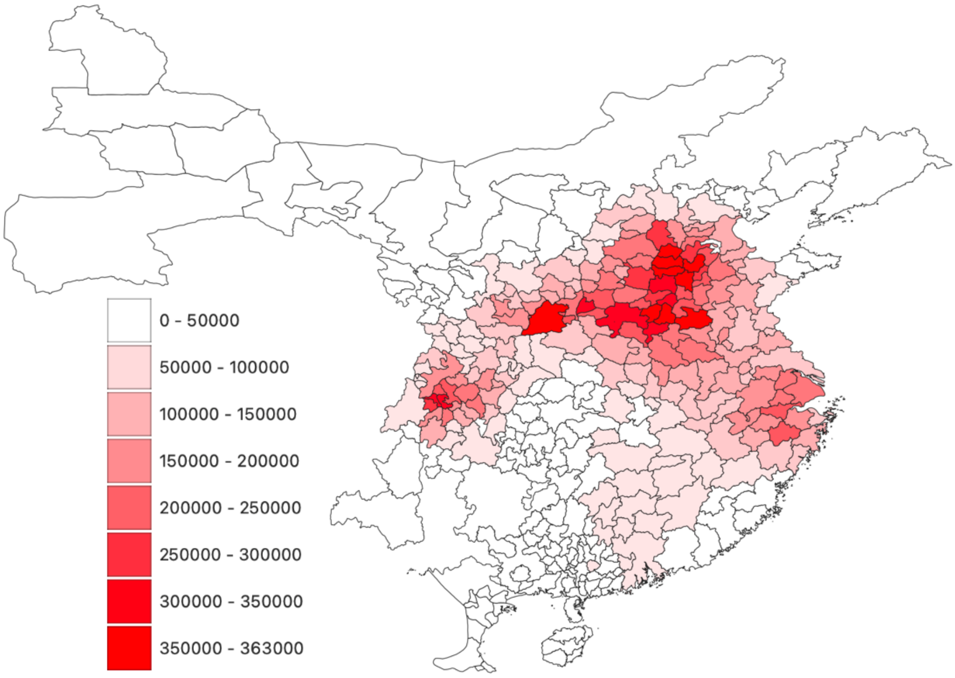


Figure 7-10 Transportation Accessibility of Different Prefectures in 742
(Drawn by the author).

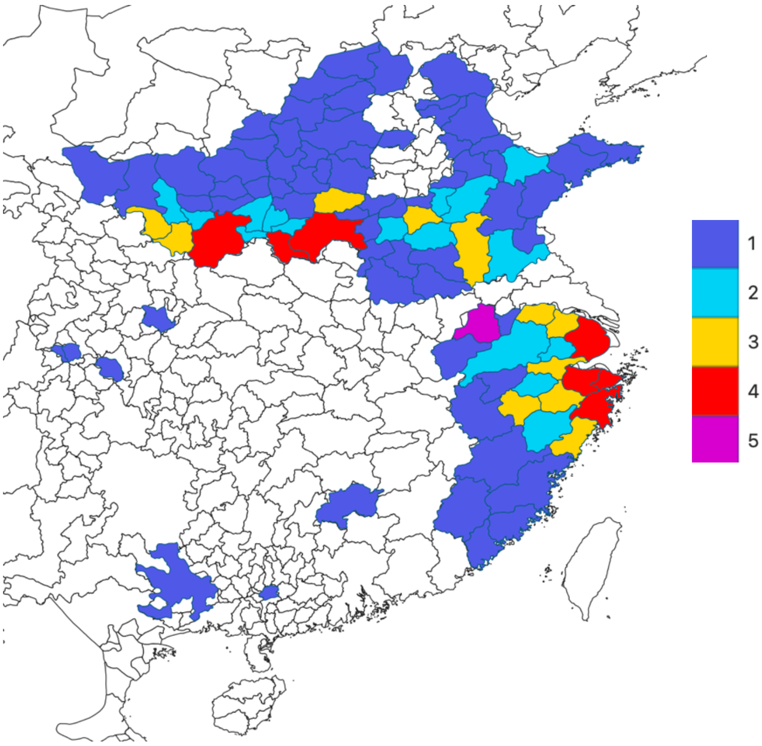


Figure 7-11 Pandemic Frequency of Different Prefectures in Tang Dynasty
([91], Drawn by the author).

8. Modern Societal Implications

Chapter 8 navigates through the evolving vistas of China's modern transportation infrastructure, weaving a narrative that links the past's pathways to the present's highways. The chapter embarks on a journey of discovery, tracing how the arteries of transportation have pulsed through the urban landscape, molding the cities and culture of a nation on the move.

In the opening section, a panorama of China's transportation evolution unfolds. Here, the narrative explores how these networks have not just moved people and goods but have sculpted urban development itself, influencing the very shape and heartbeat of cities.

The narrative then shifts to an in-depth examination of the current transportation system and spatial governance in China, revealing a complex dance between administrative mandates and the veins of transit that crisscross the land. This analysis delves into the symbiotic relationship between governance structures and transportation planning, laying bare the effects on network efficiency, accessibility, and the blossoming of transport pathways.

Attention turns to Section 8.3, this section encapsulates the author's journey through internships at UNESCO Beijing and UN-Habitat ROAP, providing a real-world backdrop to the theoretical framework of this thesis. These internships allowed the author to actively engage in projects and initiatives that resonated with the research topic, offering a unique vantage point on modern transportation challenges and sustainable development. The hands-on experience gained here enriched the author's perspective on the historical evolution of transportation systems in China, linking ancient practices to contemporary issues in urban planning and policy analysis.

In summary, this chapter presents a multidimensional narrative, interlacing historical insights with practical experiences gained from international internships. These experiences not only enriched the author's understanding of ancient Chinese transportation systems but also provided a contemporary perspective on urban planning and sustainable development. This enriches the thesis, offering a comprehensive view of the transformation and socio-economic impact of transportation systems from ancient China to the present day.

8.1 The Unchanging Role of Transportation in Shaping Urban Development Through Chinese History

The evolution of transportation, from ancient times to the present day, has always played a pivotal role in shaping the development of urban landscapes. This section will explore this unchanging influence through various historical periods, focusing on how transportation systems have directed the rise and fall of cities, determined economic centers, and influenced political and military strategies.

Prior to the Sui and Tang dynasties, the concurrent prominence of the eastern capital, Luoyang, and Chang'an, reflected the significance of the Yellow River basin's twin economic heartlands. This dual-capital structure aligned with the dynastic ambitions to exert control over the Central Plains and the southern regions. The Sui and Tang eras heralded the excavation of the Grand Canal, centered on

Luoyang, establishing an extensive transportation network. This canal system interlinked the sea and major river systems, including the Yellow, Huai, Yangtze, and Qiantang rivers, thus interconnecting the North China Plain, the Huai River region, and the middle and lower reaches of the Yangtze River. It essentially redefined the economic lifelines of the era.

During the mid to late Tang period, the Guanzhong area faced overpopulation, excessive deforestation, and reclamation of wastelands, leading to frequent droughts and floods. This environmental crisis precipitated a significant drop in agricultural productivity. As a result, the once fertile Guanzhong region, known as the "Land of Plenty," could no longer sustain its role as a political and economic hub. The Grand Canal, supporting north-south grain transportation, became a lifeline for the state. However, the political, military, and geographical advantages of Chang'an as the capital were no longer viable due to the high human and material costs associated with grain transport. Consequently, cities along the canal, such as Luoyang and Kaifeng, gained prominence.

Figure 8-1 Major Cities of Ancient China (Left) [8].

Figure 8-2 Cities along the Grand Canal During the Qing Dynasty (Right) [92].

By the end of the Tang Dynasty, the severance of the canal by the southeastern powers led to the collapse of the Tang Empire, which had heavily relied on the Jianghuai region for financial and grain support. From the Qin and Han dynasties to the Sui and Tang periods, the capital's relocation from Xianyang near the Wei River to Chang'an and then to Luoyang by the Yellow River was a response to the economic decline in Guanzhong. However, Luoyang subsequently suffered considerable devastation during the An Lushan Rebellion, and further turmoil during the late Tang, the Five Dynasties and Ten

Kingdoms period, and the Wei and Jin dynasties. The once-glorious capital never recovered its former stature.

With the decline of Luoyang, Bianzhou (present-day Kaifeng, Henan Province), strategically located at the junction of the Yellow River and the Grand Canal, rose to prominence, benefiting from its economic and geographic importance. This led to a rapid elevation in its military and political status. In 907, Zhu Wen established the Later Liang dynasty and renamed Bianjing as Dongjing, Kaifeng Prefecture, making it the capital for successive dynasties. During the Northern Song period, Kaifeng became the largest hub for north-south economic and trade activities, thanks to the canal system. The city's political status as the capital contributed to its urban expansion and elevation in status, drawing an increasing number of people and facilitating the circulation of goods.

The political center of the Song Dynasty relocated to Hangzhou in 1129, marking a significant shift in Chinese ancient society. The economic and political focus moved from Guanzhong to the Central Plains along the Yellow River and eventually gravitated towards the Jiangnan and Lingnan regions due to warfare. The once economically backward regions of Jiangnan and Lingnan prospered due to their thriving port trades and were spared from the northern warfare and the spread of northern industrial and agricultural technologies. This shift resulted in a considerable enhancement of agricultural production and overall economic prosperity in the Jiangnan region.

The Mongol-established Yuan dynasty positioned its capital in Dadu (present-day Beijing), leveraging its strategic location for nomadic production, military support, and its proximity to Mongolia. The Yuan dynasty's focus on maritime grain transportation led to the further excavation of the Grand Canal. This expansion of over 2000 li (approximately 1000 kilometers) along the canal's banks catalyzed the emergence of new towns and shifted the national economic center further eastward. Cities like Tianjin flourished due to the demand for sea-based grain transport, while others like Dezhou, Dongchang, Jining in Shandong, and Huaian and Yangzhou in Jiangsu prospered as vital economic hubs along the canal.

During the Ming and Qing dynasties, the Jiangsu-Zhejiang region witnessed the emergence of significant commercial cities like Suzhou, Songjiang, Yangzhou, Changzhou, Zhenjiang, Wuxi, Huaiyin, Yizheng, and Xuzhou, propelled by the Grand Canal trade and the industrial and commercial development of the Jiangnan area.

Traditional cities in this era were often situated along major waterways and post roads. They served as political centers (e.g., Beijing, Baoding, Jinan, Taiyuan, Kaifeng, Shenyang, Nanjing, Suzhou, Guangzhou, Hankou, Chongqing, Xi'an, Lanzhou), post road hubs (e.g., Zhengding, Handan, Xuchang, Zhengzhou, Xuzhou), or river transport hubs (e.g., Tianjin, Linqing, Jining, Dezhou, Zhoukou, Yangzhou, Huaiyin). Many were renowned commercial cities like Tianjin, Linqing, Jining, Suzhou, and Hangzhou, but the majority were political centers. Cities like Tianjin, Yantai, Qingdao, and Shanghai, which lacked sufficient modern industrial resources and were established for administrative or military purposes, required economic support from surrounding agricultural areas.

Since the Opium War of 1840, Western powers, under the pretext of the Treaty of Nanjing, coerced the Qing dynasty into opening ports such as Shanghai, Ningbo, Guangzhou, Xiamen, and Fuzhou for international trade. This move ended the monopoly of Guangzhou as the sole trading port and established these harbors as pivotal markets. The Yangtze and Pearl River systems served as the arteries for deep inland transportation. Despite plans for railway and highway construction, there was no large-scale implementation. By 1914, Western powers and Japan had established 74 concessions in China's southeastern coastal cities. These actions triggered the growth and prosperity of a plethora of trading ports.

These cities were characterized by several key factors: First, their strategic location on the eastern coastline provided natural harbors, serving as vital transshipment points for both maritime and riverine trade during the Ming and Qing dynasties. Cities like Shanghai, Tianjin, Hankou, Guangzhou, and Xiamen exemplified this. Second, many of these cities, including Suzhou, Hangzhou, and Jiangning, were already hubs of handicraft production. Third, these locales often functioned as local administrative centers, capable of strong consumption, like Shenyang, Suzhou, Hankou, and Guangzhou. Fourth, most were established regional economic and trade centers, underpinned by robust economic hinterlands, evident in cities like Tianjin, Yantai, and Dalian.

This multifaceted foundation facilitated the development of modern Chinese cities, with southeastern coastal port cities leading the charge. The integration of railways and shipping networks connected these urban areas with the central and western rural regions, sparking a transformation towards agricultural industrialization and manufacturing. The eastern cities, driven by foreign trade and transportation industries, spurred the growth of manufacturing and financial sectors. The proliferation of industrial jobs attracted rural populations to urban areas, resulting in rapid urban expansion and differentiation of urban functional zones, marking the emergence of the modern urban form. These port cities, with their unique natural conditions and strategic locations, not only became gateways for China's integration into the global economy but also frontiers in the nation's modern societal transformation.

In modern Chinese urban development, cities in North and Northeast China predominantly centered around transportation hubs like railways, ports, and shipping. These included emerging industrial and mining towns, reflecting a shift in urban economic functions from traditional administrative and military roles to commercial and industrial ones. This transformation of urban landscapes in response to industrialization and trade dynamics exemplifies the enduring impact of transportation on urban development throughout Chinese history.

From the Ming and Qing dynasties onward, cities were predominantly distributed along the north-south official roads, forming a multilayered network of provincial, prefectural, and county-level administrative governance. While the function of these cities as north-south trade transit hubs remained relatively stable, the modern era's east-west economic and trade movement led to a reorganization and distinct division of labor among primary, secondary, and ultimate markets. Over the years, the traditional layout of cities along the north-south Grand Canal and the east-west Yellow and Yangtze Rivers underwent significant changes with the advent of ports, railways, and industrial development. During the Republic of China era, these cities experienced accelerated growth following industrialization. The urbanization process, driven by industry and trade, led to a natural selection in terms of resource sourcing, service areas, cost, and labor, resulting in functional specialization within urban economies, characteristic of modern urbanization and industrialization [9].

The unchanging influence of transportation systems in shaping urban development is evident throughout history. From the ancient capitals dependent on waterways to the modern cities thriving due to global trade and railway networks, transportation has been a constant driving force in urban growth and economic development. This historical journey underscores the critical role of transportation in urban planning and policymaking, even in contemporary times.

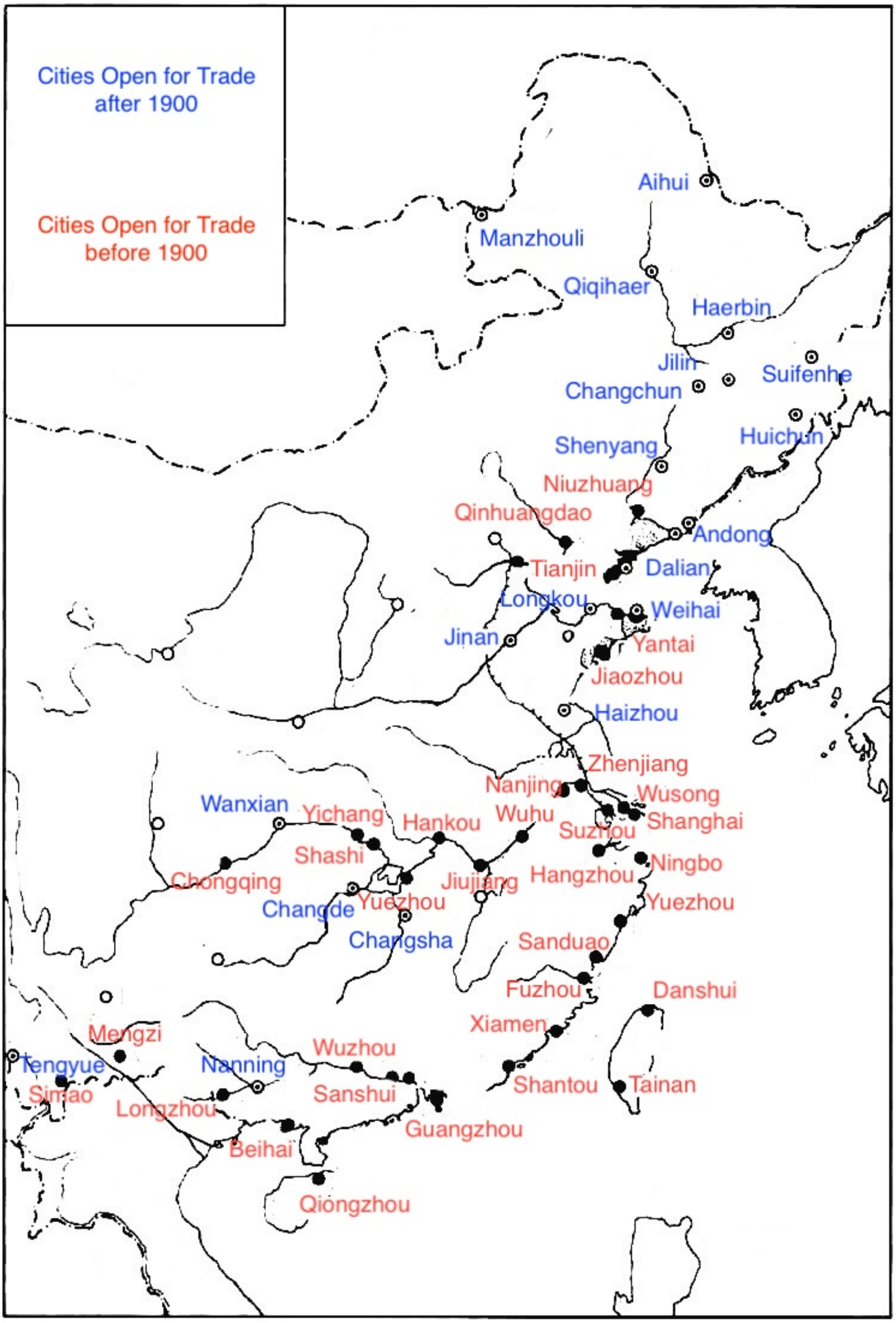


Figure 8-3 Opened International Trade Ports in China (1840~1949).

8.2 Transportation Development and Spatial Governance of Modern China

The introduction of advanced Western transportation technologies to China commenced in the latter half of the 19th century. At that time, steamship navigation first linked areas of China suitable for water transport, leading to the continuous expansion of various treaty port cities due to commercial growth. Following the First Sino-Japanese War, the Qing government permitted private sector factory establishment, resulting in a gradual establishment of modern industrial enterprises at these ports. These enterprises were particularly sensitive to the transportation costs of raw materials and products. Cities like Xi'an and Lanzhou, which lacked modern transportation, found industrial development to be extremely challenging. Against this backdrop, at the beginning of the 20th century, the Qing government initiated large-scale railway construction, which, although significantly behind the global trend, still brought new vitality to many inland cities. In particular, the material transport in North China had relied mainly on animal and human power (water transport was limited by the scarcity of rivers, insufficient water volume, and marked seasonality). Such an outdated material supply system could not support the development of populous cities, hence the development speed of North China's cities was far slower than that of the Yangtze River Basin. By the time of the Xinhai Revolution in 1911, a North China railway network had been preliminarily formed, centered around Beijing with four main lines: Jingfeng, Jinghan, Jingzhang, and Jinpu, and connected by four secondary lines: Zhentai, Bianluo, Jiaoji, and Daoqing. South of the Yangtze River, there were only the Huhang, Huhang, Zhuping, and Zhuchang lines. In South China, there were only short lines such as Guangjiu, Guangsan, Chaoshan, and Zhangxia. In the southwest, there was only the Yunnan-Vietnam line [93].

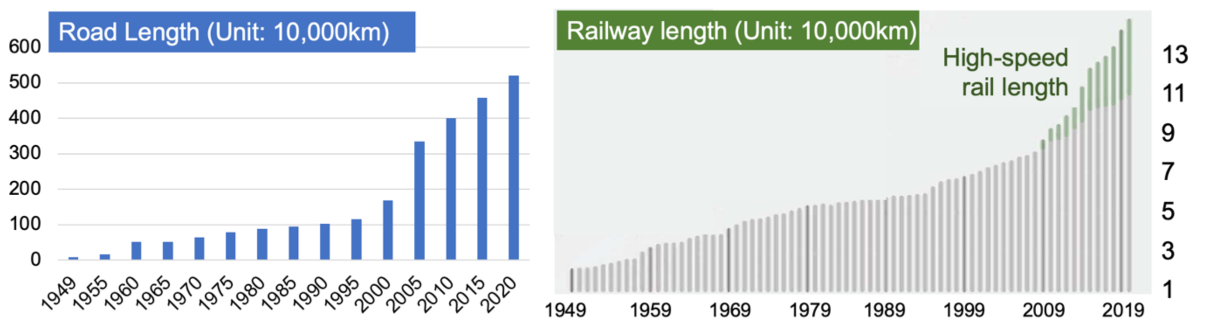


Figure 8-4 Length of Roads and Railways in China from 1949 ([94], Plotted by the author).

In the 1930s, although China's steamship navigation was mainly confined to the southern water systems like the Yangtze and Pearl Rivers, and the railway network was not widely distributed throughout the country, the Nationalist government achieved some success in developing a lower-cost road network. Before 1937, China had a total road length of 109,500 kilometers. However, the number of vehicles on the roads was small, and the actual effectiveness of the roads could not compare with rail and water transport. They only played a supplementary role in the transportation outside cities, especially in the eastern regions. Many inland areas-built roads, but these did not significantly improve the external transportation situation of inland cities. At the beginning of the PRC, the transportation situation was very backward. The total length of railways was only 21,800 kilometers, with half in a paralyzed state. The passable roads were only 80,800 kilometers, and there were only 51,000 civilian cars. Inland waterways were left in their natural state. There were only 12 civil aviation routes, and the postal service network was limited. The main means of transportation were still animal-drawn carts and wooden sailing ships.

After the establishment of the PRC, the first task was to repair the damaged transportation facilities and equipment during the three-year recovery period of the national economy and to restore water, land, and air transportation. Starting in 1953, the construction of transportation infrastructure was planned and initiated. Especially after the reform and opening up, with the rapid development of the commodity economy, the demand for transportation soared. In the 1990s, the central government began to consider transportation investment as a driver of economic growth. During this period, the scale of construction investment in China's transportation infrastructure saw extraordinary growth. During the 10th Five-Year Plan period, the total investment completed in the construction of roads, waterways, and other transportation facilities exceeded the total investment completed in the 51 years since the establishment of the PRC. The new mileage of expressways was 1.5 times the total of the 8th and 9th Five-Year Plans, and during the 11th Five-Year Plan period, the investment in railway construction was 6.3 times that of the 10th Five-Year Plan, with railway operational mileage increasing by 20.7%. By the beginning of the 20th century, China had basically formed a relatively comprehensive transportation network system.

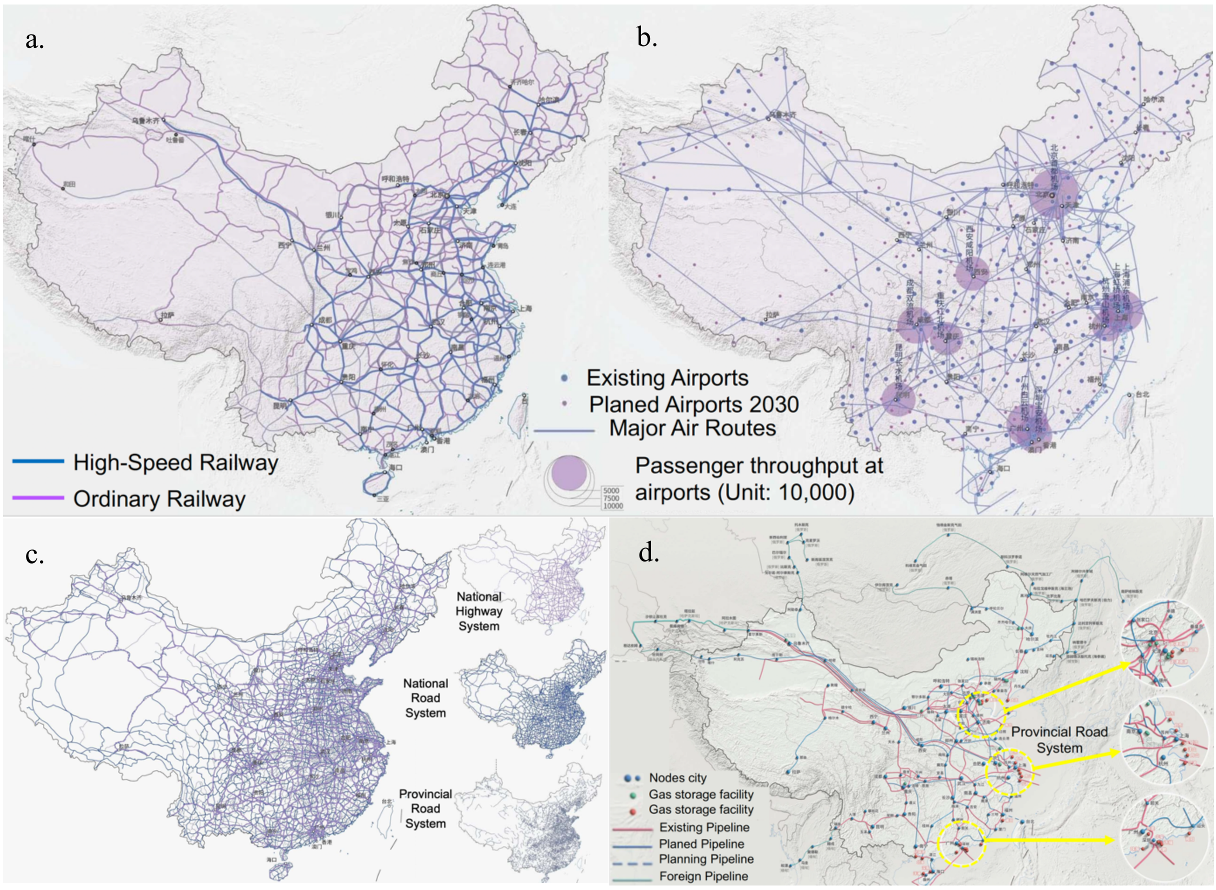


Figure 8-5 Current Railway (a), Airline (b), Road (c), and Pipeline (d) System of China [94].

The following section explores the intricacies of China's modern territorial spatial planning post-2012, elucidating the relationship between land use classification and the strategic transportation framework known as the "Two Horizontal and Three Vertical" axes. It delves into how this planning underpins China's urbanization strategy and supports the development of major city clusters and urbanized areas.

The spatial planning map of China, post-2012, delineates four distinct zones for land development: red for optimized development, orange for key development, yellow for agricultural production, and green for crucial ecological functions [95]. Intersecting these zones is the nation's "Two Horizontal and Three Vertical" development axes, marked by black lines, representing a strategic urbanization pattern. Each color-coded zone represents a tier of developmental focus and ecological preservation, reflecting the country's priorities in balancing economic growth with sustainable practices. The optimized and key development zones are often aligned with areas of significant transportation infrastructure, demonstrating the role of transport in regional development. The "Two Horizontal" axes consist of land bridge passages and routes along the Yangtze River, while the "Three Vertical" axes include coastal routes and pathways along the Beijing-Harbin, Beijing-Guangzhou, and Baotou-Kunming corridors. These axes not only facilitate connectivity but also bolster the growth of urban clusters and peripheral urbanized regions.

Transportation infrastructure serves as the backbone of this spatial planning, ensuring that connectivity and accessibility drive the development of urban areas. The axis-based city clusters benefit from enhanced mobility, trade, and communication, which in turn contributes to the regional and national economy. The relationship between China's modern territorial spatial planning and its transportation infrastructure is deeply intertwined. The strategic designation of land development zones, coupled with the "Two Horizontal and Three Vertical" transport axes, illustrates a comprehensive approach to orchestrating China's urban expansion and rural conservation efforts in tandem with bolstering transportation networks.

In recent years, the Chinese government has embarked on an ambitious initiative to enhance urbanization and regional development through a meticulously crafted urban cluster development strategy. This initiative, as delineated in the strategic schematic released by the State Council since 2018, has identified four national city clusters: the Beijing-Tianjin-Hebei region, the Yangtze River Delta, the Pearl River Delta, and the Chengdu-Chongqing area. Alongside these, seven regional and eight subregional city clusters have been recognized, shaping a multi-tiered structure of urban development that is designed to harness and amplify the intrinsic economic strengths of each cluster [96].

The layout of these clusters reveals a deliberate design, with most regional city clusters situated within a geometrically strategic diamond-shaped area demarcated by the four national city clusters. This configuration is not merely coincidental but is indicative of a larger strategic vision. The national and regional clusters within this diamond are positioned to be the epicenters of inter-city communication and economic exchange, further driving China's urbanization thrust forward.

The positioning and development of the city clusters are not standalone phenomena but are inextricably linked to the country's transportation infrastructure. Within the diamond-shaped core area, the clusters benefit from an already established and dense network of transportation links, facilitating rapid and efficient exchange of goods, services, and human capital. The national and regional clusters are well-serviced by a web of high-speed rail lines, expressways, and major ports, which not only link the cities within the cluster but also connect them to international markets, fostering global trade and economic integration.

However, beyond this core area, the eight subregional city clusters have historically been at a relative disadvantage due to their peripheral location and less developed transportation frameworks. Recognizing this, the state's strategy underscores the importance of enhancing transnational transportation connectivity to elevate the role of these clusters as potential hubs of economic activity. The diamond's external subregional clusters, once better connected through improved transportation links, stand to become key players in China's broader regional development narrative.

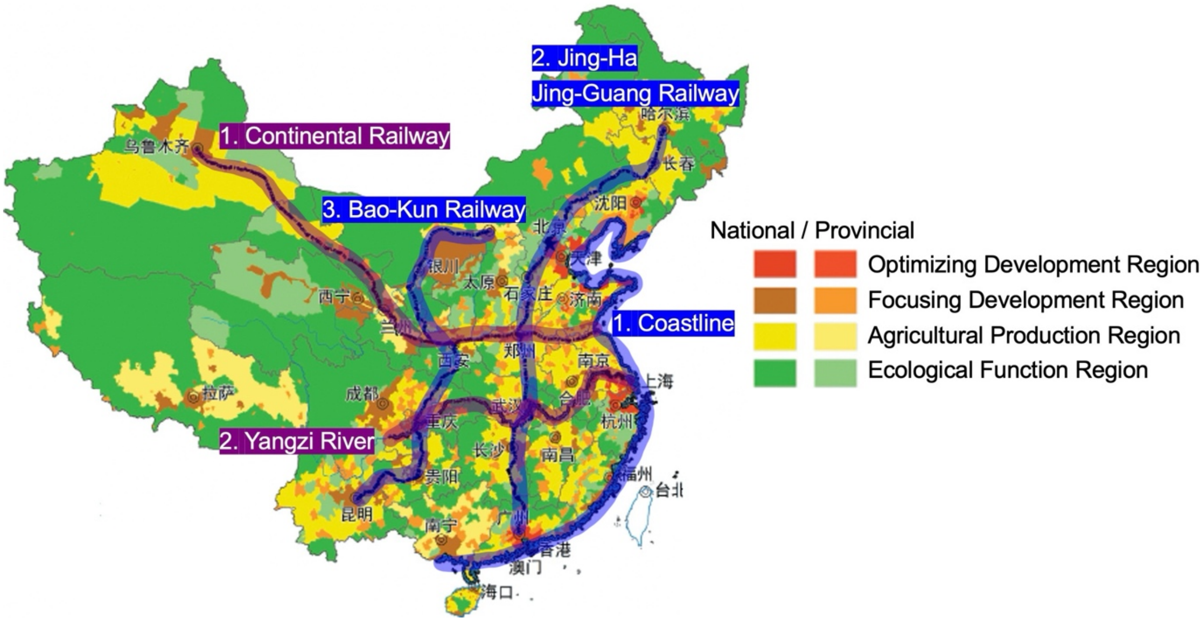


Figure 8-6 Spatial Planning of China in 2012
([97], National Development Axis Marked by the author).

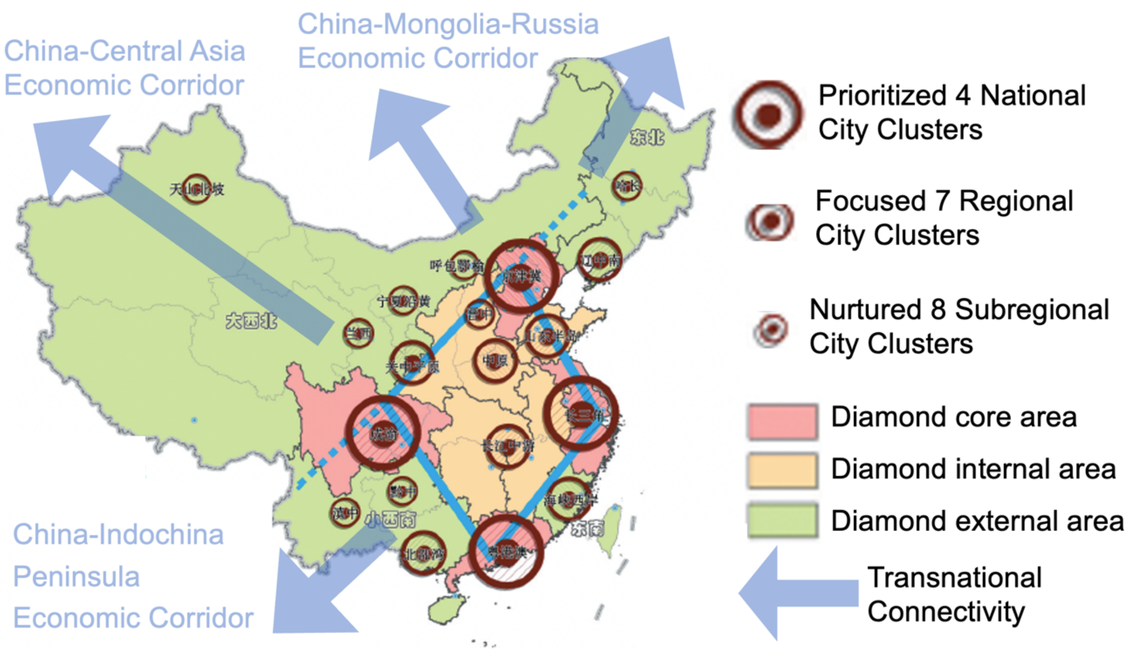


Figure 8-7 City Clusters' Development of China from 2018
([98][99], Transnational Connectivity drawn by the author).

As the urban clusters within the diamond area continue to thrive on intra-regional exchanges, the growth of the subregional clusters relies significantly on the state's ability to create efficient and reliable transportation corridors. These corridors are envisioned to not only bridge the infrastructural gaps but also to knit a more cohesive economic tapestry that includes the peripheral regions into the national and global economic fabric.

The significance of transportation in the urban cluster development strategy of China is thus multifaceted. It serves as the circulatory system that delivers the lifeblood of economic vitality to both the thriving core and the emerging peripheries of China's urban landscape. By investing in transportation, the Chinese government is committing to a future where balanced regional development is not an aspiration but a tangible reality, where the accelerated growth of national clusters is matched by the nurtured expansion of regional and subregional clusters, all intricately connected and integrated through a robust and resilient transportation network.

This comprehensive approach to urban and regional development through strategic transportation investment highlights China's recognition of the critical role that mobility and connectivity play in the era of globalization. It reflects a profound understanding that the health and growth of urban clusters are deeply contingent on the arteries of transportation that support them, ensuring that as the nation marches forward, no region is left behind.

8.3 Integrating Practical Experience and Research

This dissertation delves into the confluence of engineering and historical studies, seeking to merge the realms of ancient and modern methodologies. Central to this exploration is the amalgamation of theoretical understanding with tangible, on-site experiences. Such a fusion not only broadens the comprehension of societal contributions but also facilitates the real-world application of academic studies, aligning them with overarching goals like the United Nations' Sustainable Development Goals (SDGs). The author's dedication to employing scientific and engineering principles for promoting sustainability motivated the pursuit of impactful opportunities within the United Nations framework.

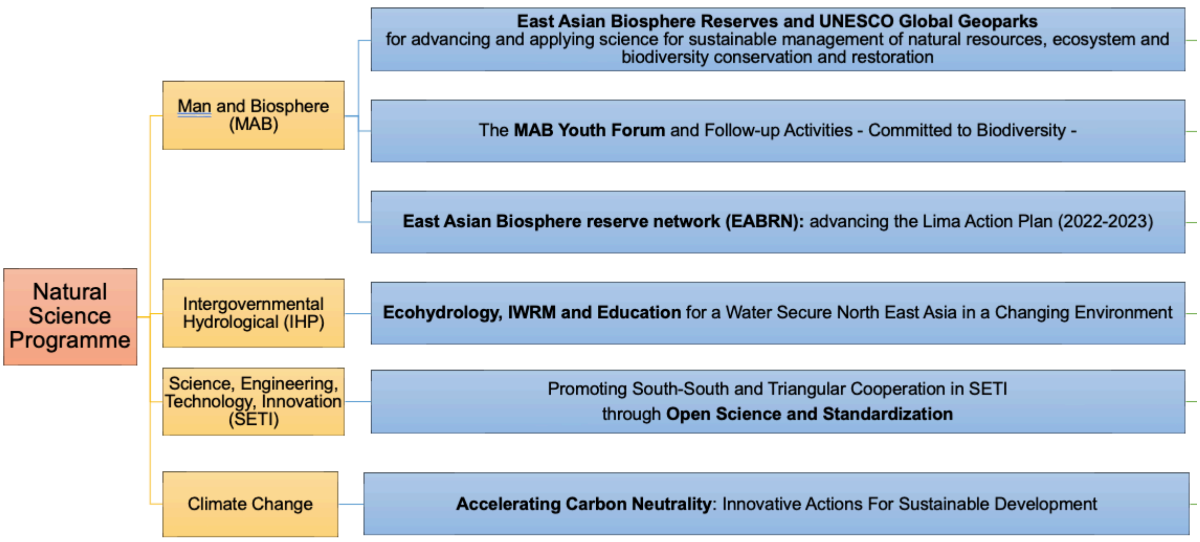


Figure 8-8 Engaged Projects During the Internship at UNESCO Beijing Office.

In 2022, the author undertook a six-month internship at the UNESCO Beijing Cluster Office. This period was marked by an immersion in the operations of an international organization and a focus on the interplay between theoretical research and practical implementation. Activities during this tenure included significant involvement in the Man and Biosphere Programme, the Intergovernmental Hydrological Programme, and efforts in promoting South-South and Triangular Cooperation in Science, Technology, and Innovation. This experience was pivotal in augmenting the author's comprehension of sustainable development, particularly in relation to historical transportation systems. These experiences were invaluable in contextualizing historical transportation methods within a contemporary sustainability framework, thereby enriching the thesis through a unique synthesis of ancient transportation frameworks and modern sustainable practices.

Figure 8-9 Lecture, Participants, and the Panel Discussion of the Workshop.

After the internship at UNESCO, a comprehensive workshop was organized, aimed at melding the experiences garnered at UNESCO with ongoing research at Kyoto University. The workshop, focusing on sustainable development goals, facilitated an in-depth understanding of global challenges and solutions, particularly in water management and environmental science. This directly correlates with the thesis, offering insights into the historical perspective of resource management and infrastructure, vital for comprehending the evolution and socioeconomic impacts of transportation systems in ancient China. The seminar provided a beneficial forum for idea exchange between academic circles and international organizations, thus enriching the thesis with a broad spectrum of perspectives and contemporary relevance. The details of the previous internship, workshop, project-based research are attached in Appendix 4.

In 2023, an internship at the UN-Habitat Regional Office for Asia and the Pacific (ROAP) offered profound insights into urban policy analysis, culminating in participation at the 6th Spatial Planning Platform (SPP) Conference. Here, the author presented research directly linked to this doctoral thesis. This engagement provided a unique vantage point on contemporary urban development challenges, facilitating a comparative analysis with ancient Chinese transportation systems. The involvement in this conference, and subsequent analysis, deepened the author's understanding of the influence of historical transportation infrastructure on socioeconomic patterns, a pivotal aspect of the thesis. The insights gained from this experience, detailed in Sections 8.1 and 8.2 of this thesis, substantially enriched the research, bridging the gap between ancient and contemporary urban planning practices.

Figure 8-10 The Author Presenting and Responding at 6th SPP Meeting [99].

9. Conclusions and Outlook

In the final chapter of this thesis, we draw together the strands of our extensive exploration into the profound influence of transportation on the societal fabric of historical China. This chapter is a culminating reflection that synthesizes our discoveries and situates them within the expansive vista of both historical context and contemporary relevance.

Section 9.1 encapsulates the key conclusions of this dissertation, providing a quantitative lens through which to view the historical impact of transportation on Chinese society and its economy, and forges a link between engineering disciplines and historical analysis. It introduces the Historical Accessibility Database and underscores the critical role of transportation in societal transformation, setting the stage for future interdisciplinary research.

Expanding the scope, Section 9.2 connects our conclusions with broader societal themes, illuminating the central role of accessibility in shaping social dynamics, governance, cultural evolution, and public health. It highlights the potency of quantitative analysis in piercing through the veils of antiquity, providing a robust platform for historical interpretations.

The narrative then progresses to Section 9.3, which opens a dialogue with the future, suggesting avenues for continued research. It envisions how the methodologies refined in this thesis might be applied to comparative studies across different historical periods or to assess the impact of historical international trade patterns.

In Section 9.4, the chapter turns introspective, addressing the limitations of our study. Here, we confront the challenges posed by the assumptions regarding historical data reliability, the simplifications required by our models, and the dearth of continuous transportation data. This section is not merely an exercise in academic humility but a call to action for subsequent scholarship to expand upon the groundwork laid herein.

Thus, the final chapter transcends a simple summarization; it is a reflective epitome that not only consolidates our research but also casts a guiding light for future scholarly voyages in the unending narrative of human society and its ceaseless mobility.

9.1 Research Conclusions

This dissertation has provided critical insights into the spatial effects of transportation supply, elucidating its determinant role in shaping society and the economy throughout the course of Chinese history. The research has substantiated general assumptions about the significance of transportation infrastructure and has quantitatively analyzed its enduring effects over the long run. By effectively combining and applying methodologies from both historical and engineering disciplines, the study has bridged the gap between these fields, fostering an interdisciplinary approach that enhances our comprehension of historical dynamics.

The Processing Procedure developed and demonstrated in this research has proven to be feasible and robust, underpinned by a justified selection of material, rational assumptions, and the employment of appropriate mathematical and computational models. This process has been crucial in dissecting and reconstructing the complex interplay between transportation networks and societal changes across various epochs of Chinese history.

One of the pivotal accomplishments of this thesis is the creation of a Historical Accessibility Database, a resource that stands to serve as a foundation for future studies. This open-access repository offers a rich compendium of data that spans from the Han Dynasty through to the Ming Dynasty, enabling subsequent researchers to delve into the multifaceted impacts of transportation systems with greater ease and precision.

In conclusion, this dissertation has affirmed the essential role of transport supply in historical contexts and has quantified its long-term effects, providing a comprehensive analysis that contributes to a better understanding of the spatial effects of transportation on society and the economy. By developing and applying novel methods that accommodate elements from both historians' and engineers' research repertoires, the study establishes a reasonable connection between the two, highlighting the value of an interdisciplinary approach.

9.2 Research Implications

In this segment, the research transcends specific historical analysis to present broader implications for our understanding of societal dynamics. The study underscores accessibility as a key determinant in deciphering social dynamics, influencing everything from population flows to the formation of social networks. The research also reveals the intricate relationship between transportation, government administration, cultural development, and public health. By connecting historical transportation infrastructure with the production of government officials, literary works, and the spread of epidemics, this thesis presents a comprehensive view of the multifaceted role of accessibility in shaping societal structures. Furthermore, the application of quantitative methods in historical analysis emerges as a significant theme, highlighting how a numbers-driven approach can enhance our understanding of historical events and decisions.

9.2.1 Accessibility is the Key to Deciphering Social Dynamics

The essence of this doctoral research transcends its empirical findings, delving into the broader implications of how accessibility has been a pivotal force in shaping social dynamics throughout history. The study's comprehensive analysis illuminates the overarching role of transportation accessibility, not merely as a physical facilitator but as a critical catalyst influencing societal development and interactions.

Central to this discussion is the conceptualization of accessibility as more than a logistical attribute; it is a determinant that shapes and is shaped by political, economic, and cultural forces. This research highlights the dynamic interplay between transportation infrastructure and societal patterns, where each continually influences and reshapes the other. The evolution of transportation systems reflects the societal priorities and advancements of each era, while simultaneously steering the course of social developments, be it in population movements, social network formation, or cultural exchanges.

A significant insight from the research is the relationship between transportation accessibility and demographic dynamics. The study moves beyond traditional narratives that attribute population movements solely to major historical events. Instead, it positions accessibility as a crucial factor that accelerates and amplifies these movements, suggesting a more nuanced understanding of historical population shifts.

Similarly, the study's exploration of the Modified Gravity Model and its applications in social network analysis represents a step forward in comprehending urban and social structures. By integrating advanced analytical methods, the research challenges existing paradigms and introduces new ways of understanding the complexities of social connections in urban settings.

Moreover, this thesis sheds light on the often-overlooked impact of transportation on cultural and intellectual realms. It reveals how enhanced accessibility has historically facilitated not just physical mobility but also the flow of ideas, contributing to cultural vibrancy and intellectual discourse. Conversely, it also highlights the darker side of increased connectivity, such as the accelerated spread of epidemics, thereby underscoring the multifaceted impact of transportation systems.

In conclusion, this research offers a holistic view of the role of accessibility in shaping societal structures, extending its implications far beyond the realm of transportation studies. It underscores the need for a multidisciplinary approach in understanding the complex interdependencies between transportation, social dynamics, and cultural developments. The findings from this research not only enrich our historical understanding but also provide valuable insights for contemporary and future societal planning, emphasizing the continuing significance of accessibility in shaping our world.

9.2.2 Embracing Quantitative Analysis in Historical Discourse

The essence of this segment of my doctoral thesis lies in advocating for the paradigm 'Number Explained History Better,' a notion that champions the integration of quantitative research methods into historical studies. This approach underscores a fundamental shift from conventional narrative-driven historical analysis to a more data-centric perspective, highlighting how numerical analysis can enrich our understanding of history.

The thesis posits that quantitative methods bring a new dimension of clarity and objectivity to historical research. By converting historical events, trends, and decisions into quantifiable data, these methods allow for a more precise and nuanced understanding of the past. This approach transcends the traditional reliance on narrative and qualitative analysis, offering a more concrete and measurable perspective on history.

In adopting this methodology, the thesis illustrates how quantitative analysis can unveil patterns and correlations that might remain obscured in purely narrative forms of history. This is not to diminish the value of traditional historical methods but to suggest that the integration of quantitative data can provide a complementary lens through which to view the past.

Furthermore, the adoption of quantitative methods in historical research aligns with the broader trend towards interdisciplinary studies. It bridges the gap between history and other fields such as economics, political science, and geography, fostering a more holistic understanding of the past. This interdisciplinary approach is crucial in an era where understanding complex historical phenomena requires insights from multiple perspectives.

In conclusion, the thesis asserts that the use of quantitative methods in historical research is not just a supplementary tool but a necessary evolution in the discipline. It emphasizes that numbers, when used effectively, can tell a story of the past that is as compelling and insightful as traditional narratives. This perspective opens up new avenues for historical research, promising a richer and more comprehensive understanding of our past.

9.2.3 Emphasizing the Macro Perspective: Implications for Future Societal

Evolution

This section of the concluding chapter of my doctoral thesis shifts focus from specific historical instances to the broader implications of understanding large-scale spatial and temporal dynamics in shaping societies. The exploration of extensive historical data, particularly in the context of transportation and societal development, has underscored the vital role of macro-scale research in comprehending and influencing contemporary and future societal structures.

Emphasizing a macro perspective involves extrapolating from specific historical data to broader trends and patterns. This approach moves beyond the detailed analysis of individual events or periods, such as the influence of the Grand Canal on regional development, to a more comprehensive understanding of how transportation has historically functioned as a catalyst for societal change. It entails recognizing patterns over centuries and across vast geographies, thereby facilitating a deeper understanding of how past infrastructures and policies have shaped present societal norms and might influence future developments.

By adopting this broader lens, we can discern overarching themes and long-term trends that are instrumental in formulating strategies for current and future societal challenges. For instance, the historical relationship between transportation accessibility and societal aspects such as governance, cultural development, and public health offers insights that are crucial in contemporary policy-making, especially in an increasingly interconnected and rapidly changing global landscape.

The thesis argues for the importance of integrating macro-scale analyses into contemporary research and policy formulation. This perspective is particularly pertinent in the context of global challenges such as climate change, urbanization, and public health crises. Understanding the long-term impacts of historical decisions can guide current policy-making, ensuring that strategies are not only effective in the short term but also sustainable in the long run.

In conclusion, this section of the thesis advocates for a paradigm shift in academic research and policy formulation, from a focus on micro-level, event-specific analysis to a broader, macro-scale perspective. This shift is crucial for a holistic understanding of societal dynamics and for crafting policies and strategies that are robust, sustainable, and capable of addressing the complex challenges of modern societies.

9.3 Research Outlook

The concluding part of my doctoral thesis presents a forward-looking outlook, proposing future research avenues building upon the quantitative approach that has significantly enriched our understanding of history. This section outlines potential areas of exploration that could further illuminate the dynamics of ancient societies, focusing on comparative studies across different eras and the quantification of international trade's impact in historical contexts; the study of modern times and its invaluable connection to contemporary society; and the role of continuous research in anticipating societal transformations.

9.3.1. Comparison Study on Other Ancient Times

One of the promising future research directions is a comparative study across various ancient periods. The rationale behind this approach stems from the success of quantitative methods in historical analysis, as demonstrated in my research. By comparing population and transportation data on different scales across various ancient times, it's possible to unearth new insights into historical phenomena. This approach's uniqueness lies in examining the differences in population scales and transportation modes, alongside the consistent structures of transportation networks and societal organization. Despite changes in population sizes and road networks, societies predominantly remained agrarian with similar modes of transportation, such as horses, wagons, and ships. These comparisons could reveal fundamental patterns and deviations in societal evolution and infrastructure development.

Another intriguing area for future research is the quantification of international trading's influence in ancient times. As indicated in Table 9-1 of my thesis, understanding the historical context requires considering new challenging factors, even for ancient times. There was a strong connection between China and foreign countries through the Silk Road and maritime trade routes, with international trade becoming a crucial aspect of foreign policy since the late Ming Dynasty. Quantifying this aspect would require developing innovative methodologies to measure the impact of international trade on ancient societies accurately. This research could offer valuable insights into the economic and political strategies of ancient states and their interactions with the wider world.

In conclusion, the potential future research outlined in my thesis aims to deepen our understanding of historical societies using quantitative methods. By conducting comparative studies across different ancient times and quantifying aspects like international trade, future research can provide a more nuanced and comprehensive understanding of historical dynamics. These future studies hold the promise of not only advancing historical knowledge but also offering lessons applicable to contemporary global interactions and policy-making. The outlook presented in my doctoral thesis is a testament to the evolving nature of historical research and its increasing relevance in a world where understanding the past is crucial to navigating the future.

Table 9-1 Challenging Factors for Study Periods.

<table>
<tr><th>Age</th><th>Represent Year (C.E.)</th><th>Challenging Factors Need to Consider</th></tr>
<tr><td>Shui-Tang Age
(581 C.E.~907 C.E.)</td><td>742</td><td>The Grand Canal was built.
The economic center was shifted to the south.</td></tr>
<tr><td>Yuan Age
(1271 C.E.-1368 C.E.)</td><td>1290</td><td rowspan="2">New Network: International Transportation
(Silk Road / Transportation on the Sea)</td></tr>
<tr><td>Ming-Qing Age
(1368 C.E.~1912 C.E.)</td><td>1820</td></tr>
<tr><td>Modern Age
(1912 C.E.~1978 C.E.)</td><td>1934
1978</td><td>New Vehicles: Railway, Steamboat, Airlines</td></tr>
<tr><td>Contemporary Era
(1978 C.E. ~ Now)</td><td>2016</td><td>New Industry: Information Industry</td></tr>
</table>

9.3.2. Continuous Study on Modern Times

The transition from ancient to modern transportation systems presents a rich area for exploration. Over the past two centuries, the introduction of Western transportation technologies such as railways, airlines, and steamships has revolutionized Chinese society. These advancements have led to a more complex travel mode landscape compared to ancient times, offering a unique opportunity to study their transformative impacts.

1. Diverse Cost Factors in Accessibility Calculation: In modern times, the calculation of accessibility

must account for a broader range of cost factors beyond mere travel time. The variety of travel modes introduces the financial cost as a critical parameter. Not everyone can afford the fastest mode of travel, like airlines, making financial cost an essential factor in categorizing the population. This aspect of modern transportation provides a nuanced understanding of accessibility and its socio-economic implications.

2. The Impact of Information Technology and Industrial Industry: Another fundamental shift in the contemporary period is the advent of the Industrial Industry and Information Technology. These developments have fundamentally altered how people communicate and interact, necessitating their inclusion in modern transportation studies. Information technology, in particular, has dramatically enhanced interpersonal interactions and its influence on societal structures cannot be overlooked.
3. Utilizing Diverse Socioeconomic Indexes: Modern times offer a wealth of data that can be used to measure the impact of transportation on society. Unlike in ancient times, where population dynamics were the primary focus due to data limitations, contemporary studies can leverage a variety of socio-economic indexes. These include Gross Domestic Product (GDP), traffic flow volume, and other precise transportation metrics. The availability of these data allows for a more comprehensive understanding of how transportation influences various aspects of modern society.

In conclusion, extending the study of transportation and accessibility into modern times presents an exciting and valuable research trajectory. By exploring how recent advancements in transportation and technology have reshaped societal dynamics, this future research can provide deeper insights into the current and future societal structure. The transition from ancient to modern transportation offers a unique lens through which we can understand the continuous evolution of society, making it a crucial area of study for comprehending and shaping the world we live in today.

9.3.3. Possible Study on Future Societies

The ultimate pursuit of historical and contemporary research is its applicability in predicting and shaping the future. My doctoral thesis, which intricately examines the relationship between accessibility and societal development, sets the stage for applying these insights to forecast the societal changes of tomorrow. This section extrapolates from my previous work to propose a future research trajectory that anticipates the societal impacts of forthcoming advancements in transportation and information technology.

The interplay between accessibility and society, thoroughly analyzed in historical contexts, can now be projected into the future with the aid of machine learning techniques. By integrating the potential evolution of transportation infrastructures and advancements in information technology, we can begin to model and quantify future societal shifts. Innovations like self-driving cars, air buses, and the implementation of 5G networks are poised to bring revolutionary changes to our societal fabric [101].

Future research could focus on quantifying the effects of these transportation and information industry developments on various societal dimensions. The scope of this inquiry may encompass population dynamics, fluctuations in land or property prices, transformations in the job market, alterations in the economic structure, and varying measures of productivity. Additionally, such research can address critical issues of poverty and growth, providing insights into the redistribution of wealth and opportunities that may arise from these technological changes.

Continued research into the past and present serves as a compass for navigating the future. By understanding the historical mechanisms that have shaped societal evolution, we can better prepare for the transformations that await us. The proposed future research offers a visionary approach to quantifying the impact of imminent technological shifts, thereby contributing valuable knowledge that can inform policy-making, urban planning, and social welfare initiatives. As we stand on the cusp of a new era marked by rapid technological advancement, the need for such forward-looking research has never been more pronounced. It is through this lens that we can envision a future society that is not only technologically advanced but also socially equitable and economically robust.

9.4 Research Limitations

This section dedicated to the discussion of the study's limitations is critical for acknowledging the inherent constraints and for guiding future research. Despite the comprehensive nature of the study, one must recognize the tentative reliability of historical assumptions, such as the assumptions underpinning the regression analyses of population dynamics and transportation accessibility, as presented in Chapter 4. The study's analytical framework postulates that population changes can be bifurcated into local effects, representing direct births and deaths, and accessibility effects, signifying migratory inflows and outflows related to transportation. While these assumptions are rational and align with conventional wisdom, they undoubtedly simplify the complex reality of historical population dynamics. The primary focus of this research has been to identify and assume key underlying mechanisms, leveraging data from ancient times to validate these suppositions. However, the potential divergence between these assumptions and the actualities of ancient societies represents one of the study's principal limitations.

Furthermore, the methodological limitations of the historical models employed must be acknowledged. The accessibility model, the regression model correlating accessibility with population changes, and the two models pertaining to social networks—the Modified Gravity Model and the accessibility-based model—boast relatively simplistic mathematical forms. The advantage of such simplicity is the clear elucidation of the fundamental mechanisms underlying the issues studied. The straightforward mathematical representations facilitate an unambiguous understanding of the correlations between transportation accessibility and other social variables. Nonetheless, the actual intricacies of historical social dynamics are likely more complex. This simplification warrants the introduction of more sophisticated machine learning models in Section 5 of Chapter 6 to address the shortcomings of the Modified Gravity Model. Striking a balance between the readability (simplicity) and the complexity of models is crucial. Given the limited nature of ancient data, the adoption of simple models to capture essential mechanisms is arguably the most feasible approach under the current constraints.

The most significant limitation, however, lies in the paucity of data regarding changes in transportation over time. Although the study incorporates transportation networks from four different dynastic periods, there is an absence of transitional data between these epochs. The effort to delineate the impact of transportation on society has been maximized within the bounds of available data. The lack of continuous historical transportation data hinders a more nuanced understanding of the evolution of transportation networks and their societal implications. This gap in the data presents a considerable challenge and underscores the need for cautious interpretation of the study's findings.

In summary, while this dissertation offers substantial contributions to the understanding of ancient transportation networks and their social impacts, it is imperative to acknowledge the inherent limitations.

These include the presumptive reliability of historical records, the methodological constraints of the models employed, and the significant gaps in historical transportation data. Future research should aim to address these limitations, perhaps by integrating more complex models and seeking out additional data sources, to provide an even deeper understanding of the historical intricacies of transportation and its societal effects.

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Appendix 1 Algorithm for Network Analysis of Social Connection

Algorithm A1-1 Calculation Algorithm for Network Analysis of Social Connection

```
#Original Data Check
import pandas as pd
df1 = pd.read_csv("Con-Edges6.csv")
df1
```

Outputs:

	Source	Target	Type	Id	Label	Weight	edge_desc	edgetype	L-StartY	L-EndY	...	TS_Total_Hors	TS_Total_Wago	TS_Total_Leng	CLoops
0	1	333	Undirected	0	與Y結黨	1	Coalition associate of	N	1042	1110	...	39.339865	60.099454	1.375622e+06	0
1	1	333	Undirected	1	支持	1	Supported	N	1042	1110	...	39.339865	60.099454	1.375622e+06	0
2	1	1488	Undirected	2	不合	1	Disagreed with views of	N	1042	1094	...	23.976405	36.769625	8.404826e+05	0
3	1	1488	Undirected	3	陷害Y	1	did harm to	N	1042	1094	...	23.976405	36.769625	8.404826e+05	0
4	1	1649	Undirected	4	與Y結黨	1	Coalition associate of	N	1047	1117	...	48.008693	69.761335	1.679161e+06	0
...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
55894	562661	29570	Undirected	90344	拜訪	1	Visited	N	1462	1503	...	36.188045	53.904994	1.265686e+06	0
55895	563084	30359	Undirected	90359	下屬為Y	1	subordinate was	N	1140	1144	...	0.000000	0.000000	0.000000e+00	1
55896	563174	3134	Undirected	90362	為Y之部將	1	Officer under command of	N	1088	1146	...	31.174651	50.418651	1.088184e+06	0
55897	563293	562997	Undirected	90364	為Y之學生	1	Student of	N	1604	1666	...	0.000000	0.000000	0.000000e+00	1
55898	563453	34748	Undirected	90365	幫助Y	1	aided	N	1606	1653	...	3.697541	6.237500	1.291846e+05	0

55899 rows × 35 columns

S_H_UNICOD_1	S_NewPID	S_NewCID	T_H_UNICOD_1	T_NewPID	T_NewCID
渠	4	147	建	7	217
渠	4	147	建	7	217
渠	4	147	絳	11	292
渠	4	147	絳	11	292
渠	4	147	泉	7	213
...	...	...	...	...	...
越	7	202	廣	1	16
齊	9	246	齊	9	246
潞	11	291	蘇	7	204
洪	6	181	洪	6	181
杭	7	201	越	7	202

```
import pandas as pd
import networkx as nx
from operator import itemgetter

rows = []
# Initialize the dataframe for the results
df_year = pd.DataFrame(columns=['Year', 'Total Link Number', 'Loops Number', 'Non-Loops Number',
                        'Average Degree', 'Nodes Number', 'Network Diameter', 'Network Density',
                        'Node ID with Maximum Total Degree', 'Maximum Node Degree',
                        'Node ID with Maximum Loops Degree', 'Maximum Node Loops Degree',
                        'Node ID with Maximum Non-Loops Degree', 'Maximum Node Non-Loops Degree',
                        'Average Travel Time (Days)', 'Average Distance (Kilometers)', 'Average Speed (Kilometers/Days)',
                        'Average Travel Time for Top 20% (Days)', 'Average Distance for Top 20% (Kilometers)',
                        'Average Speed for Top 20% Links (Kilometers/Days)'])

for year in range(580, 1911, 10):
   G = nx.MultiGraph()
   for _, row in df1.iterrows():
      if row['L-StartY'] <= year <= row['L-EndY']:
         G.add_edge(row['S_NewCID'], row['T_NewCID'], distance=row['ST_Total_Leng'], time=row['ST_Total_Wago'])
         G.add_edge(row['T_NewCID'], row['S_NewCID'], distance=row['TS_Total_Leng'], time=row['TS_Total_Wago'])

   # Calculate various metrics
   total_link_number = G.number_of_edges()
   loops_number = nx.number_of_selfloops(G)
   non_loops_number = total_link_number - loops_number
   average_degree = sum(dict(G.degree()).values()) / len(G)
   nodes_number = G.number_of_nodes()
   network_diameter = nx.diameter(G) if nx.is_connected(G) else 0
   network_density = nx.density(G)
   max_degree_node = max(G.degree(), key=itemgetter(1))
   max_loop_node = max(((n, len(list(nx.selfloop_edges(G, data=False, keys=True, default=False)))) for n in G.nodes()), key=itemgetter(1)) if loops_number > 0 else (0, 0)
   max_non_loop_node = max(((n, d) for n, d in G.degree() if n != max_loop_node[0]), key=itemgetter(1), default=(0, 0))

   average_distance = sum(edge[2]['distance'] for edge in G.edges(data=True)) / (1000 * non_loops_number) if non_loops_number > 0 else 0
   average_time = sum(edge[2]['time'] for edge in G.edges(data=True)) / non_loops_number if non_loops_number > 0 else 0
   average_speed = average_distance / average_time if average_time >0 else 0

   distances_times = sorted([(edge[2]['distance'], edge[2]['time']) for edge in G.edges(data=True)], key=itemgetter(0))
   if len(distances_times) >= 5:
      top_20_index = int(len(distances_times) * 0.2)
      distances_times_latter_20 = distances_times[-top_20_index:]
```

```
        top_20_avg_distance = sum(dt[0] for dt in distances_times_latter_20) / (1000 * top_20_index)
        top_20_avg_time = sum(dt[1] for dt in distances_times_latter_20) / top_20_index
        top_20_avg_speed = top_20_avg_distance / top_20_avg_time

    else:
        if distances_times:  # list is not empty
            top_20_avg_distance = distances_times[-1][0]/1000  # last item after sorting is the maximum
            top_20_avg_time = distances_times[-1][1]  # last item after sorting is the maximum
            top_20_avg_speed = top_20_avg_distance / top_20_avg_time if top_20_avg_time >0 else 0
        else:  # list is empty
            top_20_avg_distance = 0
            top_20_avg_time = 0
            top_20_avg_speed = 0

    # Add the data for each year to the list
    rows.append({'Year': year, 'Total Link Number': total_link_number, 'Loops Number': 
loops_number,
                'Non-Loops Number': non_loops_number, 'Average Degree': average_degree,
                'Nodes Number': nodes_number, 'Network Diameter': network_diameter,
                'Network Density': network_density, 'Node ID with Maximum Total Degree': 
max_degree_node[0],
                'Maximum Node Degree': max_degree_node[1], 'Node ID with Maximum Loops Degree': 
max_loop_node[0],
                'Maximum Node Loops Degree': max_loop_node[1], 'Node ID with Maximum Non-Loops 
Degree': max_non_loop_node[0],
                'Maximum Node Non-Loops Degree': max_non_loop_node[1],
                'Average Travel Time (Days)': average_time,
                'Average Distance (Kilometers)': average_distance,
                'Average Speed (Kilometers/Days)':average_speed,
                'Average Travel Time for Top 20% (Days)': top_20_avg_time,
                'Average Distance for Top 20% (Kilometers)': top_20_avg_distance,
                'Average Speed for Top 20% Links (Kilometers/Days)':top_20_avg_speed,
                })
    # Merge all rows into one dataframe
    df_year = pd.concat([pd.DataFrame([row]) for row in rows], ignore_index=True)
df_year
```
Outputs:

	Year	Total Link Number	Loops Number	Non-Loops Number	Average Degree	Nodes Number	Network Diameter	Network Density	Node ID with Maximum Total Degree	Maximum Node Degree	Node ID with Maximum Loops Degree	Maximum Node Loops Degree	Node ID with Maximum Non-Loops Degree
0	580	38	8	30	6.909091	11	4	0.690909	308	26	191	8	308
1	590	68	10	58	7.555556	18	0	0.444444	308	42	191	10	308
2	600	208	44	164	14.857143	28	4	0.550265	308	196	191	44	308
3	610	230	52	178	15.862069	29	4	0.566502	308	216	191	52	308
4	620	236	52	184	15.733333	30	4	0.542529	308	218	191	52	308
...	...	...	...	...	...	...	...	...	...	...	...	...	...
129	1870	1416	406	1010	26.716981	106	0	0.254447	204	330	201	406	204
130	1880	1260	364	896	25.454545	99	5	0.259740	204	290	201	364	204
131	1890	952	274	678	21.885057	87	0	0.254477	16	262	201	274	16
132	1900	722	214	508	19.000000	76	0	0.253333	16	250	201	214	16
133	1910	502	172	330	15.687500	64	0	0.249008	16	224	200	172	16

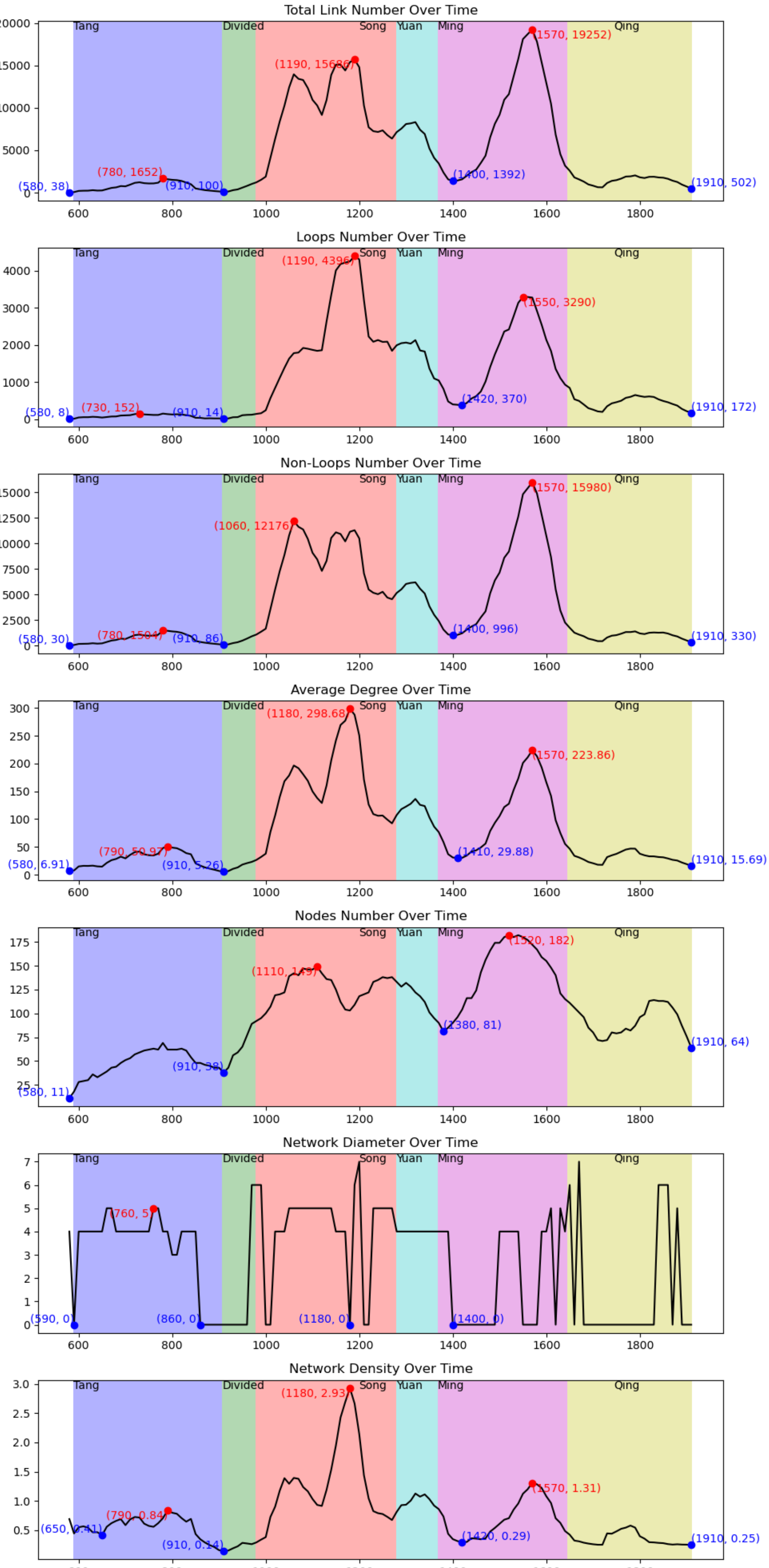
134 rows × 20 columns

Maximum Node Non-Loops Degree	Average Travel Time (Days)	Average Distance (Kilometers)	Average Speed (Kilometers/Days)	Average Travel Time for Top 20% (Days)	Average Distance for Top 20% (Kilometers)	Average Speed for Top 20% Links (Kilometers/Days)
26	39.075757	818.680247	20.951104	49.716776	1037.460338	20.867410
42	38.838782	813.681572	20.950234	53.766447	1148.658671	21.363857
196	37.626003	789.351772	20.978890	62.177858	1311.357623	21.090428
216	37.927482	795.711977	20.979826	63.164771	1325.726669	20.988387
218	38.811215	814.284353	20.980646	65.402516	1375.933939	21.037936
...	...	...	...	...	...	...
330	36.823498	773.261095	20.999121	71.968672	1509.568998	20.975363
290	37.140371	779.929095	20.999497	73.986440	1551.836412	20.974606
262	37.916664	796.690085	21.011608	75.400198	1582.389210	20.986539
250	37.970897	798.223991	21.021994	74.876112	1571.819314	20.992267
224	37.728301	793.641312	21.035703	73.984654	1552.885401	20.989291

Algorithm A1-2 Data Virtualization Algorithm for Social Network Characteristics

```
import matplotlib.pyplot as plt
from scipy.signal import argrelextrema
import numpy as np

# df_year = df_year.set_index('Year')  # Set the year as an index
label_offsets = [0, 0, 220, 0, 0, 100, 0]  # offsets for the period labels to avoid overlapping
periods = [
    (589, 907, 'Tang'),
    (907, 979, 'Divided'),
    (979, 1279, 'Song'),
```

```
    (1279, 1368, 'Yuan'),
    (1368, 1644, 'Ming'),
    (1644, 1912, 'Qing'),
]

# Create a sufficient number of subgraphs
fig, axs = plt.subplots(len(df_year.columns[:7]), figsize=(10, 20))
colors = ['b', 'g', 'r', 'c', 'm', 'y', 'y']

# Loop through each column of data
for ax, (column, color) in zip(axs, zip(df_year.columns[:7], colors)):
    data = df_year[column]

     # Plotting line graphs
    ax.plot(data, label=column, color='black')

     # Drawing titles
    ax.set_title(column + ' Over Time')

     # Mark different areas
    for j, (start, end, label) in enumerate(periods):
        ax.axvspan(start if start is not None else data_to_plot['Year'].min(),
                   end if end is not None else data_to_plot['Year'].max(),
                   facecolor=colors[j % len(colors)], alpha=0.3)

        ax.text((start if start else data_to_plot['Year'].min()) + label_offsets[j % len(label_offsets)],
ax.get_ylim()[1], label, fontsize=10, verticalalignment='top')

    # Add extrema points
    y_values = data.to_numpy()
    x_values = data.index.to_numpy()

    max_idx = argrelextrema(y_values, np.greater_equal, order=20)[0]  # Find local maxima
    min_idx = argrelextrema(y_values, np.less_equal, order=20)[0]  # Find local minima

    points = [(x_values[idx], y_values[idx]) for idx in np.concatenate([max_idx, min_idx])]
    points.sort()  # Sort by x value

    # Remove points if too close in x
    points = [point for idx, point in enumerate(points) if idx == 0 or point[0] - points[idx - 1][0] > 80]

    for x, y in points:
        ax.plot(x, y, 'ro' if y in set(y_values[max_idx]) else 'bo')
        ax.text(x, y, f'({int(x) if x.is_integer() else round(x, 2)}, {int(y) if y.is_integer() else round(y,
2)})',
                ha='right' if x < np.median(x_values) else 'left',
                va='bottom' if y < np.median(y_values) else 'top',
                color = 'red' if y in set(y_values[max_idx]) else 'blue')

plt.tight_layout()
plt.savefig('df_year_plots1.png')
plt.show()
```
Outputs:

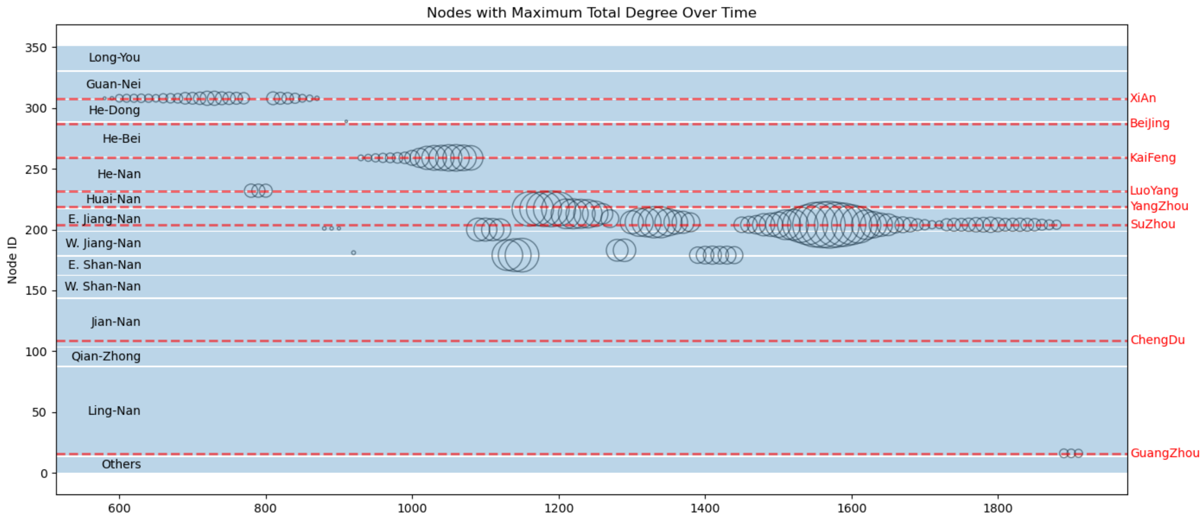

Total Link Number Over Time
Tang
Divided
Song
Yuan
Ming
Qing
(580, 38)
(780, 1652)
(910, 100)
(1190, 15686)
(1400, 1392)
(1570, 19252)
(1910, 502)
Loops Number Over Time
(580, 8)
(730, 152)
(910, 14)
(1190, 4396)
(1420, 370)
(1550, 3290)
(1910, 172)
Non-Loops Number Over Time
(580, 30)
(780, 1504)
(910, 86)
(1060, 12176)
(1400, 996)
(1570, 15980)
(1910, 330)
Average Degree Over Time
(580, 6.91)
(790, 50.97)
(910, 5.26)
(1180, 298.68)
(1410, 29.88)
(1570, 223.86)
(1910, 15.69)
Nodes Number Over Time
(580, 11)
(910, 38)
(1110, 149)
(1380, 81)
(1520, 182)
(1910, 64)
Network Diameter Over Time
(590, 0)
(760, 5)
(860, 0)
(1180, 0)
(1400, 0)
Network Density Over Time
(650, 0.41)
(790, 0.84)
(910, 0.14)
(1180, 2.93)
(1420, 0.29)
(1570, 1.31)
(1910, 0.25)

Algorithm A1-3 Data Virtualization Algorithm for Social Network Hub Nodes

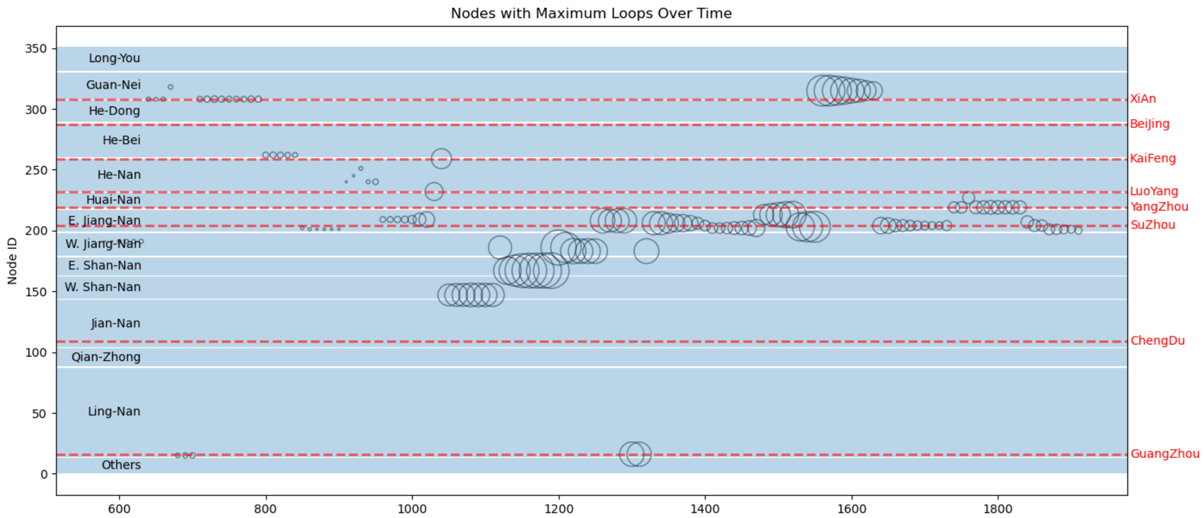
```
import matplotlib.pyplot as plt
import numpy as np

fig, axs = plt.subplots(3, 1, figsize=(16, 24))

# Information on the three subgraphs
subplots_info = [
    (8, 9, 'Nodes with Maximum Total Degree Over Time'),
    (10, 11, 'Nodes with Maximum Loops Over Time'),
    (12, 13, 'Nodes with Maximum Non-Loops Links Over Time'),
]

# y values corresponding to regions and labels
periods = [
    (0, 13, 'Others'),
    (14, 87, 'Ling-Nan'),
    (88, 103, 'Qian-Zhong'),
    (104, 143, 'Jian-Nan'),
    (144, 162, 'W. Shan-Nan'),
    (163, 178, 'E. Shan-Nan'),
    (179, 198, 'W. Jiang-Nan'),
    (199, 217, 'E. Jiang-Nan'),
    (218, 231, 'Huai-Nan'),
    (232, 259, 'He-Nan'),
    (260, 288, 'He-Bei'),
    (289, 307, 'He-Dong'),
    (308, 330, 'Guan-Nei'),
    (331, 351, 'Long-You')
]

# y values corresponding to horizontal dashed lines and labels
cities=[
    (16, 'GuangZhou'),
    (109, 'ChengDu'),
    (204, 'SuZhou'),
    (219, 'YangZhou'),
    (259, 'KaiFeng'),
    (232, 'LuoYang'),
    (287, 'BeiJing'),
    (308, 'XiAn'),
]

for i, (y_col, size_col, title) in enumerate(subplots_info):
    ax = axs[i]

    # Mapping bubbles
    scatter = ax.scatter(df_year['Year'], df_year.iloc[:, y_col], s=(df_year.iloc[:, size_col]/5),
alpha=0.5, color='none', edgecolors='black')

    # Setting the title
    ax.set_title(title)
```

```
    # Set the y-axis labels
    ax.set_ylabel('Node ID')

    # Mark areas
    for start, end, label in periods:
        ax.axhspan(start, end, alpha=0.3)
        ax.text(df_year['Year'].min()+50, (start + end) / 2, label, va='center', ha='right')

    # Draw horizontal dotted lines
    for y, label in cities:
        ax.axhline(y, color='red', linestyle='--', alpha=0.6, linewidth=2)
        ax.text(df_year['Year'].max()+70, y, label, va='center', ha='left', color='red',fontsize=10)

# Add bubble size legend
# Create legend with specific size

# Output Image
plt.savefig('df_year_plots2.png')

plt.show()
```

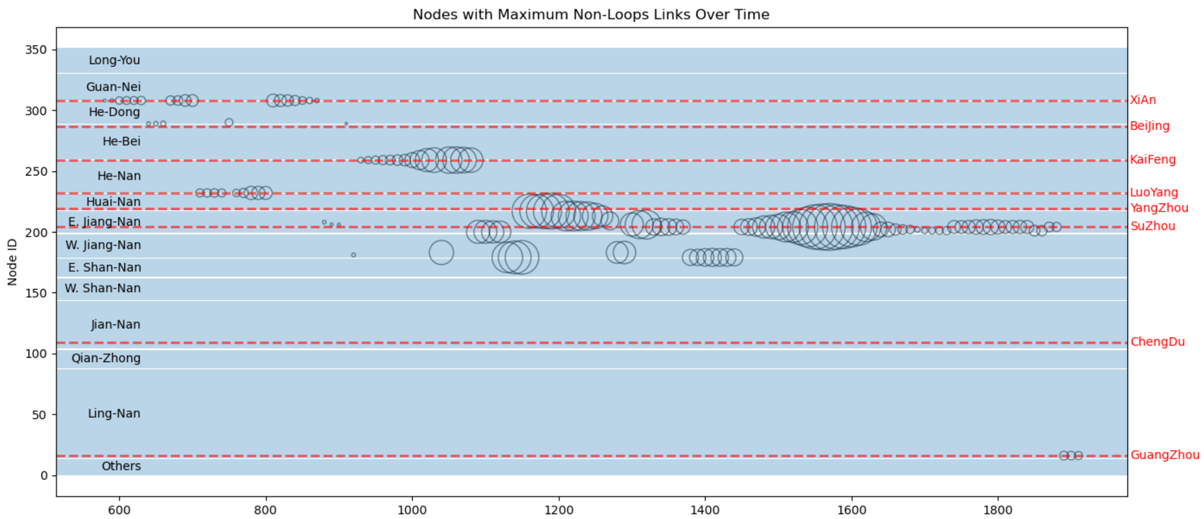
Outputs:



Nodes with Maximum Total Degree Over Time
Long-You
Guan-Nei
He-Dong
He-Bei
He-Nan
Huai-Nan
E. Jiang-Nan
W. Jiang-Nan
E. Shan-Nan
W. Shan-Nan
Jian-Nan
Qian-Zhong
Ling-Nan
Others
Node ID
XiAn
BeiJing
KaiFeng
LuoYang
YangZhou
SuZhou
ChengDu
GuangZhou



Nodes with Maximum Loops Over Time
Long-You
Guan-Nei
He-Dong
He-Bei
He-Nan
Huai-Nan
E. Jiang-Nan
W. Jiang-Nan
E. Shan-Nan
W. Shan-Nan
Jian-Nan
Qian-Zhong
Ling-Nan
Others
Node ID
XiAn
BeiJing
KaiFeng
LuoYang
YangZhou
SuZhou
ChengDu
GuangZhou



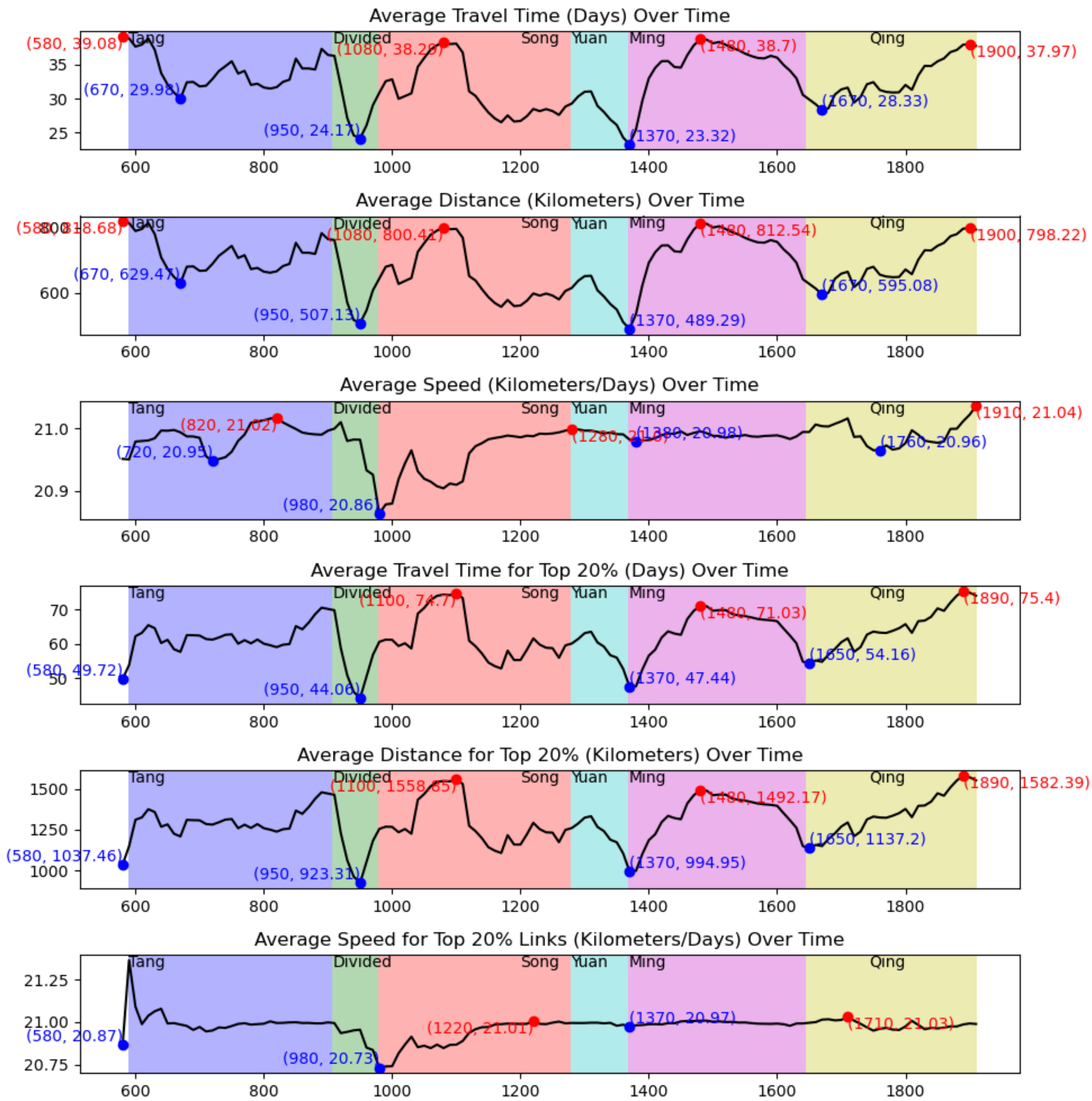
Nodes with Maximum Non-Loops Links Over Time
Long-You
Guan-Nei
He-Dong
He-Bei
He-Nan
Huai-Nan
E. Jiang-Nan
W. Jiang-Nan
E. Shan-Nan
W. Shan-Nan
Jian-Nan
Qian-Zhong
Ling-Nan
Others
Node ID
XiAn
BeiJing
KaiFeng
LuoYang
YangZhou
SuZhou
ChengDu
GuangZhou

Algorithm A1-4 Data Virtualization Algorithm for Transportation Related Social Network Characteristics

```
import matplotlib.pyplot as plt
from scipy.signal import argrelextrema
import numpy as np

#df_year = df_year.set_index('Year')  # Set the year as an index
label_offsets = [0, 0, 220, 0, 0, 100, 0]  # offsets for the period labels to avoid overlapping
periods = [
    (589, 907, 'Tang'),
    (907, 979, 'Divided'),
    (979, 1279, 'Song'),
    (1279, 1368, 'Yuan'),
    (1368, 1644, 'Ming'),
    (1644, 1912, 'Qing'),
]

# Create a sufficient number of subgraphs
fig, axs = plt.subplots(len(df_year.columns[13:19]), figsize=(10, 10))
colors = ['b', 'g', 'r', 'c', 'm', 'y', 'y']

# Loop through each column of data
for ax, (column, color) in zip(axs, zip(df_year.columns[13:19], colors)):
    data = df_year[column]

    # Plotting line graphs
    ax.plot(data, label=column, color='black')

    # Drawing titles
    ax.set_title(column + ' Over Time')

    # Mark different areas
    for j, (start, end, label) in enumerate(periods):
        ax.axvspan(start if start is not None else data_to_plot['Year'].min(),
                   end if end is not None else data_to_plot['Year'].max(),
                   facecolor=colors[j % len(colors)], alpha=0.3)

        ax.text((start if start else data_to_plot['Year'].min()) + label_offsets[j % len(label_offsets)],
ax.get_ylim()[1], label, fontsize=10, verticalalignment='top')

    # Add extrema points
    y_values = data.to_numpy()
    x_values = data.index.to_numpy()

    max_idx = argrelextrema(y_values, np.greater_equal, order=20)[0]  # Find local maxima
    min_idx = argrelextrema(y_values, np.less_equal, order=20)[0]  # Find local minima

    points = [(x_values[idx], y_values[idx]) for idx in np.concatenate([max_idx, min_idx])]
    points.sort()  # Sort by x value

    # Remove points if too close in x
    points = [point for idx, point in enumerate(points) if idx == 0 or point[0] - points[idx - 1][0] > 80]
```

```
    for x, y in points:
        ax.plot(x, y, 'ro' if y in set(y_values[max_idx]) else 'bo')
        ax.text(x, y, f'({int(x) if x.is_integer() else round(x, 2)}, {int(y) if y.is_integer() else round(y, 2)})',
                ha='right' if x < np.median(x_values) else 'left',
                va='bottom' if y < np.median(y_values) else 'top',
                color = 'red' if y in set(y_values[max_idx]) else 'blue')

plt.tight_layout()
plt.savefig('df_year_plots1.png')
plt.show()
```

Output:



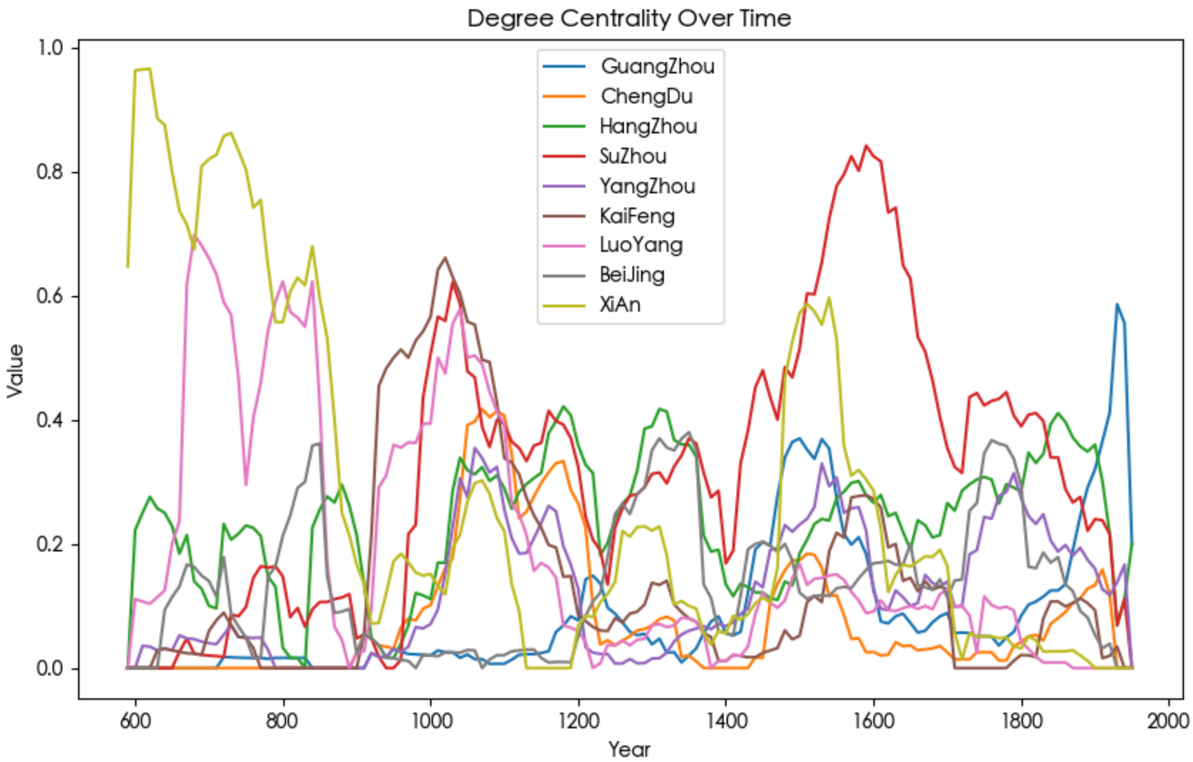
Algorithm A1-5 Calculation Algorithm for Social Network Characteristics (Community Detection, Centrality, Betweenness, Closeness, PageRank, etc.)

```
import pandas as pd
import numpy as np
import networkx as nx
from community import community_louvain
import warnings
warnings.filterwarnings('ignore')
df4 = pd.read_csv("NewIDCities.csv")

# Initialise an empty DataFrame
df_DegreeCentrality = df4[['H_UNICOD_1', 'NewCID']]
df_BetweennessCentrality = df4[['H_UNICOD_1', 'NewCID']]
df_ClosenessCentrality = df4[['H_UNICOD_1', 'NewCID']]
df_PageRank = df4[['H_UNICOD_1', 'NewCID']]
df_Community = df4[['H_UNICOD_1', 'NewCID']]

# Set to NewID for indexing
df_DegreeCentrality.set_index('NewCID', inplace=True)
df_BetweennessCentrality.set_index('NewCID', inplace=True)
df_ClosenessCentrality.set_index('NewCID', inplace=True)
df_PageRank.set_index('NewCID', inplace=True)
df_Community.set_index('NewCID', inplace=True)

# Iterate for each decade interval
for year in range(590, 1960, 10):
   # Filtering eligible edges
   df_temp = df1[(df1['L-StartY'] <= year) & (df1['L-EndY'] >= year)]

   # Create an undirected graph from edge information
   G = nx.from_pandas_edgelist(df_temp, 'S_NewCID', 'T_NewCID')

   # Calculate and save centrality and PageRank
   df_DegreeCentrality[year] = pd.Series(nx.degree_centrality(G))
   df_BetweennessCentrality[year] = pd.Series(nx.betweenness_centrality(G))
   df_ClosenessCentrality[year] = pd.Series(nx.closeness_centrality(G))
   df_PageRank[year] = pd.Series(nx.pagerank(G))

   # Calculate and save community structures
   communities = community_louvain.best_partition(G)
   # Sorting and assigning values to community numbers
   communities_df = pd.DataFrame.from_dict(communities, orient='index').sort_values(0,
ascending=False)
   communities_df.columns = [year]
   df_Community = pd.merge(df_Community, communities_df, left_index=True, right_index=True,
how='left')

# Use 0 to fill NaN values
df_DegreeCentrality.fillna(0, inplace=True)
df_BetweennessCentrality.fillna(0, inplace=True)
df_ClosenessCentrality.fillna(0, inplace=True)
df_PageRank.fillna(0, inplace=True)
df_Community.fillna(0, inplace=True)
```

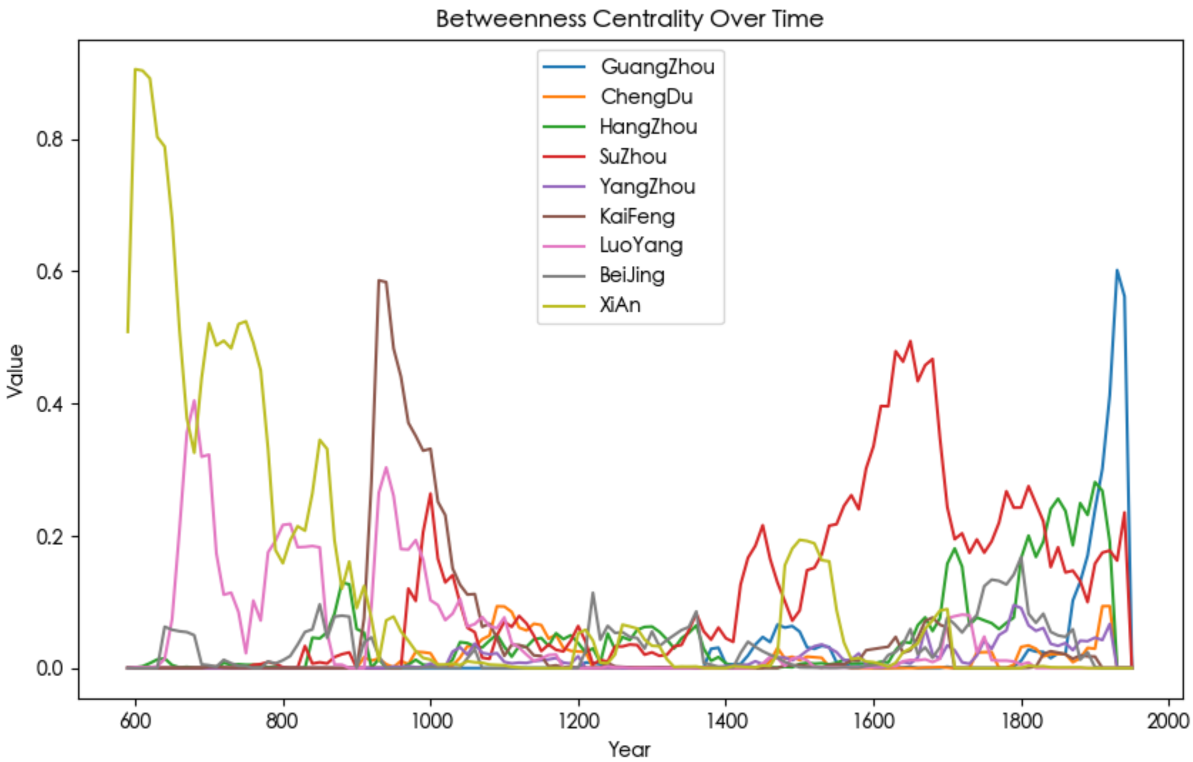
Algorithm A1-6 Data Virtualization Algorithm for Social Network Characteristics (Centrality, Betweenness, Closeness, PageRank) over Several Important Cities.

```
import matplotlib.pyplot as plt
import matplotlib
matplotlib.rcParams['font.sans-serif'] = ['Heiti TC']

# Selected cities
cities = [
    (16, 'GuangZhou'),
    (109, 'ChengDu'),
    (201, 'HangZhou'),
    (204, 'SuZhou'),
    (219, 'YangZhou'),
    (259, 'KaiFeng'),
    (232, 'LuoYang'),
    (287, 'BeiJing'),
    (308, 'XiAn')
]

# Mapping of city IDs and names
city_dict = dict(cities)

# Functions that generate line graphs
def plot_graph(df, title):
    plt.figure(figsize=(10,6))
    for city_id, city_name in cities:
        plt.plot(df.columns[1:], df.loc[city_id][1:], label=city_name)

    plt.xlabel('Year')
    plt.ylabel('Value')
    plt.title(title)
    plt.legend()
    # Save images
    plt.savefig(title + '.png')
    plt.show()

# Generate line charts for each DataFrame
plot_graph(df_DegreeCentrality, 'Degree Centrality Over Time')
plot_graph(df_BetweennessCentrality, 'Betweenness Centrality Over Time')
plot_graph(df_ClosenessCentrality, 'Closeness Centrality Over Time')
plot_graph(df_PageRank, 'PageRank Over Time')
```

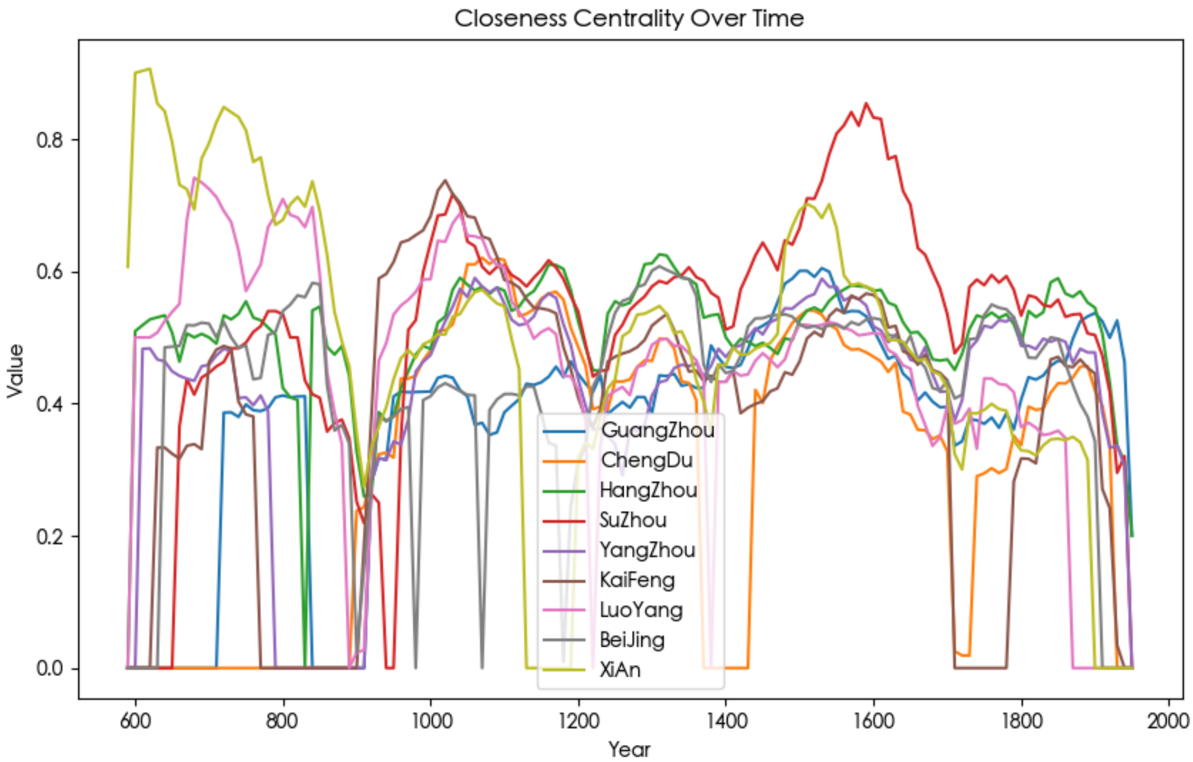
Output:

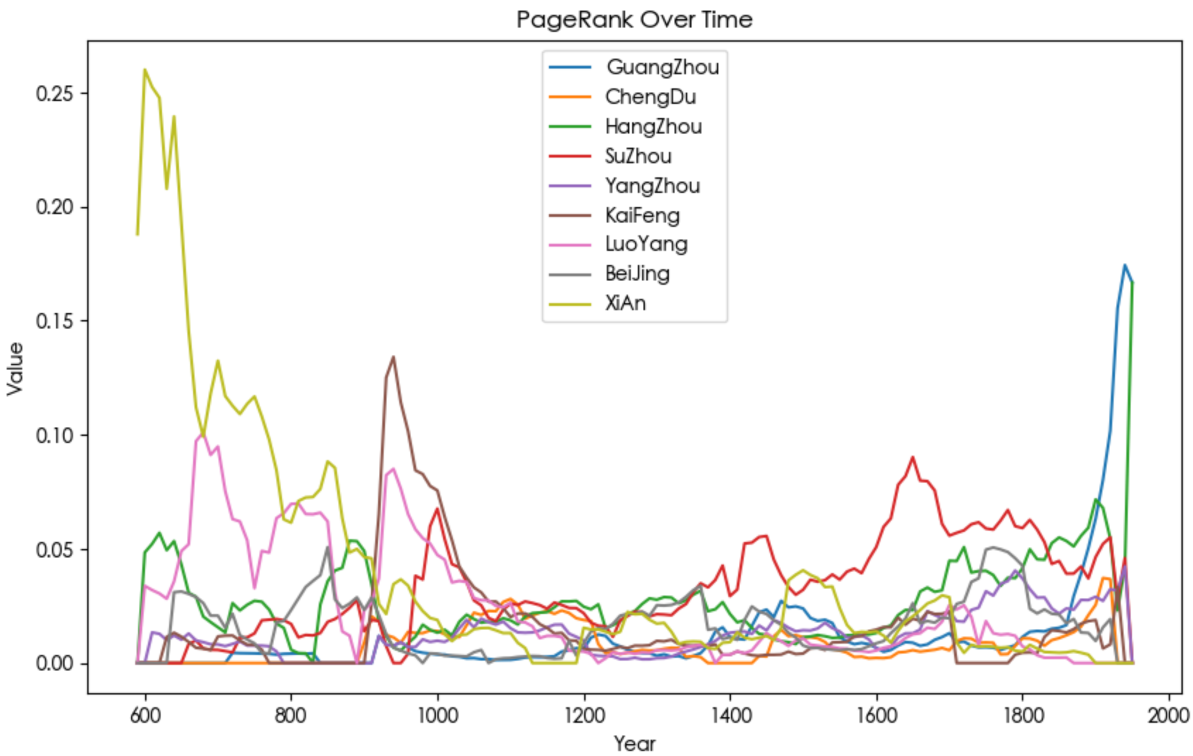


Degree Centrality Over Time
Value
Year
GuangZhou
ChengDu
HangZhou
SuZhou
YangZhou
KaiFeng
LuoYang
BeiJing
XiAn
0.0
0.2
0.4
0.6
0.8
1.0
600
800
1000
1200
1400
1600
1800
2000



Betweenness Centrality Over Time
Value
Year
GuangZhou
ChengDu
HangZhou
SuZhou
YangZhou
KaiFeng
LuoYang
BeiJing
XiAn
0.0
0.2
0.4
0.6
0.8
600
800
1000
1200
1400
1600
1800
2000


Closeness Centrality Over Time
Value
Year
0.0
0.2
0.4
0.6
0.8
600
800
1000
1200
1400
1600
1800
2000
GuangZhou
ChengDu
HangZhou
SuZhou
YangZhou
KaiFeng
LuoYang
BeiJing
XiAn

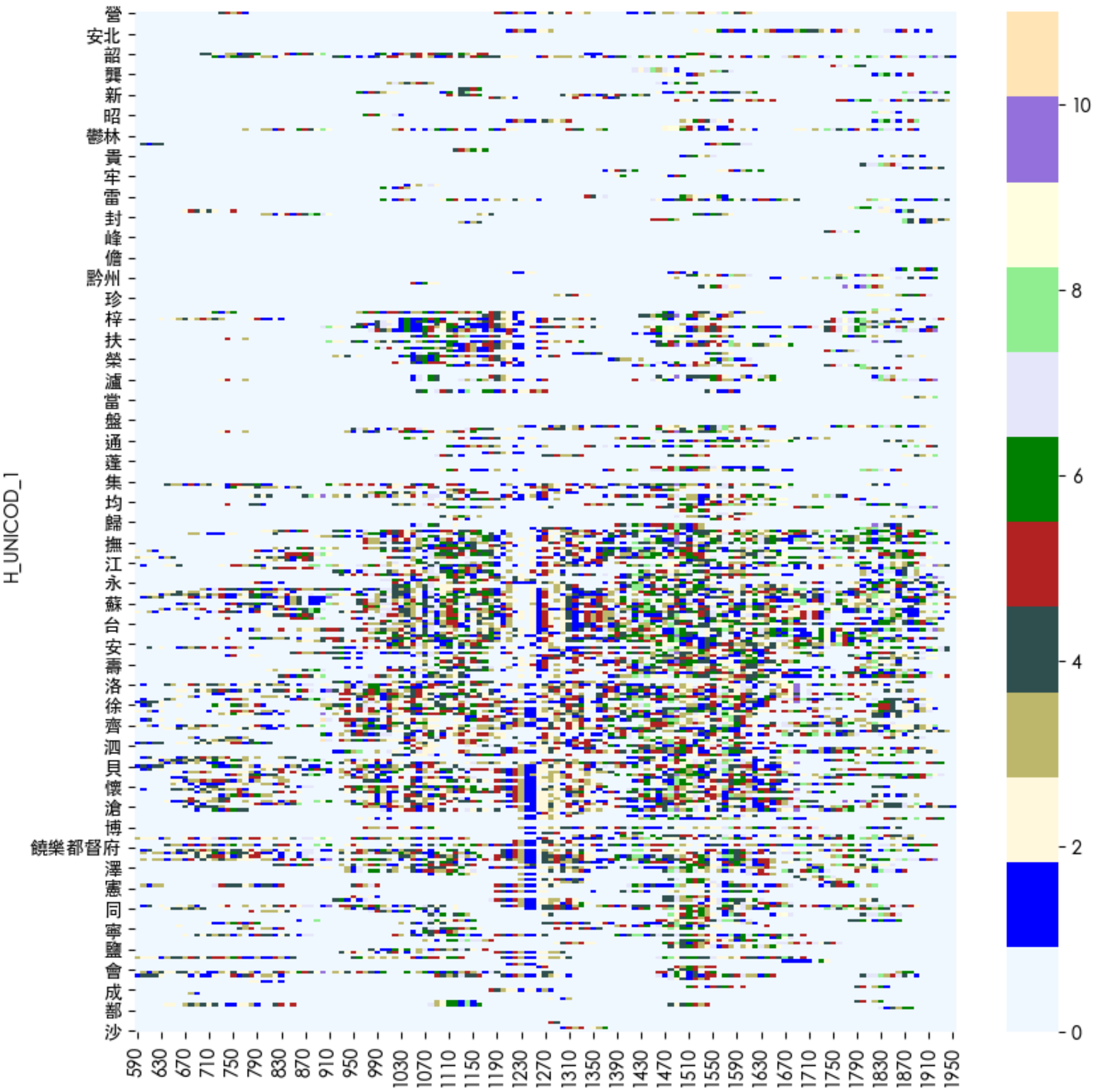

PageRank Over Time
Value
Year
0.00
0.05
0.10
0.15
0.20
0.25
600
800
1000
1200
1400
1600
1800
2000
GuangZhou
ChengDu
HangZhou
SuZhou
YangZhou
KaiFeng
LuoYang
BeiJing
XiAn

Algorithm A1-7 Data Virtualization Algorithm for Social Network's Community Characteristics

```
from matplotlib.colors import ListedColormap
import numpy as np
import matplotlib.colors as mcolors

# Get all the colors from matplotlib
colors = mcolors.CSS4_COLORS

# Select 15 colors
colors = list(colors.keys())[::len(colors)//15][:15]
# List of colors for color mapping
# 'white' represents a value of 0, other colors represent values from 1 to the maximum
#colors = ['white', 'blue', 'red', 'green', 'yellow', 'purple', 'orange']

# Generate a color map based on the maximum value in the data
# Use np.linspace to generate a linearly spaced array from 1 to the maximum value
cmap = ListedColormap(colors[:int(df_heatmap.max().max()) + 1])

plt.figure(figsize=(10,10))
sns.heatmap(df_heatmap, cmap=cmap)
plt.savefig('community.png')
plt.show()
```

Output:

(The community label follows their size's ranking. The X-axis indicates time, and the Y-axis indicates different cities. Different color represent their community and community's ranking)



H_UNICOD_1
營
安北
韶
龔
新
昭
鬱林
貫
牢
雷
封
峰
儋
黔州
珍
梓
扶
榮
瀘
當
盤
通
蓬
集
均
歸
撫
江
永
蘇
台
安
壽
洛
徐
齊
泗
貝
懷
滄
博
饒樂都督府
澤
憲
同
寧
鹽
會
成
鄯
沙
590
630
670
710
750
790
830
870
910
950
990
1030
1070
1110
1150
1190
1230
1270
1310
1350
1390
1430
1470
1510
1550
1590
1630
1670
1710
1750
1790
1830
1870
1910
1950
0
2
4
6
8
10

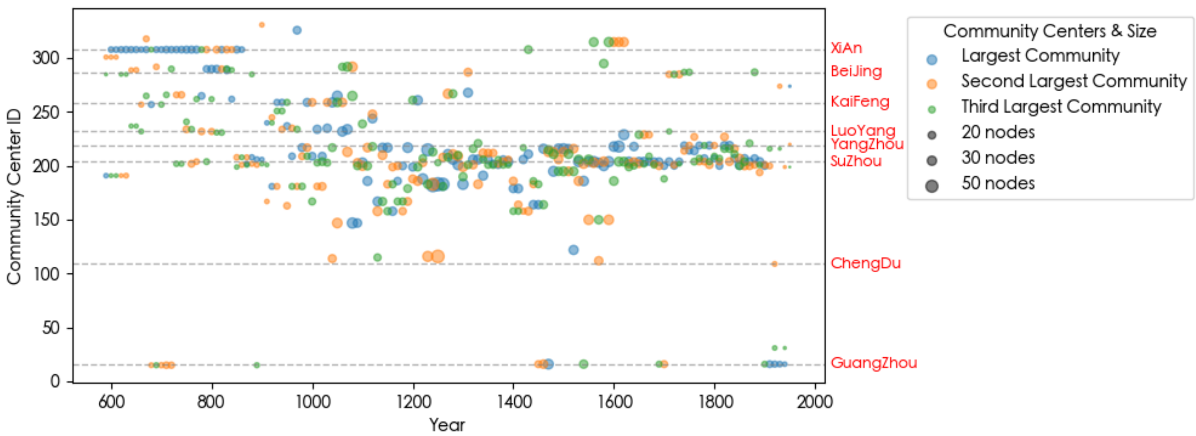
Algorithm A1-8 Data Virtualization Algorithm for Social Network’s Community Characteristics by Marking the Top 3 Communities’ Center Nodes and Their Community Size.

```
import pandas as pd
import networkx as nx
import community as community_louvain  # Correct import for community detection
import matplotlib.pyplot as plt
import numpy as np

# Horizontal dashed lines and labels corresponding to y-values
cities = [
    (16, 'GuangZhou'),
    (109, 'ChengDu'),
    (204, 'SuZhou'),
    (219, 'YangZhou'),
    (259, 'KaiFeng'),
    (232, 'LuoYang'),
    (287, 'BeiJing'),
    (308, 'XiAn'),
]

periods = [
    (0, 13, 'Others'),
    (14, 87, 'Ling-Nan'),
    (88, 103, 'Qian-Zhong'),
    (104, 143, 'Jian-Nan'),
    (144, 162, 'W. Shan-Nan'),
    (163, 178, 'E. Shan-Nan'),
    (179, 198, 'W. Jiang-Nan'),
    (199, 217, 'E. Jiang-Nan'),
    (218, 231, 'Huai-Nan'),
    (232, 259, 'He-Nan'),
    (260, 288, 'He-Bei'),
    (289, 307, 'He-Dong'),
    (308, 330, 'Guan-Nei'),
    (331, 351, 'Long-You')
]

# Initialize the result dataframe
columns = ['year', 'community_1_center', 'community_1_id', 'community_1_size',
           'community_2_center', 'community_2_id', 'community_2_size',
           'community_3_center', 'community_3_id', 'community_3_size']
df_result = pd.DataFrame(columns=columns)

for year in range(590, 1951, 10):
    # Create graph structure
    G = nx.Graph()
    # Filter data by year
    df_year = df1[(df1['L-StartY'] <= year) & (df1['L-EndY'] >= year)]
    # Add nodes and edges
    for index, row in df_year.iterrows():
        G.add_edge(row['S_NewCID'],     row['T_NewCID'],     weight=(row['ST_Total_Wago']     +
row['TS_Total_Wago']) / 2)
```

```
    # Community detection
    partition = community_louvain.best_partition(G, weight='weight')  # Use correct module name for community detection
    # Obtain communities
    communities = {}
    for node, com_id in partition.items():
        if com_id not in communities:
            communities[com_id] = []
        communities[com_id].append(node)
    communities = list(communities.values())
    communities.sort(key=len, reverse=True)
    # Initialize record
    record = dict.fromkeys(columns)
    record['year'] = year
    # Calculate community information
    for i in range(3):
        if i < len(communities):
            community = communities[i]
            subgraph = G.subgraph(community)
            center = min(community, key=lambda node: sum(nx.shortest_path_length(subgraph, node, weight='weight').values()))
            record[f'community_{i+1}_center'] = center
            record[f'community_{i+1}_id'] = community[0]
            record[f'community_{i+1}_size'] = len(community)
        else:
            record[f'community_{i+1}_center'] = 0
            record[f'community_{i+1}_id'] = 0
            record[f'community_{i+1}_size'] = 0
    # Add record
    df_result = df_result.append(record, ignore_index=True)

# Replace NaN values with 0 if any
df_result = df_result.fillna(0)

# Create bubble chart
plt.figure(figsize=(8,4))

# Mark areas
#for start, end, label in periods:
#    plt.axhspan(start, end, color='white', alpha=0.3)
#    plt.text(df_result['year'].max()+300, (start + end) / 2, label, va='center', ha='right')

# Draw horizontal dashed lines
for y, label in cities:
    plt.axhline(y, color='grey', linestyle='--', alpha=0.6, linewidth=1)
    plt.text(df_result['year'].max()+80, y, label, va='center', ha='left', color='red', fontsize=9)

# Create bubble chart
scatter_1 = plt.scatter(df_result['year'], df_result['community_1_id'], s=df_result['community_1_size'], alpha=0.5, label="Largest Community")
scatter_2 = plt.scatter(df_result['year'], df_result['community_2_id'], s=df_result['community_2_size'], alpha=0.5, label="Second Largest Community")
```

```
scatter_3 = plt.scatter(df_result['year'], df_result['community_3_id'], s=df_result['community_3_size'], alpha=0.5, label="Third Largest Community")

# Create a legend to represent bubble sizes
sizes = [20, 30, 50]
labels = ['20 nodes', '30 nodes', '50 nodes']
points = [plt.scatter([], [], color='black', s=s, alpha=0.5) for s in sizes]

# Legend handles and labels
handles = [scatter_1, scatter_2, scatter_3] + points
labels2 = ['Center of Largest Community', 'Center of Second Largest Community', 'Center of Third Largest Community'] + labels

plt.legend(handles, labels2, title='Community Centers & Size', bbox_to_anchor=(1.2, 1), loc='upper left', fontsize=10)

plt.xlabel('Year')
plt.ylabel('Community Center ID')

plt.legend(handles, labels, title='Community Centers & Size', bbox_to_anchor=(1.1, 1), loc='upper left', fontsize=10)
plt.savefig('community2.png')

plt.show()
```

Output:



Appendix 2 Gravity and Accessibility Models based on Standard Unit Area

1. Social Connection Network based on Standard Unit Area

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.

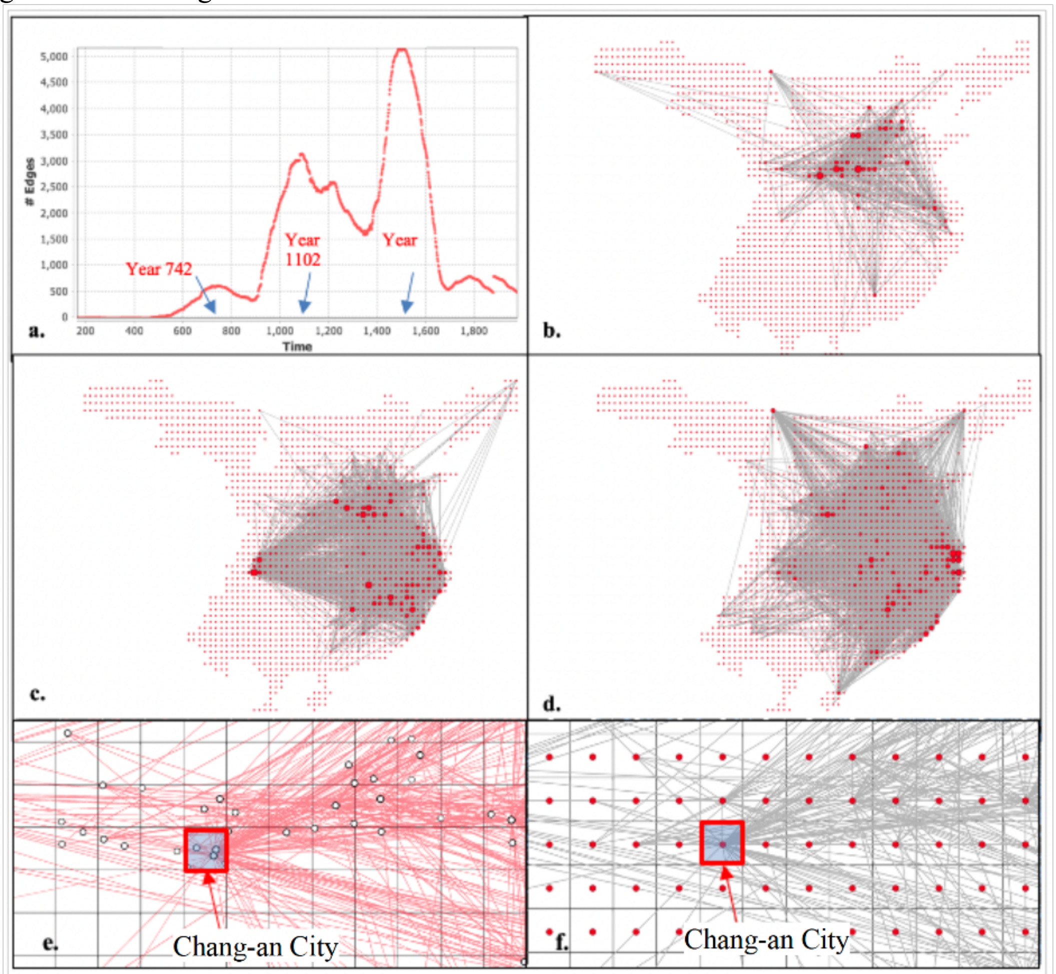


Figure A2-1 Processing of the Social Network Data.
(a): Number of Edges (Self-loops Excluded) in the Social Connection Networks between Cities for Different Time Range of 100 Years; (b)-(d): Social Connection Networks between (b) Years 692-792,

(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 Figure A2-1-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 Figure A2-1-(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. Figure A2-1-(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.

2. Modified Gravity Model based on Standard Unit Area

As depicted in Equation (A2-1), we propose a Modified 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 (A2-2) is formulated to conduct the linear regression analysis. As demonstrated in Table 4, the regression results bolster our assumptions that the Modified Gravity Model is applicable to social networks in ancient times.

$$D_{i,j,\tau} = c' \frac{\left(P_{i,\tau}\right)^{\alpha}\left(P_{j,\tau}\right)^{\beta}}{\left(t_{i,j,\tau}\right)^{\gamma}}. \tag{A2-1}$$

Hence

$$ln\,(D_{i,j,\tau}) = \alpha\, ln\left(P_{j,\tau}\right) + \beta\, ln\left(P_{j,\tau}\right) - \gamma\, ln\left(t_{i,j,\tau}\right) + \mathrm{c}. \tag{A2-2}$$

where,

$D_{i,j,\tau}$: 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,

$t_{i,j,\tau}$: 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 A2-2 Regression Details and Results for the Modified 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 Figure A2-1-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 Modified Gravity Model and analyze the discrepancies between the regression and recorded data, the difference ratio $R_{ij,\tau}$ is defined as shown in Equation (A2-3), to compare the observed degree value of the social links and the calculated degree based on our regression results.

$$R_{i,j,\tau} = \frac{\left|D_{i,j,\tau} - D_{i,j,\tau}'\right|}{D_{i,j,\tau}'} \tag{A2-3}$$

where,

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

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

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

As illustrated in Figure A2-3-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 Modified 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 Figure A2-3-a, A2-3-b, and A2-3-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 Figure A2-3-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 Modified 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 Figure A2-4, the accumulated value of the difference ratio ($\sum_j R_{i,j,\tau}$) for cities is calculated.

Table A2-3 Difference Ratio $R_{ij,\tau}$ Between the Observed and Calculated Degree of Social Links in Different Periods.

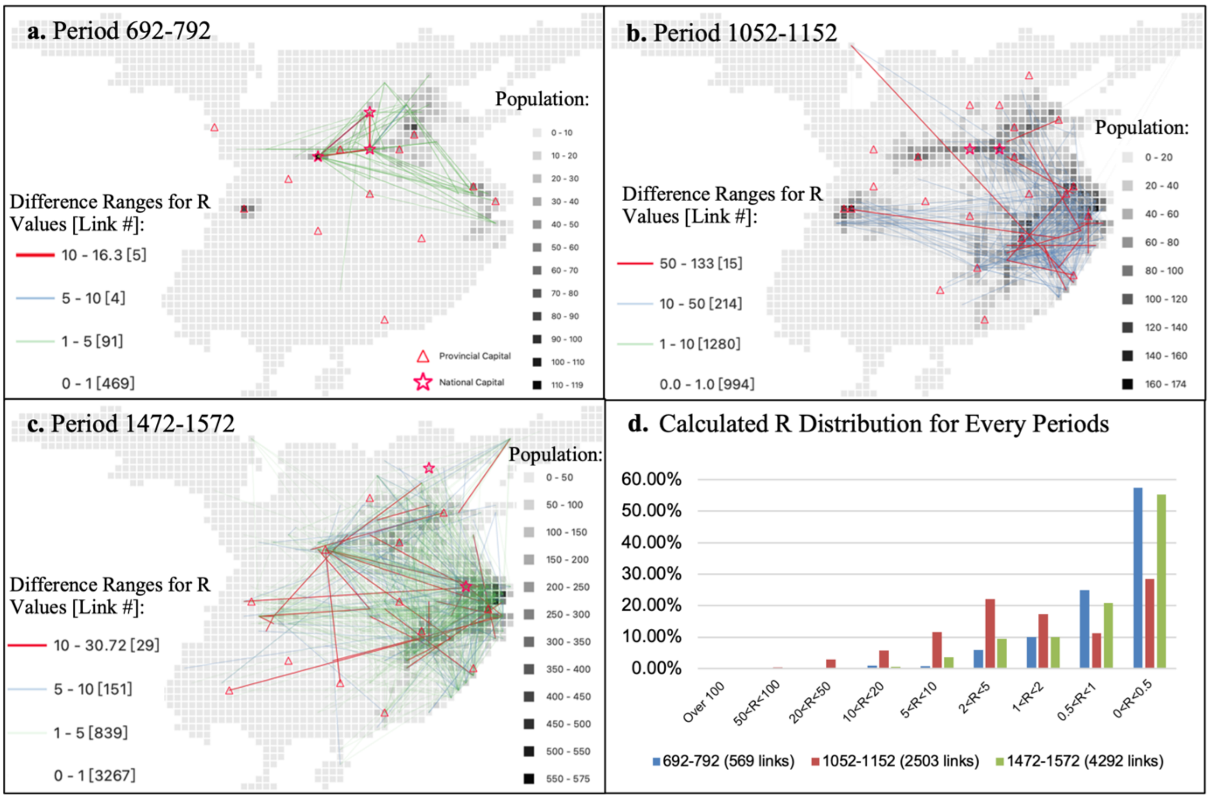
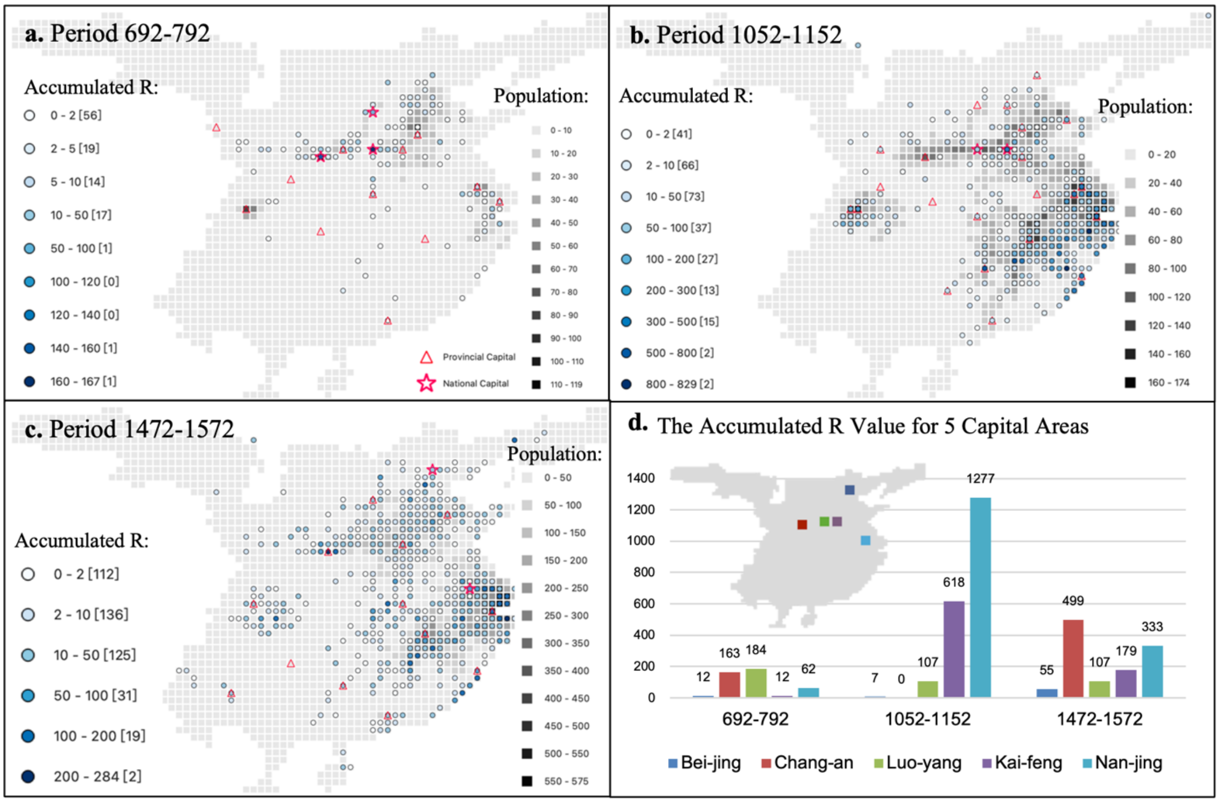


Table A2-4 Accumulated Value of Difference Ratio ($\sum_j R_{i,j,\tau}$) for Different Cities in Different Periods.



The difference ratio $R_{i,j,\tau}$ 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 Figure A2-4-a, A2-4-b, and A2-4-c for different periods. It is evident that most cities with higher difference values have a higher political ranking or a larger population.

In Figure A2-4-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 Figure A2-4-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 Figure A2-4-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.

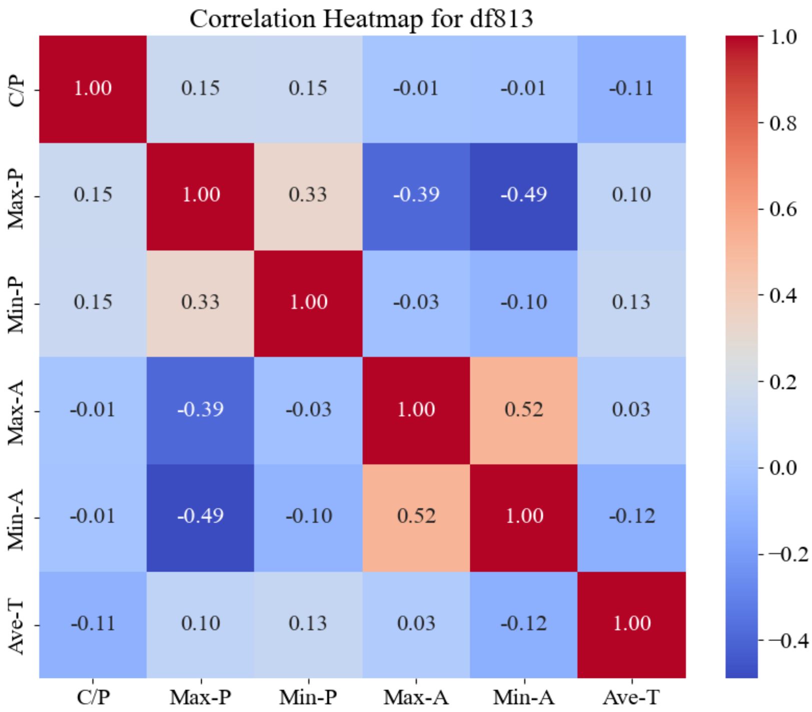
In conclusion, our proposed Modified Gravity Model could fit well for most social links but failed to describe the self-reinforcement of social networks which is in turn depending on large events, such as wars. A higher political ranking and larger population will enable a city to have a more significant 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.

Appendix 3 Machine Learning Algorithm

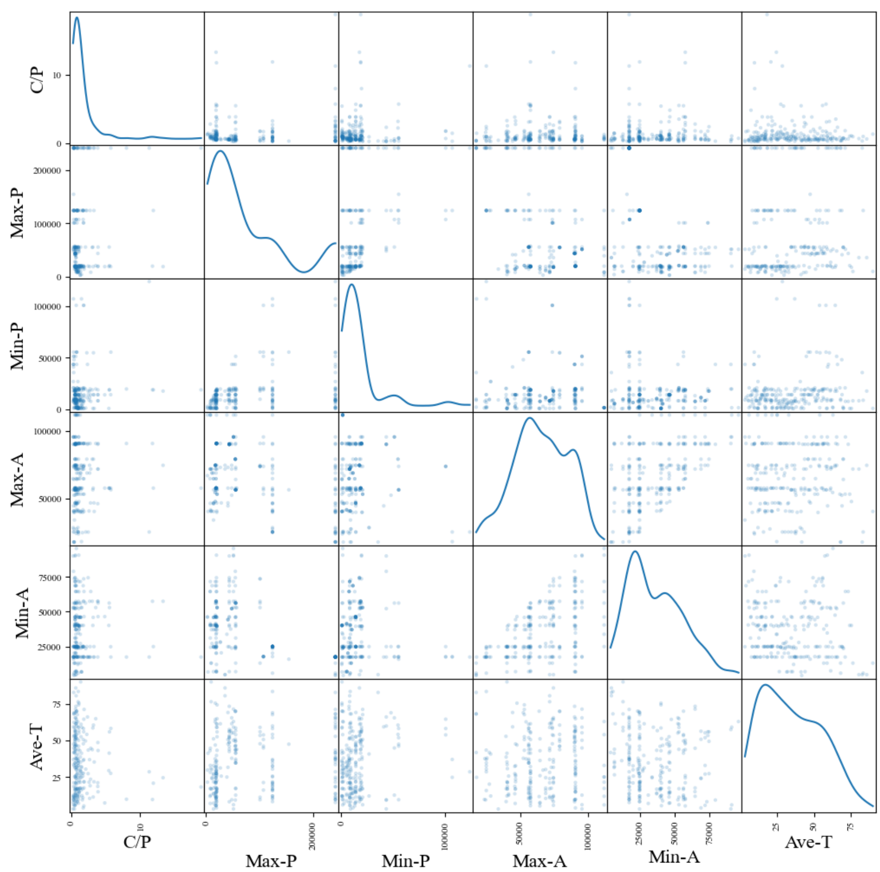
Algorithm A3-1 The Correlation Matrix and Scatter Plot Matrix for Datasets for Year 813, 1102, 1522 (C/P: $R_{ij,\tau}$; Max-P: $\hat{P}_\tau$; Min-P: $\check{P}_\tau$; Max-A: $\hat{A}_\tau$; Min-A: $\check{A}_\tau$; Ave-T: $T_{ij,\tau}$)

```
import pandas as pd
import seaborn as sns
import matplotlib.pyplot as plt
from pandas.plotting import scatter_matrix

# Load your dataframes
df813 = pd.read_excel('1204.xlsx', sheet_name='813')
df1102 = pd.read_excel('1204.xlsx', sheet_name='1102')
df1522 = pd.read_excel('1204.xlsx', sheet_name='1522')

# Function to plot correlation heatmap and scatter plot matrix
def plot_correlation_and_scatter(df, sheet_name):
    # Selecting target function and explanatory functions
    selected_df = df.iloc[:, [0] + list(range(2, df.shape[1]))]

    # Plotting correlation heatmap
    plt.figure(figsize=(10, 8))
    sns.heatmap(selected_df.corr(), annot=True, cmap='coolwarm', fmt=".2f")
    plt.title(f'Correlation Heatmap for {sheet_name}')
    plt.savefig(f'{sheet_name}_correlation_heatmap.png')
    plt.show()

    # Plotting scatter plot matrix
    scatter_matrix(selected_df, alpha=0.2, figsize=(12, 12), diagonal='kde')
    plt.suptitle(f'Scatter Plot Matrix for {sheet_name}')
    plt.savefig(f'{sheet_name}_scatter_plot_matrix.png')
    plt.show()

# Plot for each dataframe
plot_correlation_and_scatter(df813, 'df813')
plot_correlation_and_scatter(df1102, 'df1102')
plot_correlation_and_scatter(df1522, 'df1522')
```

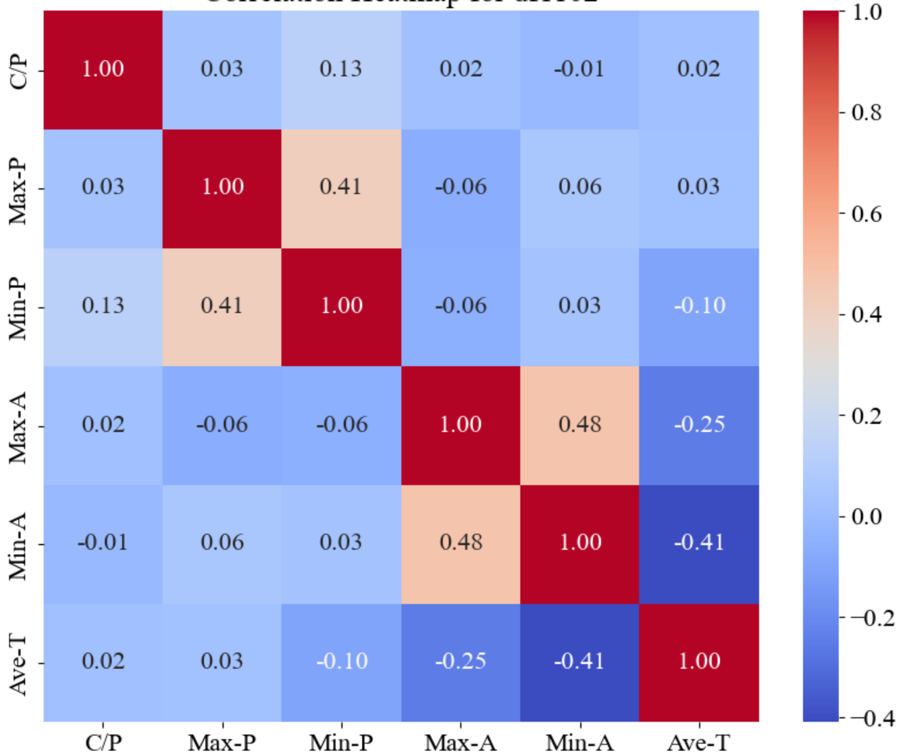
Outputs:



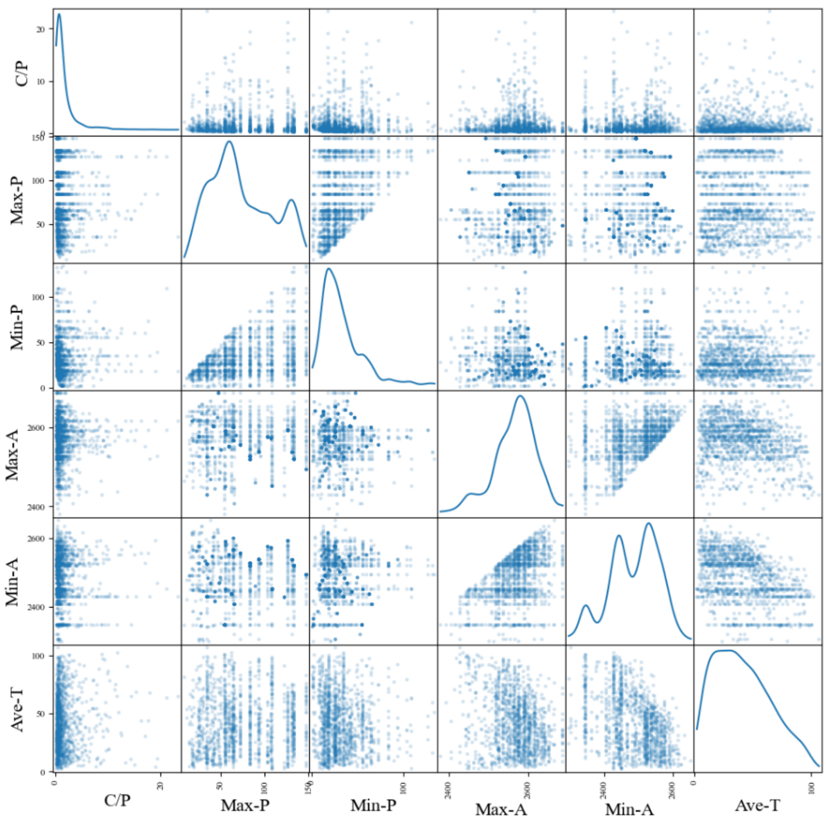
Scatter Plot Matrix for df813



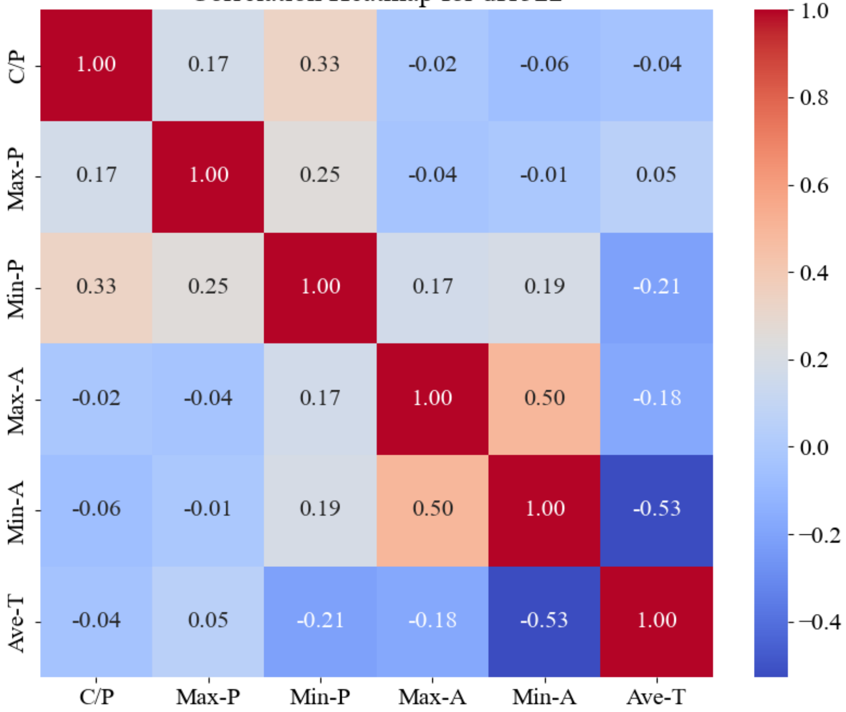
Correlation Heatmap for df1102



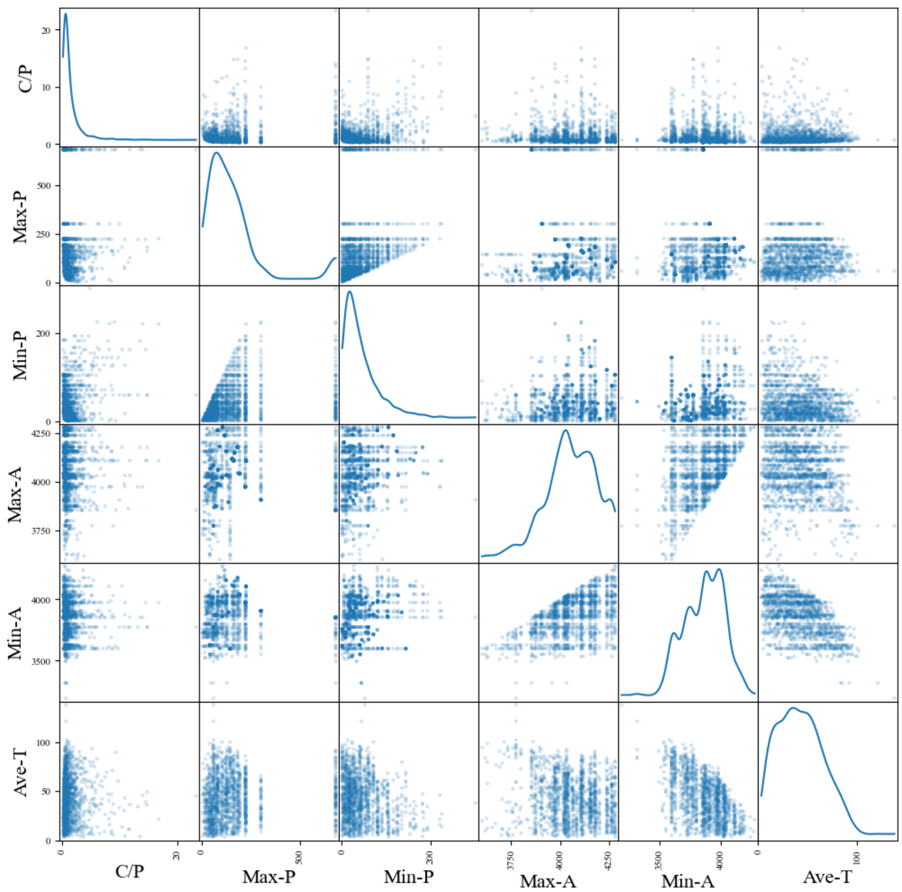
Scatter Plot Matrix for df1102



Correlation Heatmap for df1522



Scatter Plot Matrix for df1522



Algorithm A3-2 The Linear Regression Model for Datasets for Year 813, 1102, 1522
(C/P: $R_{ij,\tau}$; Max-P: $\hat{P}_{\tau}$; Min-P: $\check{P}_{\tau}$; Max-A: $\hat{A}_{\tau}$; Min-A: $\check{A}_{\tau}$; Ave-T: $T_{ij,\tau}$)

```
import pandas as pd
from sklearn.linear_model import LinearRegression
from sklearn.model_selection import train_test_split
from sklearn.metrics import mean_squared_error, r2_score

# Function to perform linear regression and output the expression, MSE, and R2
def linear_regression_analysis(df):
    # Separating target variable and feature variables
    X = df.iloc[:, 2:]  # Selecting all columns from the 3rd column onwards
    y = df.iloc[:, 0]   # Target variable (first column)

    # Splitting data for training and testing
    X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

    # Initialize and train linear regression model
    model = LinearRegression()
    model.fit(X_train, y_train)

    # Predictions on the test set
    y_pred = model.predict(X_test)

    # Calculate MSE and R2
    mse = mean_squared_error(y_test, y_pred)
    r2 = r2_score(y_test, y_pred)

    # Constructing the linear regression expression
    lr_expression = f'y = {model.intercept_:.2f} + ' + ' + '.join([f'{coef:.2f}*{col}' for coef, col in
zip(model.coef_, X.columns)])

    return lr_expression, mse, r2

# Load your dataframes
df813 = pd.read_excel('1204.xlsx', sheet_name='813')
df1102 = pd.read_excel('1204.xlsx', sheet_name='1102')
df1522 = pd.read_excel('1204.xlsx', sheet_name='1522')

best_params_813, mse_813, r2_813 = linear_regression_analysis(df813)
best_params_1102, mse_1102, r2_1102 = linear_regression_analysis(df1102)
best_params_1522, mse_1522, r2_1522 = linear_regression_analysis(df1522)

# Print results
print("Linear Regression Expression for df813:", best_params_813, "MSE:", mse_813, "R2:",
r2_813)
print("Linear Regression Expression for df1102:", best_params_1102, "MSE:", mse_1102, "R2:",
r2_1102)
print("Linear Regression Expression for df1522:", best_params_1522, "MSE:", mse_1522, "R2:",
r2_1522)
```

Algorithm Outputs:

Linear Regression Expression for df813:
y = 1.22 + 0.00*Max-P + 0.00*Min-P + 0.00*Max-A + 0.00*Min-A + -0.02*Ave-T
MSE: 1.199940188743944
R2: -0.5344899318504073

Linear Regression Expression for df1102:
y = -5.54 + -0.00*Max-P + 0.02*Min-P + 0.00*Max-A + -0.00*Min-A + 0.00*Ave-T
MSE: 9.06473592837727
R2: 0.00856477645607101

Linear Regression Expression for df1522:
y = 7.91 + 0.00*Max-P + 0.02*Min-P + -0.00*Max-A + -0.00*Min-A + -0.01*Ave-T
MSE: 2.9770153575829457
R2: 0.07685243377263529

Algorithm A3-3 The Decision Tree Regression Model for Datasets for Year 813, 1102, 1522 (C/P: $R_{ij,\tau}$; Max-P: $\hat{P}_\tau$; Min-P: $\check{P}_\tau$; Max-A: $\hat{A}_\tau$; Min-A: $\check{A}_\tau$; Ave-T: $T_{ij,\tau}$)

```
import shap
import matplotlib.pyplot as plt
from sklearn.tree import DecisionTreeRegressor
from sklearn.model_selection import train_test_split, GridSearchCV, KFold
from sklearn.preprocessing import StandardScaler
from sklearn.metrics import mean_squared_error, r2_score
import pandas as pd
import numpy as np

#def decision_tree_k_fold_validation_with_metrics(df, k=5):

# Load your dataframes
df813 = pd.read_excel('1204.xlsx', sheet_name='813')
df1102 = pd.read_excel('1204.xlsx', sheet_name='1102')
df1522 = pd.read_excel('1204.xlsx', sheet_name='1522')

def decision_tree_k_fold_validation_with_metrics(df, k=5):
    # Separating target variable and feature variables
    X = df.drop(columns=[df.columns[0], df.columns[1]])
    y = df[df.columns[0]]

    # Normalize features
    scaler = StandardScaler()
    X_scaled = scaler.fit_transform(X)

    # K-Fold Cross Validation
    kf = KFold(n_splits=k, shuffle=True, random_state=42)

    # Parameters for Grid Search
    param_grid = {
        'max_depth': [None, 3, 5, 10, 20],
        'min_samples_split': [2, 5, 10],
        'min_samples_leaf': [1, 2, 4]
    }

    # Initialize Decision Tree Regressor
    model = DecisionTreeRegressor(random_state=42)

    # Initialize Grid Search with Cross Validation
    grid_search = GridSearchCV(estimator=model, param_grid=param_grid, cv=kf,
scoring='neg_mean_squared_error', n_jobs=-1)

    # Splitting data for final evaluation
    X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

    # Fit model
    grid_search.fit(X_train, y_train)

    # Best model
    best_model = grid_search.best_estimator_
```

```
    # Predictions on the test set
    y_pred = best_model.predict(X_test)

    # Calculate MSE and R2
    mse = mean_squared_error(y_test, y_pred)
    r2 = r2_score(y_test, y_pred)

    return best_model, grid_search.best_params_, mse, r2

# Train models and get the best models along with their metrics
best_models_metrics = {
    'df813': decision_tree_k_fold_validation_with_metrics(df813),
    'df1102': decision_tree_k_fold_validation_with_metrics(df1102),
    'df1522': decision_tree_k_fold_validation_with_metrics(df1522)
}

# Assuming datasets are stored in a dictionary
datasets = {'df813': df813, 'df1102': df1102, 'df1522': df1522}

# SHAP analysis and model metrics
for dataset_name, (best_model, best_params, mse, r2) in best_models_metrics.items():
    X = datasets[dataset_name].iloc[:, 2:]
    explainer = shap.Explainer(best_model, X)
    shap_values = explainer(X)

    # Plot and save SHAP summary plot
    plt.figure()
    shap.summary_plot(shap_values, X)
    plt.savefig(f'{dataset_name}_shap.png')  # Save image
    plt.show()  # Display image
    plt.close()
    # Print best parameters, MSE, and R2
    print(f"Dataset: {dataset_name}")
    print("Best Parameters:", best_params)
    print("MSE on Test Set:", mse)
    print("R2 on Test Set:", r2)
```

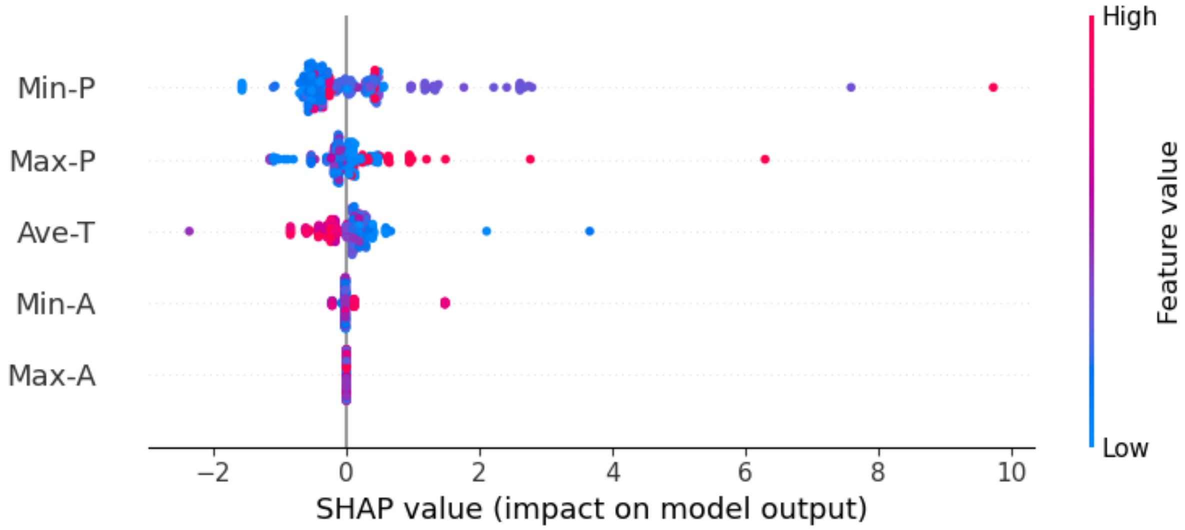
Algorithm Outputs:

Dataset: df813

Best Parameters: {'max_depth': 5, 'min_samples_leaf': 1, 'min_samples_split': 2}

MSE on Test Set: 1.942253597591838

R2 on Test Set: -1.4837642897223526

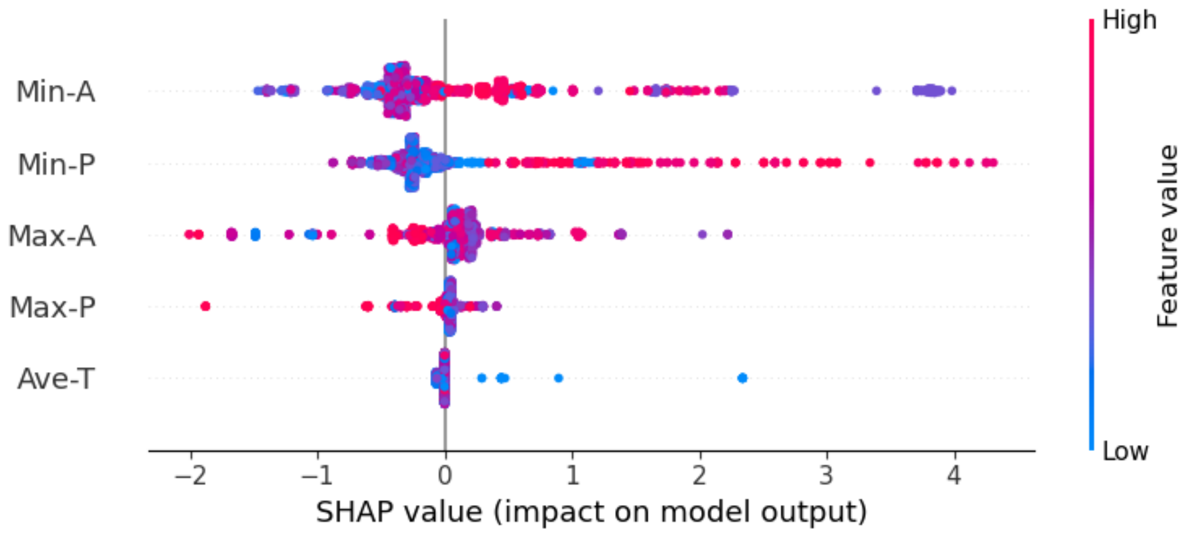


Dataset: df1102

Best Parameters: {'max_depth': 5, 'min_samples_leaf': 4, 'min_samples_split': 10}

MSE on Test Set: 7.5885452395368755

R2 on Test Set: 0.17001983230632356

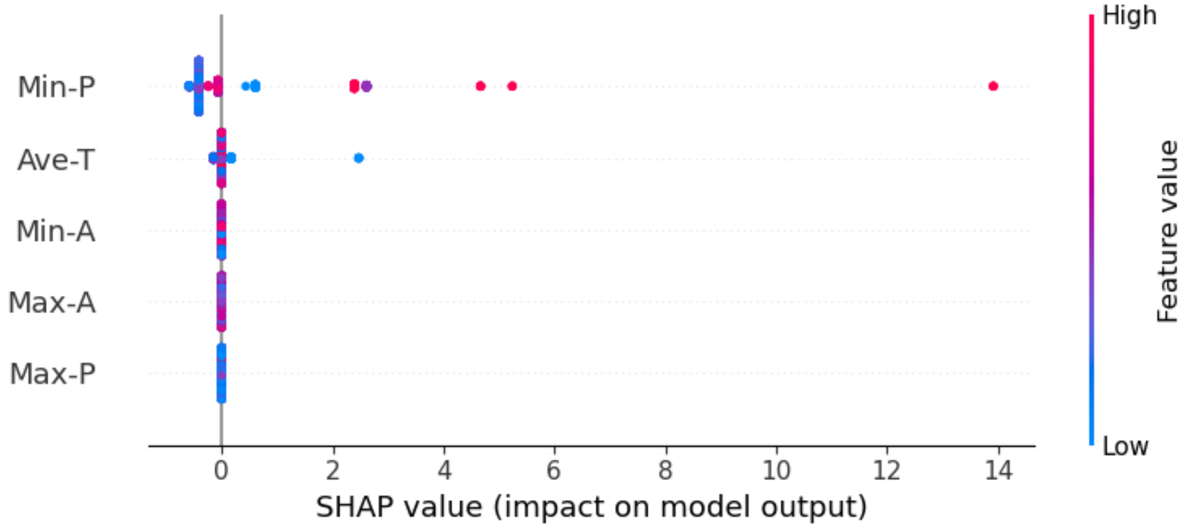


Dataset: df1522

Best Parameters: {'max_depth': 3, 'min_samples_leaf': 2, 'min_samples_split': 2}

MSE on Test Set: 2.5874198689798247

R2 on Test Set: 0.19766273668257295


Min-P
Ave-T
Min-A
Max-A
Max-P
0
2
4
6
8
10
12
14
SHAP value (impact on model output)
High
Feature value
Low

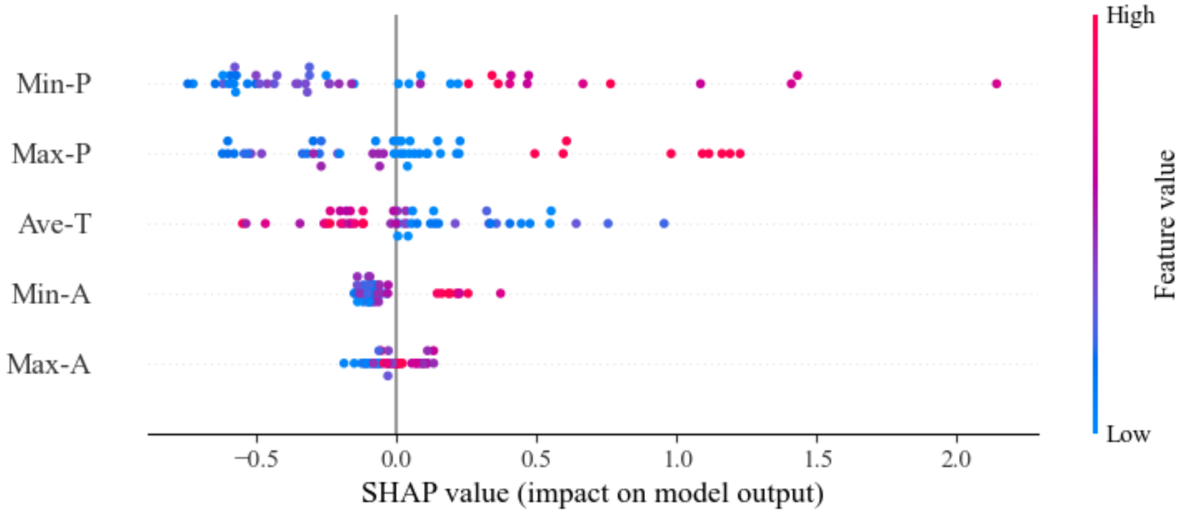
Algorithm A3-4 The Random Forest Regression Model for Datasets for Year 813, 1102, 1522 (C/P: $R_{ij,\tau}$; Max-P: $\hat{P}_\tau$; Min-P: $\check{P}_\tau$; Max-A: $\hat{A}_\tau$; Min-A: $\check{A}_\tau$; Ave-T: $T_{ij,\tau}$)

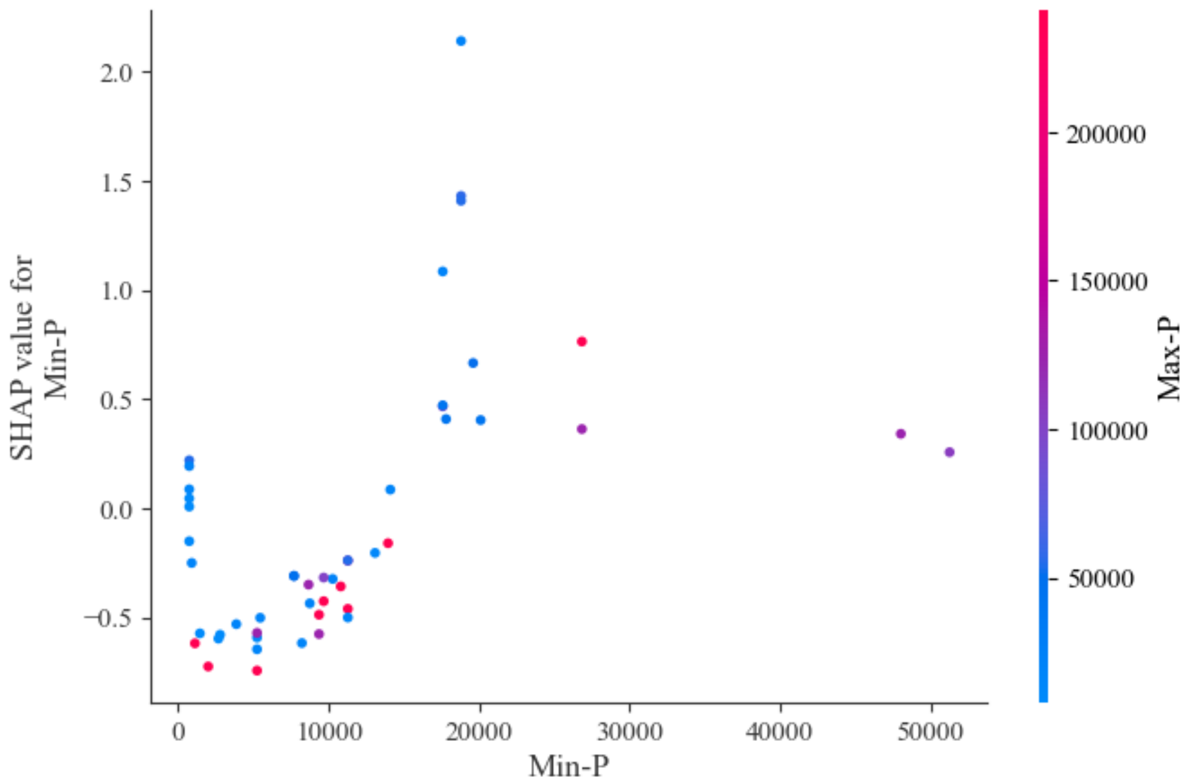
```
import shap
import matplotlib.pyplot as plt
from sklearn.ensemble import RandomForestRegressor
from sklearn.model_selection import train_test_split, GridSearchCV, KFold
from sklearn.preprocessing import StandardScaler
from sklearn.metrics import mean_squared_error, r2_score
import pandas as pd
import numpy as np

# Load your dataframes
df813 = pd.read_excel('1204.xlsx', sheet_name='813')
df1102 = pd.read_excel('1204.xlsx', sheet_name='1102')
df1522 = pd.read_excel('1204.xlsx', sheet_name='1522')

def random_forest_k_fold_validation_with_metrics(df, k=5):
    # Separating target variable and feature variables
    X = df.drop(columns=[df.columns[0], df.columns[1]])
    y = df[df.columns[0]]

    # Normalize features
    scaler = StandardScaler()
    X_scaled = scaler.fit_transform(X)

    # K-Fold Cross Validation
    kf = KFold(n_splits=k, shuffle=True, random_state=42)

    # Parameters for Grid Search
    param_grid = {
        'n_estimators': [100, 150, 200, 250, 300],
        'max_depth': [None, 3, 5, 10, 20, 30],
        'min_samples_split': [2, 5, 10],
        'min_samples_leaf': [1, 2, 4]
    }

    # Initialize Random Forest Regressor
    model = RandomForestRegressor(random_state=42)

    # Initialize Grid Search with Cross Validation
    grid_search = GridSearchCV(estimator=model, param_grid=param_grid, cv=kf,
scoring='neg_mean_squared_error', n_jobs=-1)

    # Splitting data for final evaluation
    X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

    # Fit model
    grid_search.fit(X_train, y_train)

    # Best model
    best_model = grid_search.best_estimator_
```

```
    # Predictions on the test set
    y_pred = best_model.predict(X_test)

    # Calculate MSE and R2
    mse = mean_squared_error(y_test, y_pred)
    r2 = r2_score(y_test, y_pred)

    return best_model, grid_search.best_params_, mse, r2, X_train, X_test

# Train models and get the best models along with their metrics
best_models_metrics = {
    'df813': random_forest_k_fold_validation_with_metrics(df813),
    'df1102': random_forest_k_fold_validation_with_metrics(df1102),
    'df1522': random_forest_k_fold_validation_with_metrics(df1522)
}

# Assuming datasets are stored in a dictionary
datasets = {'df813': df813, 'df1102': df1102, 'df1522': df1522}

# SHAP analysis and model metrics
for dataset_name, (best_model, best_params, mse, r2, X_train, X_test) in best_models_metrics.items():
    explainer = shap.Explainer(best_model, X_train)
    shap_values = explainer(X_test)

    # Plot and save SHAP summary plot
    plt.figure()
    shap.summary_plot(shap_values, X_test)
    plt.savefig(f'{dataset_name}_shap.png')  # Save image
    plt.show()  # Display image
    plt.close()

    # Determine the two most important features
    shap_sum = np.abs(shap_values.values).mean(axis=0)
    top_two_features = np.argsort(shap_sum)[-2:]

    # Names of the top two features
    feature_names = X_test.columns[top_two_features]

    # Plot dependence plot for the two most important features
    plt.figure()
    shap.dependence_plot(feature_names[1], shap_values.values, X_test, interaction_index=feature_names[0])
    plt.show()

    # Print best parameters, MSE, and R2
    print(f"Dataset: {dataset_name}")
    print("Best Parameters:", best_params)
    print("MSE on Test Set:", mse)
    print("R2 on Test Set:", r2)
```

Algorithm Outputs:

Dataset: df813
Best Parameters: {'max_depth': 10, 'min_samples_leaf': 4, 'min_samples_split': 2, 'n_estimators': 300}
MSE on Test Set: 0.9822400045726765
R2 on Test Set: -0.2560937718530738



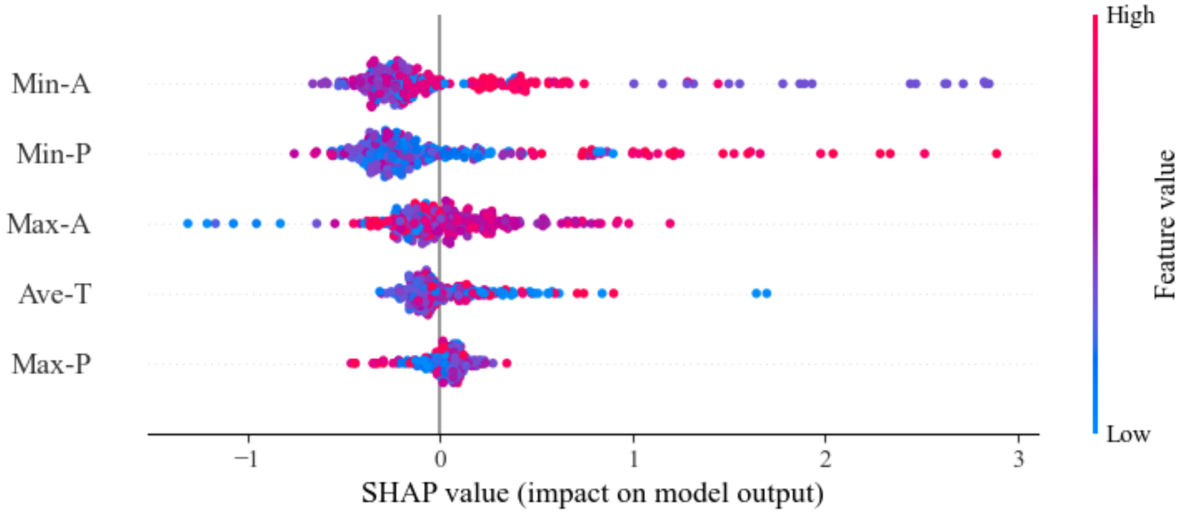


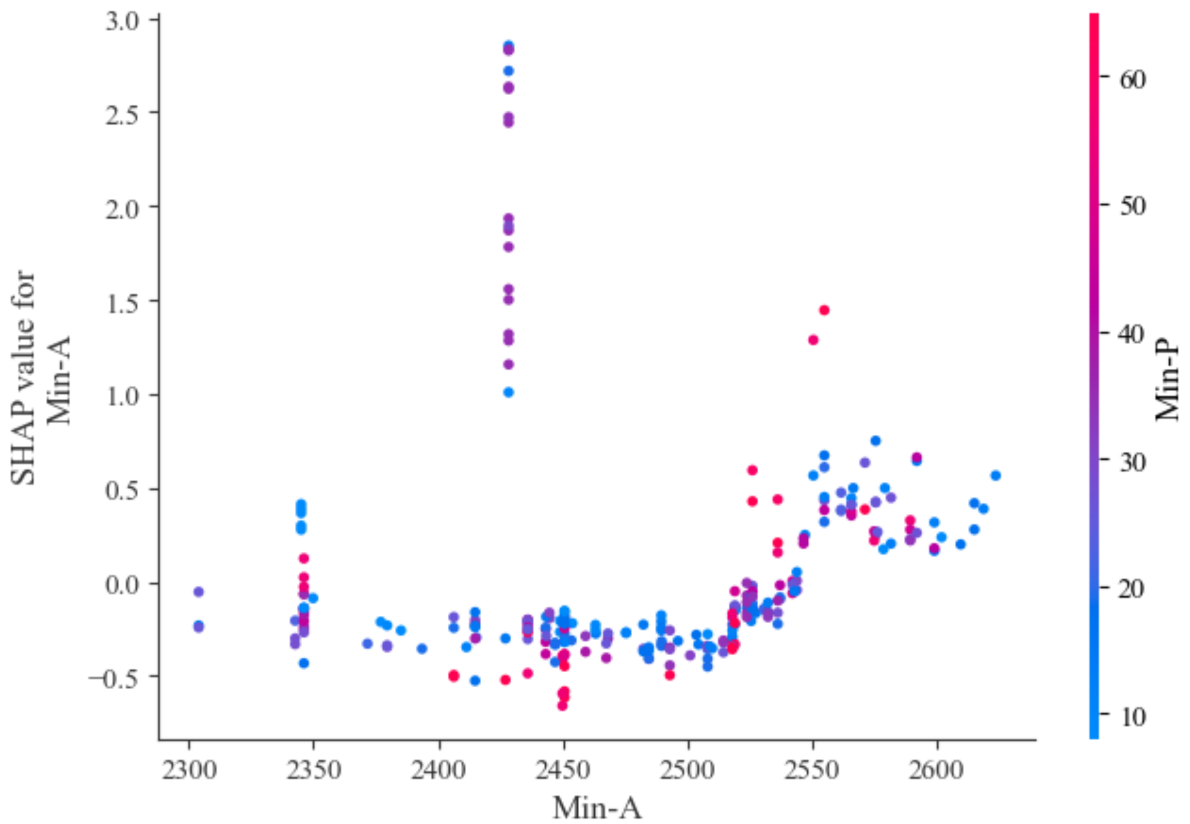
Dataset: df1102

Best Parameters: {'max_depth': 10, 'min_samples_leaf': 4, 'min_samples_split': 2, 'n_estimators': 100}

MSE on Test Set: 7.074681139847244

R2 on Test Set: 0.22622256921696082



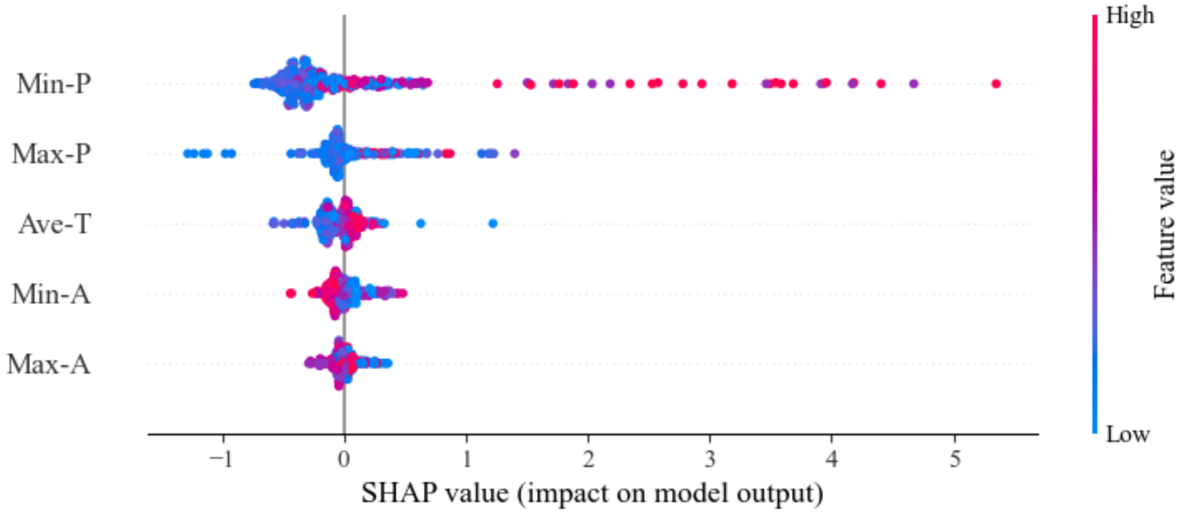


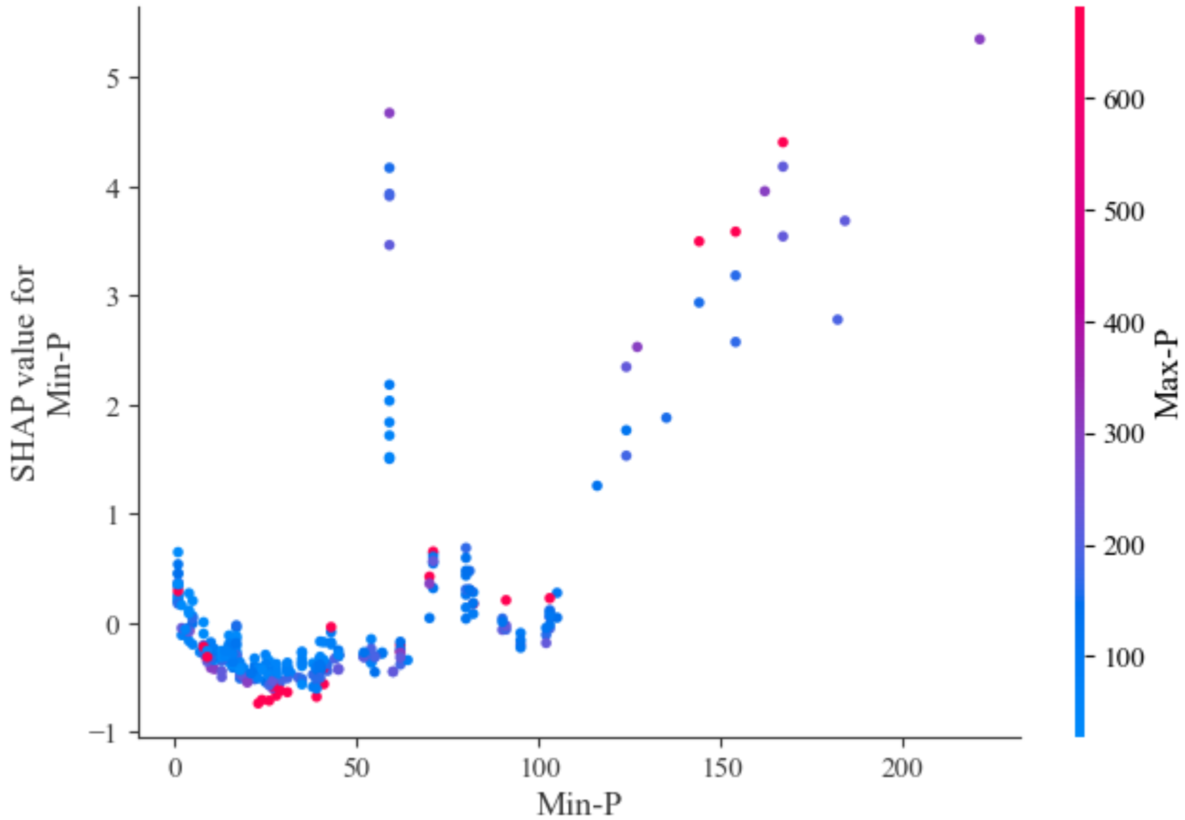
Dataset: df1522

Best Parameters: {'max_depth': 10, 'min_samples_leaf': 4, 'min_samples_split': 10, 'n_estimators': 300}

MSE on Test Set: 1.9054088997246552

R2 on Test Set: 0.4091486347329776





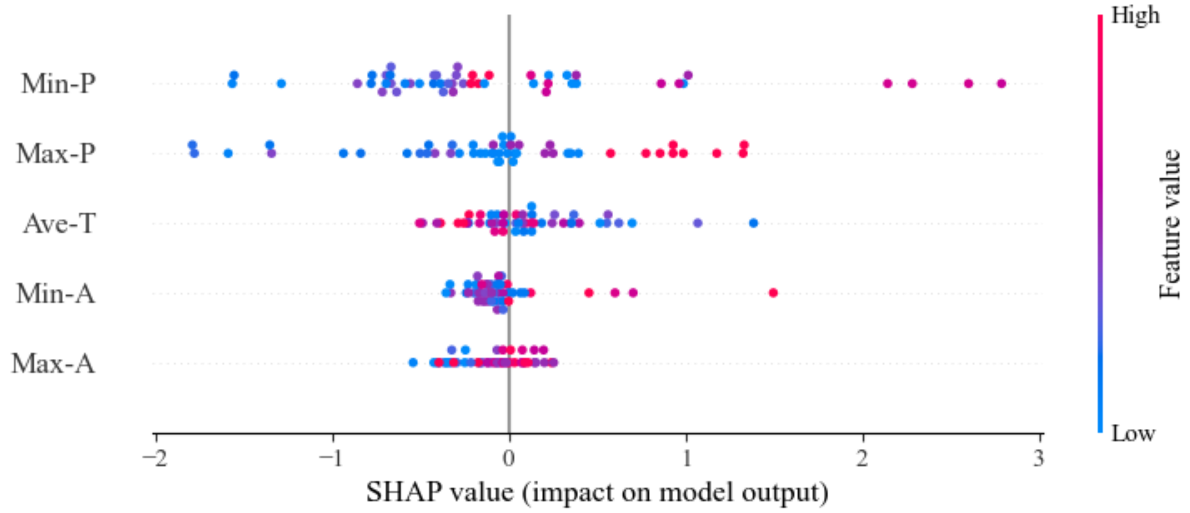
Algorithm A3-5 The GBRT Regression Model for Datasets for Year 813, 1102, 1522
(C/P: $R_{ij,\tau}$; Max-P: $\hat{P}_{\tau}$; Min-P: $\check{P}_{\tau}$; Max-A: $\hat{A}_{\tau}$; Min-A: $\check{A}_{\tau}$; Ave-T: $T_{ij,\tau}$)

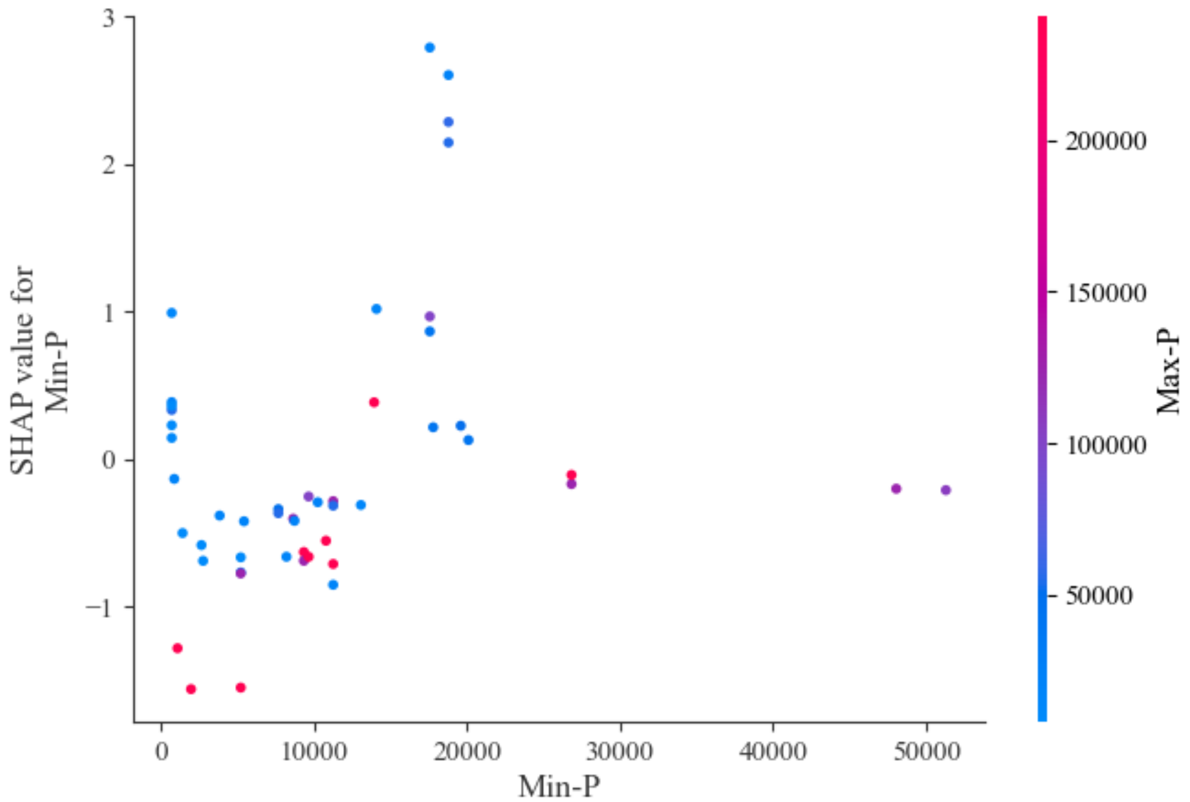
```
import shap
import matplotlib.pyplot as plt
from sklearn.ensemble import GradientBoostingRegressor
from sklearn.model_selection import train_test_split, GridSearchCV, KFold
from sklearn.preprocessing import StandardScaler
from sklearn.metrics import mean_squared_error, r2_score
import pandas as pd
import numpy as np

# Load your dataframes
df813 = pd.read_excel('1204.xlsx', sheet_name='813')
df1102 = pd.read_excel('1204.xlsx', sheet_name='1102')
df1522 = pd.read_excel('1204.xlsx', sheet_name='1522')

def gbrt_k_fold_validation_with_metrics(df, k=5):
    # Separating target variable and feature variables
    X = df.drop(columns=[df.columns[0], df.columns[1]])
    y = df[df.columns[0]]

    # Normalize features
    scaler = StandardScaler()
    X_scaled = scaler.fit_transform(X)

    # K-Fold Cross Validation
    kf = KFold(n_splits=k, shuffle=True, random_state=42)

    # Parameters for Grid Search
    param_grid = {
        'n_estimators': [100, 200, 300, 400, 500],
        'learning_rate': [0.01, 0.05, 0.1, 0.2],
        'max_depth': [3, 4, 5, 6, 7],
        'min_samples_split': [2, 4, 6],
        'min_samples_leaf': [1, 2, 3]
    }

    # Initialize Gradient Boosting Regressor
    model = GradientBoostingRegressor(random_state=42)

    # Initialize Grid Search with Cross Validation
    grid_search = GridSearchCV(estimator=model, param_grid=param_grid, cv=kf,
scoring='neg_mean_squared_error', n_jobs=-1)

    # Splitting data for final evaluation
    X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

    # Fit model
    grid_search.fit(X_train, y_train)

    # Best model
    best_model = grid_search.best_estimator_
    # Predictions on the test set
```

```
    y_pred = best_model.predict(X_test)

    # Calculate MSE and R2
    mse = mean_squared_error(y_test, y_pred)
    r2 = r2_score(y_test, y_pred)

    return best_model, grid_search.best_params_, mse, r2, X_train, X_test

# Train models and get the best models along with their metrics
best_models_metrics = {
    'df813': gbrt_k_fold_validation_with_metrics(df813),
    'df1102': gbrt_k_fold_validation_with_metrics(df1102),
    'df1522': gbrt_k_fold_validation_with_metrics(df1522)
}

# Assuming datasets are stored in a dictionary
datasets = {'df813': df813, 'df1102': df1102, 'df1522': df1522}

import numpy as np

# SHAP analysis and model metrics
for dataset_name, (best_model, best_params, mse, r2, X_train, X_test) in
best_models_metrics.items():
    explainer = shap.Explainer(best_model, X_train)
    shap_values = explainer(X_test)

    # Plot and save SHAP summary plot
    plt.figure()
    shap.summary_plot(shap_values, X_test)
    plt.savefig(f'{dataset_name}_shap.png')  # Save image
    plt.show()  # Display image
    plt.close()

    # Determine the two most important features
    shap_sum = np.abs(shap_values.values).mean(axis=0)
    top_two_features = np.argsort(shap_sum)[-2:]

    # Names of the top two features
    feature_names = X_test.columns[top_two_features]

    # Plot dependence plot for the two most important features
    plt.figure()
    shap.dependence_plot(feature_names[1], shap_values.values, X_test,
interaction_index=feature_names[0])
    plt.show()

    # Print best parameters, MSE, and R2
    print(f"Dataset: {dataset_name}")
    print("Best Parameters:", best_params)
    print("MSE on Test Set:", mse)
    print("R2 on Test Set:", r2)
```

Algorithm Outputs:

Dataset: df813
Best Parameters: {'learning_rate': 0.1, 'max_depth': 5, 'min_samples_leaf': 1, 'min_samples_split': 2, 'n_estimators': 100}
MSE on Test Set: 1.4684695352899526
R2 on Test Set: -0.8778866965779433



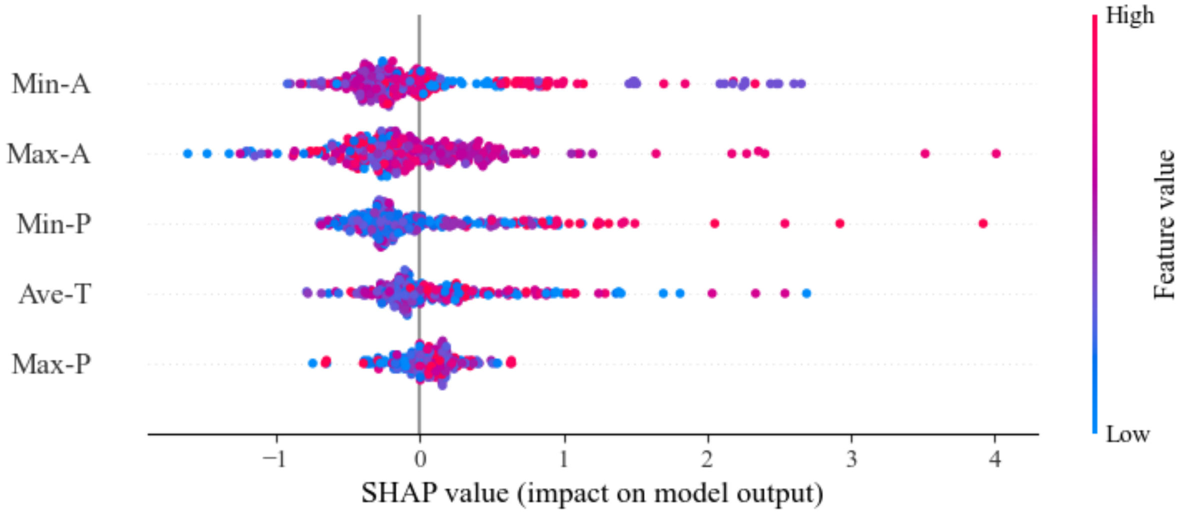


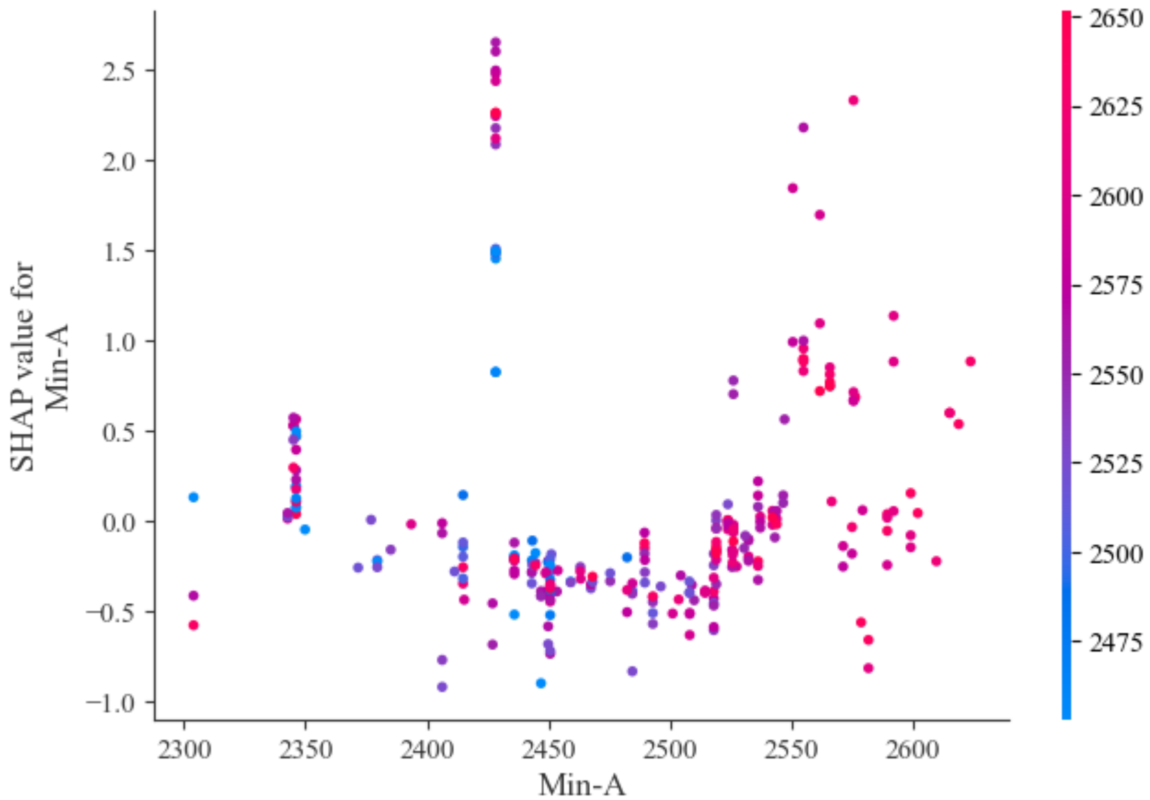
Dataset: df1102

Best Parameters: {'learning_rate': 0.05, 'max_depth': 4, 'min_samples_leaf': 3, 'min_samples_split': 2, 'n_estimators': 300}

MSE on Test Set: 6.431174346276155

R2 on Test Set: 0.29660468589163835



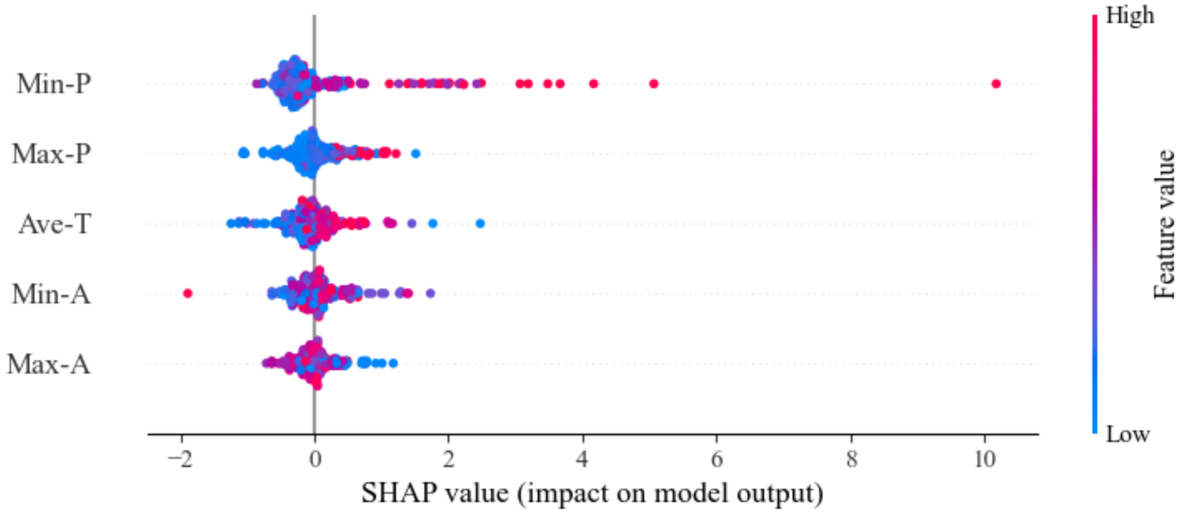


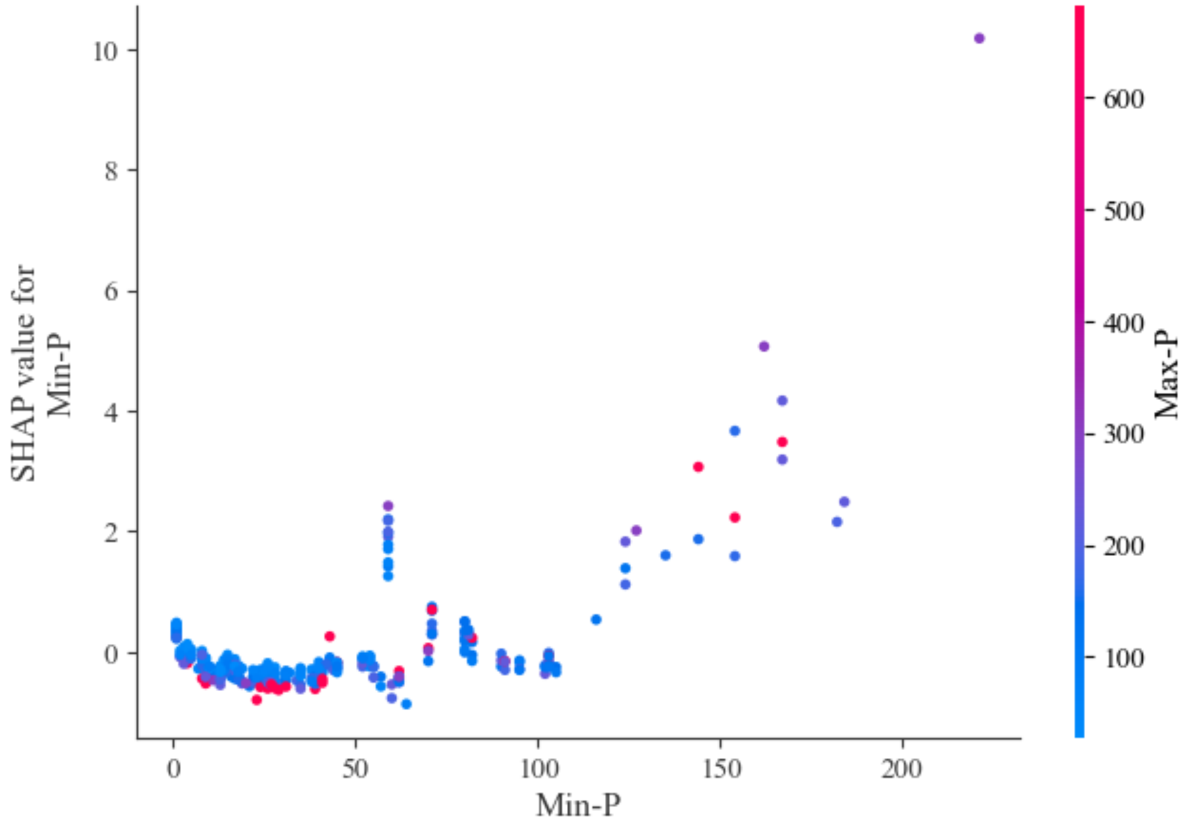
Dataset: df1522

Best Parameters: {'learning_rate': 0.1, 'max_depth': 3, 'min_samples_leaf': 1, 'min_samples_split': 6, 'n_estimators': 200}

MSE on Test Set: 1.9253566277588128

R2 on Test Set: 0.402963011088827826



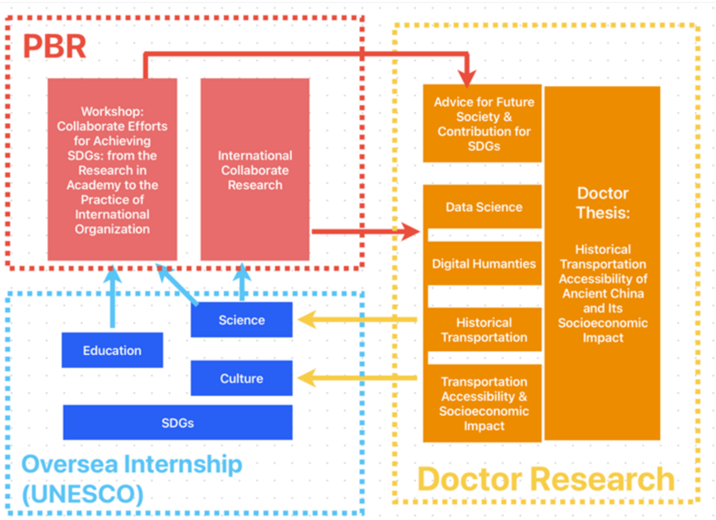


Appendix 4 Oversea Internship and Project Based Research (PBR)

TOWARDS INTERNATIONAL COOPERATION, PRACTICE AT UNESCO, AND COLLABORATION IN INTERNATIONAL RESEARCH

Abstract

This projected-based research intensifies the theoretical exploration of my doctoral study with a distinct focus on societal implementation. Firstly, through the half-year internship undertaken at the Natural Science Unit of the UNESCO Beijing Office, a profound contribution was made to UNESCO projects that interweave science and culture. The internship afforded the opportunity to garner experience in orchestrating and effectuating international programs at the intersection of science and culture. Moreover, by organizing an international workshop at Kyoto University, an essential nexus between academic research and international organization practices was established. The workshop offered both students and researchers enriched opportunities to deepen their comprehension of UNESCO and its manifold projects. Furthermore, in collaboration with prestigious institutions such as the Taiwan Academia Sinica, the Chinese Academy of Sciences, and Central China Normal University, we instituted the primary data sources and methodology for my doctoral thesis. This joint research underscored the critical role of academic cooperation in advancing knowledge and fostering novel research approaches.



1. Practice at UNESCO

As an individual deeply committed to applying my knowledge and expertise in Science and Engineering toward fostering a more sustainable world, I am keenly seeking opportunities to contribute within the framework of the United Nations. In the year 2022, I had the opportunity to serve as an intern at the UNESCO Beijing Cluster Office, a tenure lasting half a year.

The following report delineates my journey across three primary sections: the motivation and preparation leading up to the internship, the tangible contributions and implementation strategies during my tenure, and post-internship reflections and future aspirations.

This enriching internship experience has bolstered my understanding of UNESCO's mission and operational strategies, particularly from the vantage point of a field office. Furthermore, it has honed my management and communication skills, equipping me with vital competencies for future endeavors.

1.1 Introduction

1.1.1 Introduction of UNESCO Beijing Office and Its Science Unit

The United Nations Educational, Scientific and Cultural Organization (UNESCO) has long been a pillar of global unity, knowledge, and progress, championing causes that range from preserving the world's cultural heritage sites to promoting universal access to education. One of its pivotal regional hubs is the UNESCO Beijing Office, which plays a central role in promoting UNESCO's missions in the Asia-Pacific region. As a cornerstone of its operations, the Beijing Office’s Science Unit drives forward initiatives that uplift the standard and dissemination of scientific knowledge, thereby enhancing the region's capacity for sustainable development.

The UNESCO Beijing Office is a principal link between China, Japan, DPRK, ROK, Mongolia, and other Asia-Pacific countries with the organization's broad-based programs. As such, it represents a critical node in UNESCO's global network, ensuring the translation of the organization's ideals into tangible actions on the ground. The Office facilitates cross-cultural dialogue and cooperation, serving as a platform for sharing best practices, ideas, and innovation.

The Science Unit, a central part of the Beijing Office, epitomizes UNESCO's commitment to nurturing scientific cooperation and understanding. Its endeavors extend across multiple scientific disciplines, reflecting the complexity and interconnectedness of contemporary challenges that demand integrative and collaborative solutions. Through its initiatives, the Science Unit aims to equip Asia-Pacific countries with the tools, knowledge, and collaborative networks necessary to harness science for sustainable development.

The UNESCO Beijing Office, and especially its Science Unit, remains at the forefront of cultivating scientific literacy and cooperation in the region. They work tirelessly to foster an environment where science is recognized as a crucial component of societal progress, and where access to scientific knowledge is seen as a universal right rather than a privilege. Their work remains instrumental in driving the region towards a more sustainable, inclusive, and scientifically literate future.

1.1.2 Motivation and Application

In December 2021, as the Omicron variant of the coronavirus began to spread, Japan suspended all international flights, casting a cloud of uncertainty over international travel. In light of these circumstances, I sought an internship opportunity in China, my home country where I was residing at the time. In addition to the COVID-induced constraints, three other key motivations fueled my application.

Firstly, UNESCO was my prime choice for an internship. I am firmly convinced that leveraging modern technology and methodologies in the context of historical studies can establish a symbiotic relationship between science and tradition. This belief aligns with my ongoing research, which navigates transportation studies within a historical framework. My research experience will enable me to make meaningful contributions to UNESCO projects that intersect the realms of science and culture.

Secondly, my curiosity steers me towards the practical execution at field offices rather than the strategizing at headquarters of an international organization. The proverb "the last mile is the hardest" resonates strongly with me. It is crucial to translate universal standards and guidelines into locally applicable practices. Given my familiarity with East Asian countries, the UNESCO Beijing Cluster Office, which oversees projects in DPRK, ROK, Japan, Mongolia, and PRC, seemed an ideal choice.

Lastly, an internship in Beijing would offer opportunities for networking with other researchers engaged in similar studies, potentially facilitating access to relevant data and methodologies. As my research is closely tied to historical and contemporary China, this internship would also allow me to connect with related academics and researchers.

The application process unfolded smoothly. A critical factor that the interviewers appreciated was my background in engineering, which dovetails nicely with the projects undertaken in the Natural Science Sector.

1.2 Implementation and Contribution

Under the overarching guidance of the office director and the direct oversight of the programme assistant, I partook in the design, development, and execution of office activities within the domain of science, aligned with the organization's official mandate. My responsibilities encompassed the following specific projects:

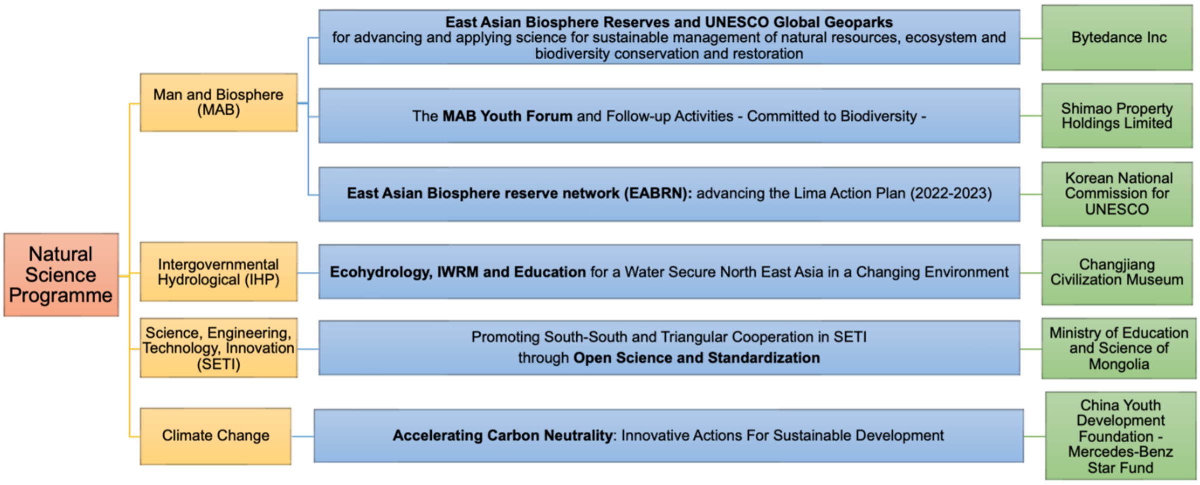


Figure 1. Participated Projects as the intern at Natural Science Unit, UNESCO Beijing Office

1.2.1 UNESCO Man and Biosphere Programme (MAB)

The Man and the Biosphere (MAB) programme is an intergovernmental scientific initiative with the objective of establishing a robust scientific foundation to enhance the relationship between people and their environments. It merges the realms of natural and social sciences with a focus on improving human livelihoods and preserving both natural and managed ecosystems. This results in fostering innovative approaches to economic development that are socially and culturally apt, as well as environmentally sustainable.

2021 marked the golden jubilee of UNESCO's Man and Biosphere Programme (MAB). This significant milestone was leveraged to heighten public awareness about the mounting challenges faced by biodiversity. From 2021 to 2022, UNESCO's multimedia exhibition, "It's About Life," is set to be showcased in urban centers worldwide, offering a glimpse into biosphere reserves, their residential communities, and the ongoing work of the MAB Programme.

Figure 2. Exhibition Posters for MAB "It's about life" Exhibition

In 2021, the Beijing Office was tasked with the responsibility of designing the online exhibition panels for the five selected Biosphere Reserves (BRs) in China and providing Chinese translations for the panels of ten other international BRs. These panels were to be featured on the UNESCO official website in commemoration of MAB's 50th Anniversary (https://en.unesco.org/mab/50years). In tandem with the theme of "Ecological Civilization-Building a Shared Future for All Life on Earth" of the 15th meeting of the Conference of the Parties (COP 15) to the Convention on Biological Diversity (CBD) held from October 11-24, 2021, in Kunming, China, the Beijing Office co-hosted the offline exhibition in Beijing and Kunming in 2021 alongside other partners.

In 2022, the MAB Secretariat planned to augment the initial number of panels for the exhibition, with a particular focus on underscoring contributions from the East Asia Biosphere Reserve Network (EABRN). Consequently, 14 panels representing BRs from EABRN member countries, excluding China (whose panels were already created), were designed. These countries include Mongolia, ROK, Russia, and Kazakhstan. My responsibility was to liaise with the national committees of these member states and officers in the selected BRs to gather the requisite materials for these panels. In addition, I coordinated with the UNESCO headquarters to discuss the budget allocation for the panel design.

Moreover, the magazine "Man and Biosphere", supported by the Chinese National Committee, planned to feature the created posters in their publication. In this regard, my role involved coordinating with the magazine editor and the designer at the UNESCO Headquarters to finalize the layout design and translation text.

Figure 3. Magazine “Man and Biosphere” Special issue for MAB’s 50th anniversary

1.2.2 UNESCO Intergovernmental Hydrological Programme

The UNESCO Intergovernmental Hydrological Programme (IHP) is the only intergovernmental cooperation programme within the UN system dedicated to water research and management, alongside related education, and capacity development. IHP addresses national, regional, and global water challenges by supporting the evolution of sustainable and resilient societies. The programme's primary tools include fostering a comprehensive understanding of water, enhancing technical capabilities, and strengthening human and institutional capacities. The work of IHP underpins evidence-based water governance and decision-making processes, leveraging transdisciplinary science, technology, and other knowledge systems.

In collaboration with the Changjiang Civilization Museum, the Beijing Office coordinated with approximately 125 related professors and experts to publish the River Culture Book. This publication represents an inaugural effort to address biological and cultural diversities in unison, portraying biocultural diversities, historical human-river relationships, threats, and practical examples of mitigating crises in riverscapes. Over 120 authors have contributed interdisciplinary studies from river systems across the globe, exploring overarching issues related to river management in the Anthropocene era.

In adherence with UNESCO's publishing policies, it was necessary to collect signed Grant Rights Letters from more than 120 authors and 241 picture owners. This was a crucial step to secure the DOI (Digital Object Identifier) and ISBN (International Standard Book Number) applications at UNESCO Headquarters. I was tasked with drafting these letters, liaising with the professors or picture owners, and subsequently filing all the letters. This entire process spanned nearly three months to complete. In 2023, the river culture book was successfully published.

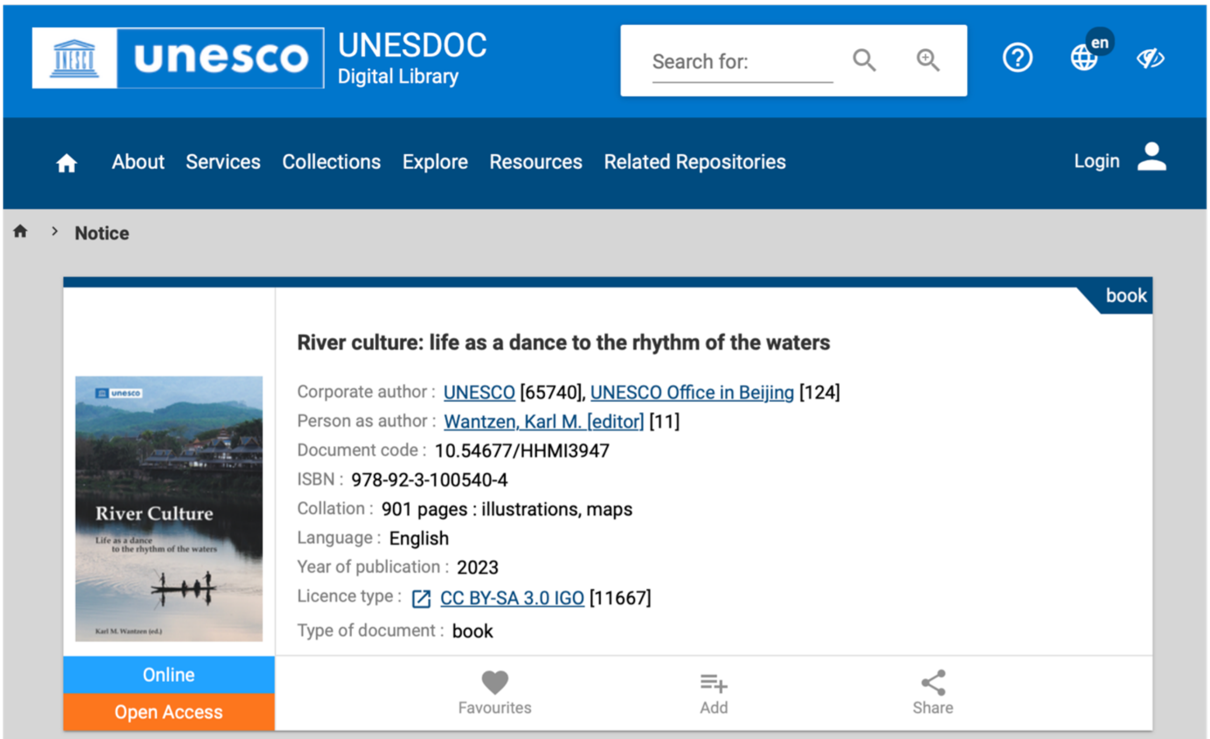


Figure 4. River Culture Book published in the UNESCO Website

1.2.3 East Asia Biosphere Reserve Network (EABRN)

The East Asian Biosphere Reserve Network (EABRN) is a regional network that supports UNESCO's MAB Programme. It was initially established with three priority themes for cooperation: eco-tourism, conservation policy, and transboundary cooperation. Officially launched in 1995 by China, the Democratic People's Republic of Korea (DPRK), Japan, Mongolia, and the Republic of Korea (ROK), the EABRN later expanded to include the Russian Federation in 1998 and Kazakhstan in 2011. The overarching aim of the project is to foster a robust and active network of well-managed Biosphere Reserves (BRs) across the seven EABRN member countries, actively engaging in bilateral and multilateral exchanges on management, research, and local development.

Following the EABRN meetings, a series of Online Training Webinars for EABRN Members are typically held. These training webinars offer a robust platform for capacity building, facilitating the exchange of information on various aspects of BR management. My role involved drafting the concept note for the subsequent online training webinars that were scheduled to follow the 16th EABRN meeting. To facilitate the selection of appropriate trainers for future webinars, I summarized all trainers previously invited by the UNESCO Beijing Office, as well as past contractors, contacts of the Biosphere Reserve managers, and other academic institutions that could potentially serve as trainers. The trainer list I compiled was shared with other partners for future cooperation and co-hosting of training webinars on various topics.

In addition to supporting my colleagues in preparing for the 16th EABRN meeting scheduled to be held in Mongolia, my primary responsibility was the maintenance and promotion of the EABRN website (https://www.unescoeabrn.org). After the former staff member responsible for the website left, its maintenance ceased, with the last edit made in 2019. I successfully gained access to edit the website and initiated its regular maintenance.

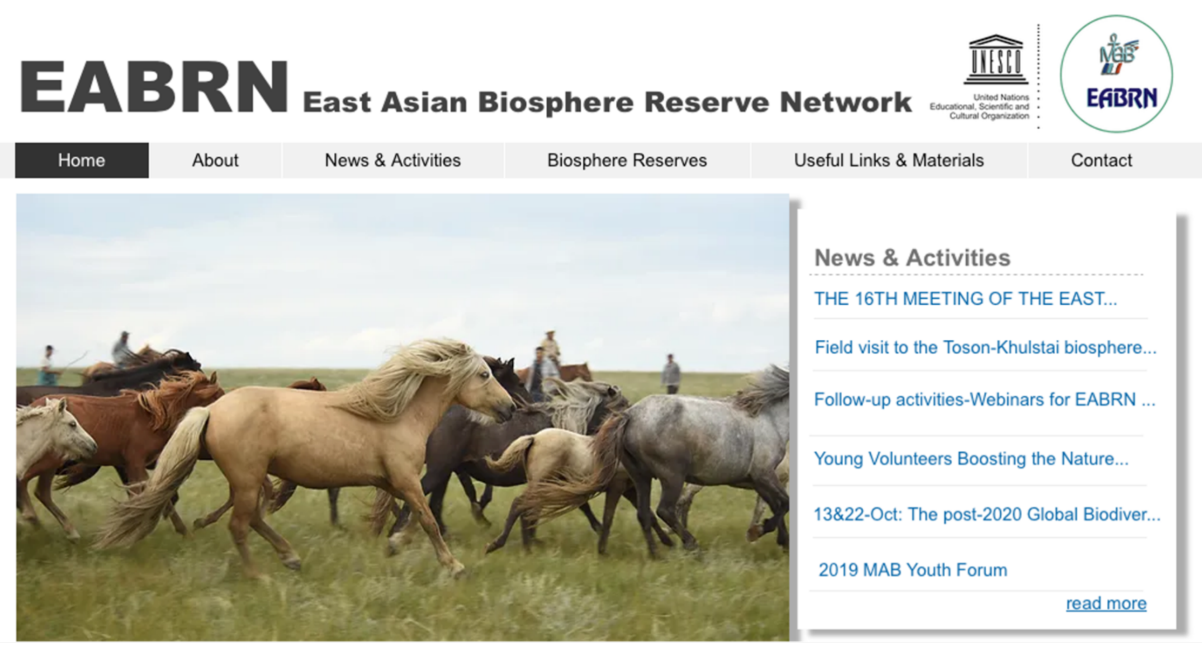


Figure 5. EABRN Website

1.2.4 MAB Youth Forum and Follow-up Activities

The MAB Youth Forumis a key component of UNESCO's initiatives aimed at ensuring the active engagement of young men and women in policies and programmes that affect them. It provides a platform for them to lead actions promoting peace and sustainable development within their respective countries and communities. The 2nd MAB Youth Forum took place in the Changbaishan Biosphere Reserve in China in September 2019. Primarily, this Forum was geared towards the 15th Conference of the Parties of the Convention on Biological Diversity (CBD COP 15), which was slated for Kunming, China, in 2020. This forum was co-organized by the MAB Programme and UNESCO Beijing, in partnership with the Global Youth Biodiversity Network (GYBN). Plans are underway for the 3rd MAB Youth Forum to take place in 2022. My responsibilities included drafting the initial concept note for the MAB Youth Forum.

1.2.5 Promoting South-South and Triangular Cooperation in SETI through Open Science and Standardization

The Science and Technology Master Plan for 2007-2020 in Mongolia was orchestrated by the Ministry of Education and Science of Mongolia, with support from UNESCO's Beijing and Jakarta offices. Over the years, this plan has been successfully integrated as a crucial part of broader national development strategies and policies. I was tasked with drafting the preliminary version of the official letter from UNESCO's Beijing Office to the Ministry of Education and Science of Mongolia. The purpose of this letter was to propose the evaluation of the preceding master plan, as this would establish a solid foundation for further implementation of some of its objectives. Moreover, it would help develop recommendations for the creation and adoption of a new Science, Technology, and Innovation (STI) Master Plan for Mongolia for the post-2020 era.

1.2.6 Accelerating Carbon Neutrality: Innovative Actions for Sustainable Development

In response to climate change challenges, the UNESCO-China Youth Development Foundation Mercedes-Benz Star Fund Funds-in-Trust launched the project "Accelerating Carbon Neutrality: Innovative Actions for Sustainable Development". This initiative aims to foster sustainability science, education for sustainable development, and capacity-building. It equips stakeholders, especially young people, with the knowledge, skills, values, and attitudes required for climate change response. This includes reducing carbon footprints, preserving ecosystems, and conserving biodiversity. The project operates through "hand-in-hand action," "forest protection action," "partnership action," and "practical education base action" to advocate for practical actions promoting ecological civilization and building a sustainable future for all.

In relation to this project, I am tasked with all associated translation work. This includes the translation of project documents and agreement contracts, as well as interpretation during various communication processes.

Figure 6. Interpretation Work during the Meeting with China Youth Development Foundation and Mercedes-Benz Star Foundation

1.2.7 Other administration work

Due to the vacant position of the Programme Specialist for the Natural Sciences Unit, many official documents require direct review by the office director. Consequently, official memos must be drafted in the name of the Programme Specialist from other units and addressed to the director. My responsibilities encompass liaising with the Programme Specialists of these other units and drafting the requisite documents for several projects currently under implementation.

I am tasked with designing, drafting, and proofreading public outreach materials and news items for certain unique events for the UNESCO website and social media platforms. For instance, I was responsible for drafting content for the Natural Science Sector in the UNESCO Beijing Office Newsletter for the period of January – April 2022.

August 12th every year is International Youth Day, and the theme of 2022 is "Inter-generational Solidarity - Building an Age-inclusive World." Under this theme, as the youth representative, I held an in-depth and friendly cross-generational dialogue with Professor Shahbaz Khan, representative of the UNESCO Beijing Office. We discussed the importance of inter-generational collaboration in the process of achieving Sustainable Development Goals.

Figure 7. Dialogue with Director for the campaign on International Youth Day

1.4 Reflection and Expectation

This internship has proven to be a significant opportunity for my personal growth and development. I have gained invaluable insights in various areas, but I also recognize the need to further hone my skills to become an efficient global leader. In the following sections, I will reflect on my experiences in different fields.

1.4.1 Insights into UNESCO

During my time at UNESCO, the first and foremost lesson has been gaining a comprehensive understanding of the organization's work and procedures, particularly from the perspective of a field office. Communicating with the UNESCO Headquarters and national committees for member states has allowed me to appreciate the dignity and professional management required as a UN staff member.

1.4.2 Communication for Social Collaboration

Given its fundamental role in unifying efforts, communication is key to the successful implementation of any project and is vital for social collaboration. Throughout this internship, I had numerous opportunities to engage in fundraising communications, especially regarding bilateral and private funding opportunities. While I am comfortable communicating with different partners in multiple languages, there were instances of misunderstanding, particularly during the initial stages of the internship. In the future, to avoid potential miscommunication, I need to double-check to ensure my understanding aligns with others.

1.4.3 Management

Knowledge about intergovernmental programs is another asset I have gained from this experience. As an engineering student, my academic background was beneficial in the implementation of various projects, especially those related to research. However, to organize or plan a successful event or project, numerous aspects need to be considered, including the background, rationales, and linkages with SDGs. A robust theory of change, timeline, potential risks, and prevention measures are also essential. A clear statistical evaluation is also necessary to measure the project's success and visibility.

However, based on feedback from my internship supervisor, I need to be more detail-oriented, especially when processing documents. In conclusion, this internship placed a very good foundation for my following project-based research.

2. Workshop: Collaborate Efforts for Achieving SDGs: from the Research in Academy to the Practice of International Organization

Upon completion of my internship at the UNESCO Beijing Office, a meticulously designed workshop was curated to amalgamate my experiences in international organizations with my ongoing research at Kyoto University. This initiative was made possible due to the substantial support from the UNESCO Beijing Office, UNESCO Chair on Water, Energy, and Disaster Management for Sustainable Development at Kyoto University (WENDI), and GSAIS. We were fortunate to host Prof. Shahbaz Khan, Director of the UNESCO Beijing Office and UNESCO Representative to China, Japan, ROK, DPRK, and Mongolia, at Kyoto University for a Special Lecture and Panel Discussion.

Figure 8. Posters for the workshop

The workshop was designed with specific objectives in mind. First, to deepen young researchers' and students' comprehension of UNESCO's mission and Kyoto University's role in achieving the Sustainable Development Goals (SDGs). Second, to foster inter-sectoral communication and stimulate innovative solutions for global issues through collaborative efforts. Lastly, from the vantage point of international organizations and academic institutions, it aimed to offer young researchers and students professional guidance on their potential contributions to the SDGs and assist them in career planning.

2.1 Introduction of GSAIS and WENDI

The welcome message was delivered by Prof. Yosuke Yamashiki first to welcome the participation of Prof. Shahbaz Khan. And a 20-minute introduction is presented by Prof. Yamashiki to explain the mission and work of the UNESCO Chair on Water, Energy, and Disaster Management for Sustainable Development at Kyoto University (WENDI), and GSAIS.


Figure 9. Presentations delivered by Prof. Yosuke Yamashiki

The objective of the UNESCO Chair on Water, Energy, and Disaster Management for Sustainable Development, Kyoto University (WENDI) is to equip students with knowledge, superior skills, and broad perspectives to address the many challenges that today's societies face. WENDI thus offers a novel and interdisciplinary Higher Education and Research for Sustainable Development (HESD) Programme, a solid certificate programme, and encourages and values students' self-learning. WENDI aims at contributing to achieving the SDGs as well as establishing resilient societies through collaborative education and research with established researchers and experts from the United Nations, international organizations, other UNESCO Chairs and Centers, governmental organizations, universities, research institutions, and private enterprises.

the Graduate School of Advanced Integrated Studies in Human Survivability (GSAIS), was established in April 2013 with the aim of building "human survivability studies" to deal with these threats to the survival of mankind. Our mission is to nurture the talents who have the intention to help develop the field of human survivability studies and to become leaders with global perspectives. The current number of students totals 75, and 21 students have completed the 5-year course so far. These Ph.D. holders work in diverse workplaces, including private companies, universities, research institutes, government offices, and non-governmental organizations. In these places, they have been welcomed as valuable resources for social innovation.

2.2 Special Lecture

Professor Shahbaz Khan, Director of the UNESCO Beijing Office and UNESCO Representative to China, Japan, ROK, DPRK, and Mongolia, provided an insightful lecture encompassing an array of topics from his experiences at UNESCO, collaborative work with various institutions, the strategic transformation at UNESCO, and the current global challenges we face. He delved into his extensive work in areas like economics, environmental law, big data, and emerging fields like remote sensing and artificial intelligence.


Figure 10. Lectures delivered by Prof. Shahbaz Khan

He addressed contemporary

global issues like climate change and biodiversity loss, highlighting their universality and crossing geographical boundaries, making international cooperation a necessity in tackling these challenges. This discourse was interwoven with the United Nations' Sustainable Development Goals (SDGs), emphasizing their interconnectedness and the concerted effort required to achieve them. The significance of international policies, such as the African 63 Initiative and the Global Climate Change Paris Agreement, was underscored, highlighting the requirement for collaboration, feedback, expertise, and strategy in effecting meaningful impact.

Professor Khan also elaborated on the complexity of understanding key issues within both large nations like China and developed countries like Japan and emphasized the universal applicability of SDGs. He affirmed that careful consideration of all factors is critical in designing a framework for progress, necessitating the acquisition of funds, planning, and adjusting over a five-year period.

One of the key topics discussed was UNESCO's initiatives and strategies to enhance water security, sustainable development, and equity, particularly within the Asian region. The professor emphasized the importance of hydrological science in addressing global water issues and showcased the pivotal role of UNESCO's International Hydrological Program (IHP) in the evolution of water management.

Current advancements, such as machine learning and data-driven approaches for water-related disaster prediction and water management, were explored. An example included the SWAT model used in China for efficient water resource management and flood prediction. Professor Khan also emphasized the commitment to hydrology education at UNESCO and the importance of integrating traditional knowledge and local experiences into scientific research.

In the latter part of the presentation, the professor focused on UNESCO's ongoing transformative strategies, its dedication to integrating artificial intelligence and big data into its approach, and its alignment with international agreements like the 2030 Agenda, the African 2063 Agenda, the Paris Agreement, and the Sendai Framework. The organization's responsibilities towards all member states were discussed, including addressing issues of poverty, disaster resilience, health, and women's empowerment.

Professor Khan concluded his presentation by emphasizing the need for inclusive and participatory problem-solving approaches, the breaking down of barriers between disciplines, and the ongoing role of UNESCO in sustainable development. He articulated that while there are no definitive solutions to these global challenges, the organization is committed to developing and implementing ongoing solutions. This illuminating lecture underscored the complexities of managing global water security and the efforts undertaken by UNESCO to address these issues through innovative technologies, comprehensive research, and inclusive strategies.

2.3 Panel Discussion

2.3.1 Introduction

The panel discussion, following the special lecture of Prof. Shahbaz Khan, brought together diverse participants from the UNESCO Beijing Office, the Graduate School of Advanced Integrated Studies in Human Survivability (GSAIS), and former interns at UNESCO. The objective was to share experiences and ideas from different perspectives to enrich the understanding of the interface between academia and practical implementation within international organizations.

2.3.2 Participants

- **Prof. Shahbaz Khan**, Director of the UNESCO Beijing Office and UNESCO Representative to China, Japan, ROK, DPRK, and Mongolia.
- **Prof. Kaoru Takara**, former Dean of GSAIS and former Chair of WENDI.
- **Prof. Yosuke Yamashiki**, Professor in GSAIS and Co-Chair of WENDI.
- **Mr. Wenlong LI**, student of GSAIS and former intern at the UNESCO Beijing Office.
- **Ms. Akiko Tanimoto**, student of GSAIS and former intern at UNESCO HQ.
- **Ms. Shoko Iwasaki**, student of GSAIS and former intern at UNESCO IICBA (International Institute for Capacity Building in Africa)

2.3.3. Discussion

The students opened the discussion, recounting their experiences and lessons learned during their internships at UNESCO. They compared the unique internal structure of UNESCO with the academic environment of universities. The differences encompassed diverse representations from countries, innovative solutions spurred by dynamic discussions, and the role of consensus in an international organization.

A key theme was the gap between academic knowledge and the practical realities in international organizations. While theoretical knowledge was deemed important, the need for practical strategies to effectively address real-world problems was underscored. The students also discussed their challenges and learning opportunities during the internships, emphasizing the importance of multidisciplinary thinking, global awareness, and strong communication skills.

Figure 11. The Panel Discussion

The discussion later moved towards the experiences of Prof. Khan, who shared his journey managing interdisciplinary projects at UNESCO. He emphasized the value of understanding the realities of the world, fostering collaboration, and utilizing different skills for problem-solving.
The panel highlighted the unique and enriching culture of UNESCO, which encourages intellectual exchanges and enhances collective strength. They shared insights into how this inclusive culture promotes impactful change and prepares individuals to face future challenges.

2.3.4 Conclusion

In conclusion, the panel discussion provided valuable insights into navigating life post-university, incorporating research into practical projects, and the importance of being prepared for unexpected challenges. The participants stressed the need for open-mindedness, multi-disciplinary learning, practical experiences, and strong networking. They also encouraged others to seek opportunities, showcase passion, and pursue dreams and aspirations, regardless of one's academic discipline or professional uncertainties. Ultimately, the discussion fostered a deeper understanding of how to bridge the gap between academic research and practical implementation in international organizations.

2.4 Q&A Session

The following is the discussion report of the 7 questions discussed during the workshop:

Question 1: Career
Regarding my curiosity about my profession, it's indeed a long story. I was born in Pakistan, studied civil engineering in the UK with a focus on water treatment, and then returned to Pakistan to handle flood issues. Later, I moved to Australia and served as an engineering consultant in the mining industry. Additionally, I was a research scientist and a director at CSIRO. My work in integrated water resources management drew the attention of UNESCO, leading me to work in Paris and then Jakarta. Presently, I am based in Beijing.

Throughout this journey, I continuously sought to improve my skills. For example, in Australia, I realized I needed to learn object modeling systems, AI, and genetic algorithms. I then familiarized myself with GIS and big data, as without them, I couldn't build good models. Seeing people fight over water resources even led me to study economics. However, my son believes that degrees aren't as crucial these days, as some tech-savvy individuals make good money without having completed one.

Figure 12. Q&A Sessions during the Workshop

Question 2: Climate Change

Addressing the query about my perspective on changing climate patterns, it's indeed true that we're facing evolving challenges. Rapid urbanization and extreme temperatures have significantly altered our planet. Despite contributing less than 1% of greenhouse gas emissions, Pakistan experiences dramatic impacts. From a civil engineering standpoint, our traditional designs and structures based on past century's data are no longer applicable. Understanding rainfall patterns and potential maximum rainfall is vital. Yet, resources to retrofit and design structures to cope with new challenges are scarce.

Question 3: Pakistan Water Issue

The question from Pakistan about predicting the impact of water is insightful. The issues in Pakistan are systemic, originating from the workings of its political system. Solving these problems needs scientific understanding and dialogue with politicians. A project I was involved in a decade ago involved evaluating glacier outflows. Our analysis showed that in the coming years, there would be a large volume of glacier runoff, and Pakistan lacked enough dams to store it. Hence, a potential water shortage is predicted. I recommend focusing on water conservation and educating political parties about it.

Question 4: Member States Participation in UNESCO

Regarding the question about resolving disagreements among members, it's indeed complex. As a diplomat, my job is to facilitate the work of member states. Each state has equal voting rights, whether it's a small island or a large nation. It can get complicated when nations bring individual issues to the table.

Question 5: UN Agencies Participation

Collaboration between UN agencies and other organizations is vital in addressing a variety of complex global issues. Successful collaborative projects require a shared vision, clear roles and responsibilities, open communication, mutual respect, and an understanding of the different cultures and operational mechanisms involved. It's a challenging but rewarding process, and I encourage participation in such collaborations, whether through work, study, or volunteer activities.

Question 6: Individuals' Contribution

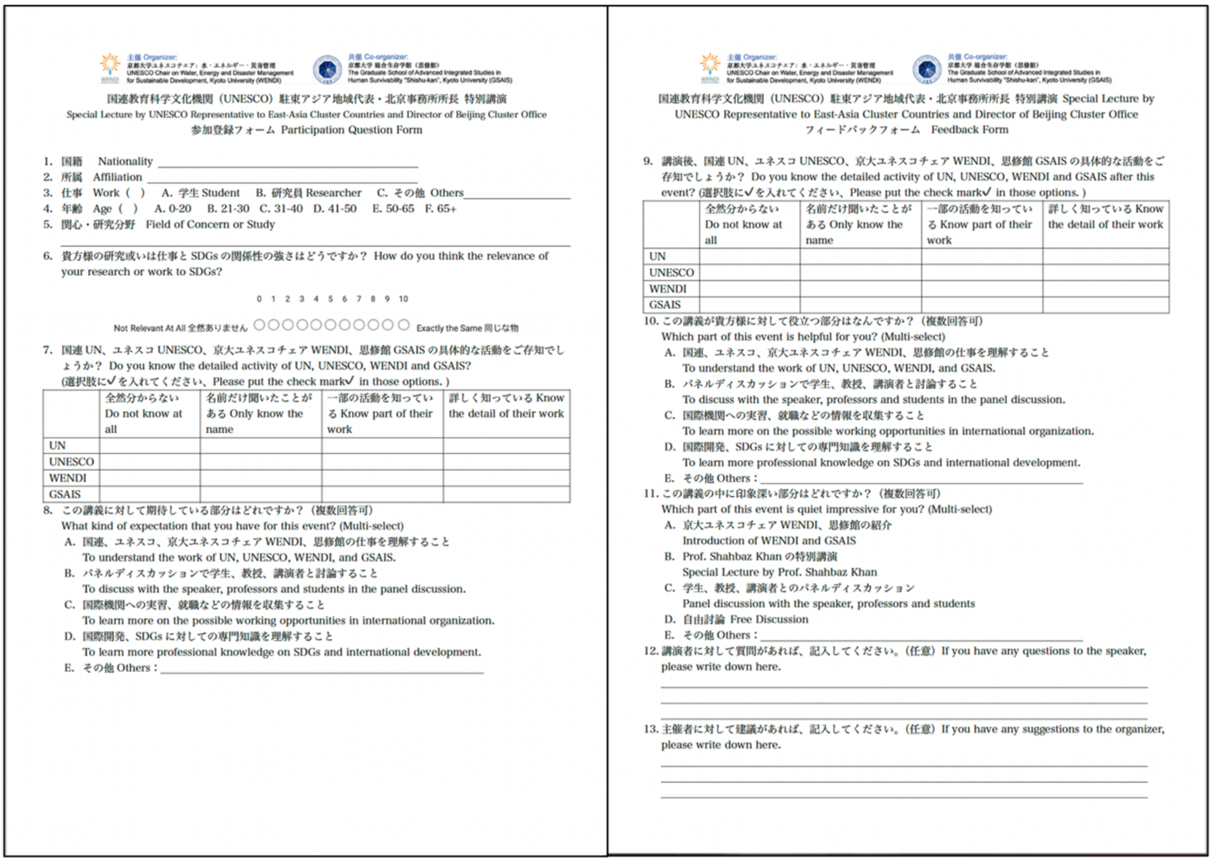
Regarding UNESCO's support for leading universities or research programs in Asia and other regions, it really depends on the individual. Those willing to work and contribute to a greater cause will find a way, regardless of their location. The beauty of the ISP part of IP lies in people from diverse backgrounds working together.

Question 7: Social Networking

As a graduate of a university in Pakistan, I've forged my career in sustainable water resources management and created a center in the headwater region located in Islamabad. I suggest volunteering with these groups. Universities have always been united as they consistently offer volunteering services beyond their academic function. Participation requires time, energy, and resources, and we need everyone to contribute. Networking can have a broader impact, hence it's crucial, whether your aim is a local or international career. I suggest dedicating a considerable amount of your time to networking.

2.5 Reflections

During the workshop, a questionnaire was designed to understand the basic information of the participants of this workshop and their comments regarding this activity. The feedback from the participants can be taken as an evaluation of our work, and also as a guide for the possible future work. We collected 20 offline questionnaires and 18 online questionnaires. The analysis of the feedback is following:



主催 Organizer:
京都大学ユネスコチェア：水・エネルギー・災害管理
UNESCO Chair on Water, Energy and Disaster Management for Sustainable Development, Kyoto University (WENDI)
共催 Co-organizer:
京都大学 総合生存学館（思修館）
The Graduate School of Advanced Integrated Studies in Human Survivability "Shishu-kan", Kyoto University (GSAIS)

国連教育科学文化機関（UNESCO）駐東アジア地域代表・北京事務所所長 特別講演
Special Lecture by UNESCO Representative to East-Asia Cluster Countries and Director of Beijing Cluster Office
参加登録フォーム Participation Question Form

1. 国籍 Nationality ____________
2. 所属 Affiliation ____________
3. 仕事 Work（ ） A. 学生 Student B. 研究員 Researcher C. その他 Others____________
4. 年齢 Age（ ） A. 0-20 B. 21-30 C. 31-40 D. 41-50 E. 50-65 F. 65+
5. 関心・研究分野 Field of Concern or Study
6. 貴方様の研究或いは仕事とSDGsの関係性の強さはどうですか？ How do you think the relevance of your research or work to SDGs?

0 1 2 3 4 5 6 7 8 9 10

Not Relevant At All 全然ありません ○○○○○○○○○○○ Exactly the Same 同じな物

7. 国連UN、ユネスコUNESCO、京大ユネスコチェアWENDI、思修館GSAISの具体的な活動をご存知でしょうか？ Do you know the detailed activity of UN, UNESCO, WENDI and GSAIS?
(選択肢に✓を入れてください、Please put the check mark✓ in those options.)

	全然分からない Do not know at all	名前だけ聞いたことがある Only know the name	一部の活動を知っている Know part of their work	詳しく知っている Know the detail of their work
UN				
UNESCO				
WENDI				
GSAIS				

8. この講義に対して期待している部分はどれですか？（複数回答可）
What kind of expectation that you have for this event? (Multi-select)
A. 国連、ユネスコ、京大ユネスコチェアWENDI、思修館の仕事を理解すること
To understand the work of UN, UNESCO, WENDI, and GSAIS.
B. パネルディスカッションで学生、教授、講演者と討論すること
To discuss with the speaker, professors and students in the panel discussion.
C. 国際機関への実習、就職などの情報を収集すること
To learn more on the possible working opportunities in international organization.
D. 国際開発、SDGsに対しての専門知識を理解すること
To learn more professional knowledge on SDGs and international development.
E. その他 Others：____________

主催 Organizer:
京都大学ユネスコチェア：水・エネルギー・災害管理
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The Graduate School of Advanced Integrated Studies in Human Survivability "Shishu-kan", Kyoto University (GSAIS)

国連教育科学文化機関（UNESCO）駐東アジア地域代表・北京事務所所長 特別講演 Special Lecture by UNESCO Representative to East-Asia Cluster Countries and Director of Beijing Cluster Office
フィードバックフォーム Feedback Form

9. 講演後、国連UN、ユネスコUNESCO、京大ユネスコチェアWENDI、思修館GSAISの具体的な活動をご存知でしょうか？ Do you know the detailed activity of UN, UNESCO, WENDI and GSAIS after this event? (選択肢に✓を入れてください、Please put the check mark✓ in those options.)

	全然分からない Do not know at all	名前だけ聞いたことがある Only know the name	一部の活動を知っている Know part of their work	詳しく知っている Know the detail of their work
UN				
UNESCO				
WENDI				
GSAIS				

10. この講義が貴方様に対して役立つ部分はなんですか？（複数回答可）
Which part of this event is helpful for you? (Multi-select)
A. 国連、ユネスコ、京大ユネスコチェアWENDI、思修館の仕事を理解すること
To understand the work of UN, UNESCO, WENDI, and GSAIS.
B. パネルディスカッションで学生、教授、講演者と討論すること
To discuss with the speaker, professors and students in the panel discussion.
C. 国際機関への実習、就職などの情報を収集すること
To learn more on the possible working opportunities in international organization.
D. 国際開発、SDGsに対しての専門知識を理解すること
To learn more professional knowledge on SDGs and international development.
E. その他 Others：____________
11. この講義の中に印象深い部分はどれですか？（複数回答可）
Which part of this event is quiet impressive for you? (Multi-select)
A. 京大ユネスコチェアWENDI、思修館の紹介
Introduction of WENDI and GSAIS
B. Prof. Shahbaz Khanの特別講演
Special Lecture by Prof. Shahbaz Khan
C. 学生、教授、講演者とのパネルディスカッション
Panel discussion with the speaker, professors and students
D. 自由討論 Free Discussion
E. その他 Others：____________
12. 講演者に対して質問があれば、記入してください。（任意）If you have any questions to the speaker, please write down here.
13. 主催者に対して建議があれば、記入してください。（任意）If you have any suggestions to the organizer, please write down here.

Figure 13. Questionnaires for the Workshop

2.5.1 Participants' Basic Information

Considering the seminar participant data, a comprehensive analysis offers the following insights:

1. Participation Method: Notably, most of the participants, specifically 20 out of 38, attended the seminar offline, while the remaining 18 participants joined online.

2. Nationality: The participants' nationalities varied, with a pronounced representation from China, accounting for nearly half of the total participants. Other countries represented included Japan, Pakistan, Nepal, El Salvador, Mexico, New Zealand, Brazil, Malaysia, the USA, Sudan, Thailand, Russia, Myanmar, and Malawi.

3. Affiliations: A significant majority of the attendees, over 80%, were affiliated with GSAIS or Engineering F. Kyodai. The remaining participants were associated with various other institutions including the University of Sussex, Honjo, GSM, Waseda University, Nagasaki University, and Kumamoto University (IMEG).

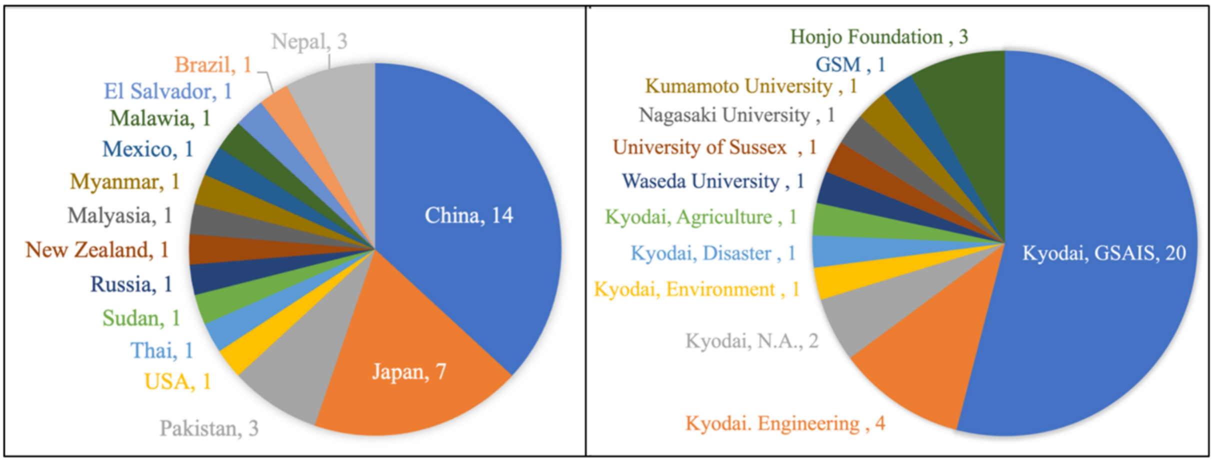

Figure 14. Nationality and Affiliation of the participants

4. Occupations: Most of the participants, about 36 out of 38, were students, with only a few members of staff from institutions such as Honjo.

5. Age Groups: The majority of participants fell within the 'B' age group, which represents individuals between the ages of 20 to 30. A smaller number of participants belonged to the 'C' (30 to 40 years) and 'D' (40 to 50 years) age groups. The 'E' (over 50 years) and 'A' (under 20 years) age groups had the least representation.

6. Areas of Interest: A wide range of research fields were represented, with an emphasis on environmental topics, such as Water Management, Climate Change, and Environmental Sciences, as well as Social Sciences and Information Sciences.

7. SDG Relevance: Lastly, most participants scored high on SDG relevance, with many scoring a maximum of 10 points, indicating a strong alignment between their work and the Sustainable Development Goals (SDGs). The average SDG relevance score was above 8, signifying a considerable focus on sustainability among participants.

This data underscores a strong representation from the younger generation, predominantly from GSAIS, with a focus on sustainable development, aligning well with the seminar's purpose.

2.5.2 Participants' Understanding Level of the Relevant Projects

Based on the information provided, the following is an analysis of the participants' comprehension of GSAIS, WENDI, UNESCO, and UN before and after the seminar.

1. GSAIS Understanding: Prior to the seminar, most participants demonstrated an intermediate to high level of understanding of GSAIS (3 or 4). Remarkably, this understanding improved after the seminar, with many participants indicating a high level of understanding (4).

2. WENDI Understanding: In contrast, the understanding of WENDI was considerably lower before the seminar, with a significant portion of participants only knowing a part of its work (2 or 3). However, the seminar appeared to have a positive impact on this, with many participants showing an improved understanding of WENDI afterward.

3. UNESCO Understanding: Before the seminar, the participants' understanding of UNESCO was quite balanced, with a slight inclination towards moderate knowledge (2 or 3). The seminar had a clear positive effect, with many participants reporting an increased understanding of UNESCO's work.

4. UN Understanding: Initially, the understanding of UN was quite high among participants, with most of them having a moderate to full understanding of UN's work (3 or 4). This high level of understanding was maintained after the seminar, demonstrating the participants' initial familiarity and continued interest in UN.

The provided data suggests the seminar was successful in enhancing the participants' understanding of these organizations, especially WENDI, which showed the most significant improvement. This is indicative of the seminar's effectiveness in information dissemination and fostering comprehension among attendees.

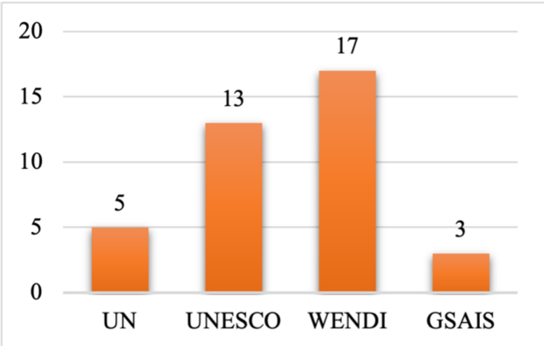

Figure 15. Number of Participant's Understanding Improved through this Workshop.

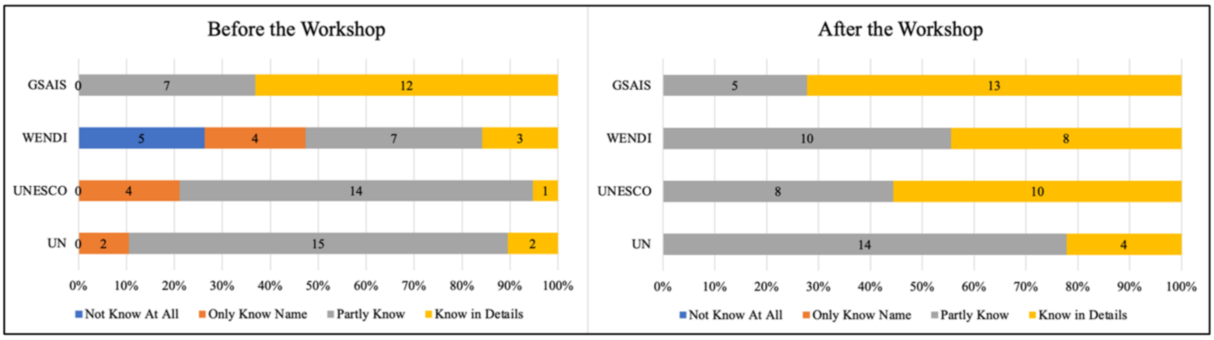

Figure 16. Participants' understanding regarding GSAIS, WENDI, UNESCO, UN

2.5.3 Participants' Evaluation of the Event

The seminar was attended by a diverse group of individuals with varying expectations. A substantial number of attendees had specific goals regarding the information they hoped to gain:
-27 attendees hoped to learn about the work of the UN, UNESCO, GSAIS, and WENDI.
-28 attendees looked forward to participating in and observing the panel discussion involving representatives and students from Kyoto University.
-25 attendees aimed to gather information about employment and internship opportunities within international organizations.

-29 attendees anticipated learning specialized knowledge related to their fields of interest.

In terms of the outcomes after the seminar, it is encouraging to note that attendees' expectations were largely met:
- 13 attendees reported gaining a better understanding of the work conducted by the UN, UNESCO, GSAIS, and WENDI.
- 28 attendees were pleased to have participated in and observed the panel discussion involving representatives and students from Kyoto University.
- 25 attendees reported successfully gathering information on employment and internship opportunities in international organizations.
- 29 attendees expressed that they acquired specialized knowledge in their respective areas of interest.

As for the parts of the seminar that left the most significant impressions on the attendees:
- 3 attendees were most impressed by the job descriptions provided during the seminar.
- 13 attendees found the special lectures delivered by the representatives to be the most memorable.
- 12 attendees highlighted the panel discussion as the most impactful part of the seminar.
- 5 attendees indicated that the Q&A session was the most engaging.

In conclusion, the seminar was highly successful in meeting the expectations of most of its attendees, offering a wealth of knowledge and interactive experiences. The panel discussion emerged as a particularly engaging component, while specialized lectures and the Q&A session were also appreciated for their insightful content. It suggests that such an integrative approach involving lectures, discussions, and interactive sessions could be beneficial for future seminars.

Figure 17. Group Photo of the Workshop

3. Collaborate Research on Historical Transportation of China

I have been actively engaged in an exploratory research project that investigates the socioeconomic impact of historical transport accessibility in China. A significant challenge faced during this research has been data scarcity, leading to a necessity for collaboration with various scholars and institutions.

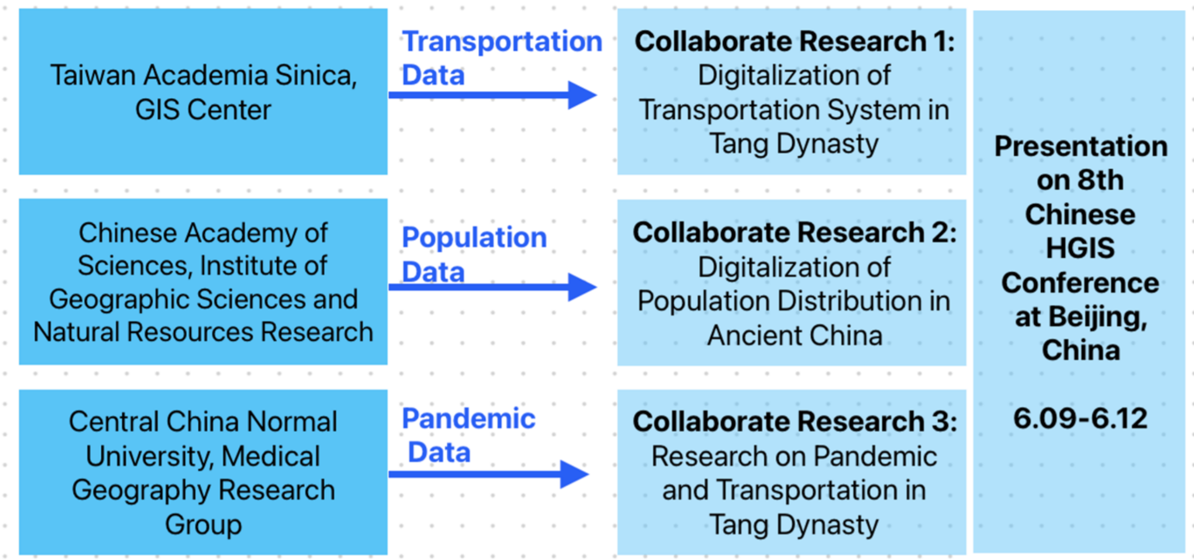

Figure 18. International Collaboration Research

3.1 Digitalization of Transportation System in Tang Dynasty

One significant partnership has been with scholars at the Academia Sinica in Taiwan. Our collaborative work has primarily focused on utilizing their Tang Dynasty transport data. By analyzing this historical data, we hope to understand the patterns and consequences of transport during this significant period in Chinese history.

3.2 Digitalization of Population Distribution in Ancient China

Another integral collaboration has been with the Institute of Geographic Sciences and Natural Resources Research at the Chinese Academy of Sciences. This collaboration has primarily revolved around using the population data they have gathered. This data has been subjected to extensive visual processing and analysis, enhancing our understanding of historical population trends and their connection to transport accessibility.

3.3 Research on Pandemic and Transportation in Tang Dynasty

Further collaboration has occurred with the Central China Normal University, with a significant emphasis on the study of the impact of transportation on pandemic-related disasters. This research intends to contribute towards our understanding of how transportation infrastructures have historically influenced the spread and management of diseases.

Lastly, the culmination of these cooperative research efforts was presented at the 8th Chinese Historical Geographic Information System Academic Salon. The presentation served as a platform to highlight the collective efforts and contributions of our research. By publishing these collaborative research findings, we aim to further the academic understanding of the socioeconomic impact of historical transport accessibility in China.

This multi-faceted collaborative research approach allows me to address the complexities of the research topic. It also facilitates the integration of diverse data sources and research expertise, enhancing the depth and comprehensiveness of the study. Through these collaborative efforts, I aim to construct a thorough understanding of China's historical transportation accessibility and its wide-ranging socio-economic impacts.

4. The Contributions of This Project Based Research to the Doctoral Dissertation

Based on the doctoral research topic focusing on "The Historical Accessibility of Ancient China and Its Socio-economic Impact," this project-based research has deepened its theoretical explorations towards societal implementation. Our research, utilizing the latest technology and methodologies, made meaningful contributions to UNESCO projects situated at the intersection of science and culture. Through an internship at the UNESCO Beijing Office's Natural Sciences Section, international implementation experiences regarding projects related to science and culture were learned. Moreover, through the hosting of international research seminars at Kyoto University, connecting academic research with the practice of international institutions, opportunities for students and researchers to gain a deeper understanding of UNESCO and its projects were provided. In addition, through joint research with Taiwan's Academia Sinica, the Chinese Academy of Sciences' Institute of Geographic Sciences and Natural Resources Research, and the Medical Geography Research Laboratory of Central China Normal University, the main data sources and methodologies for the doctoral dissertation were formed.

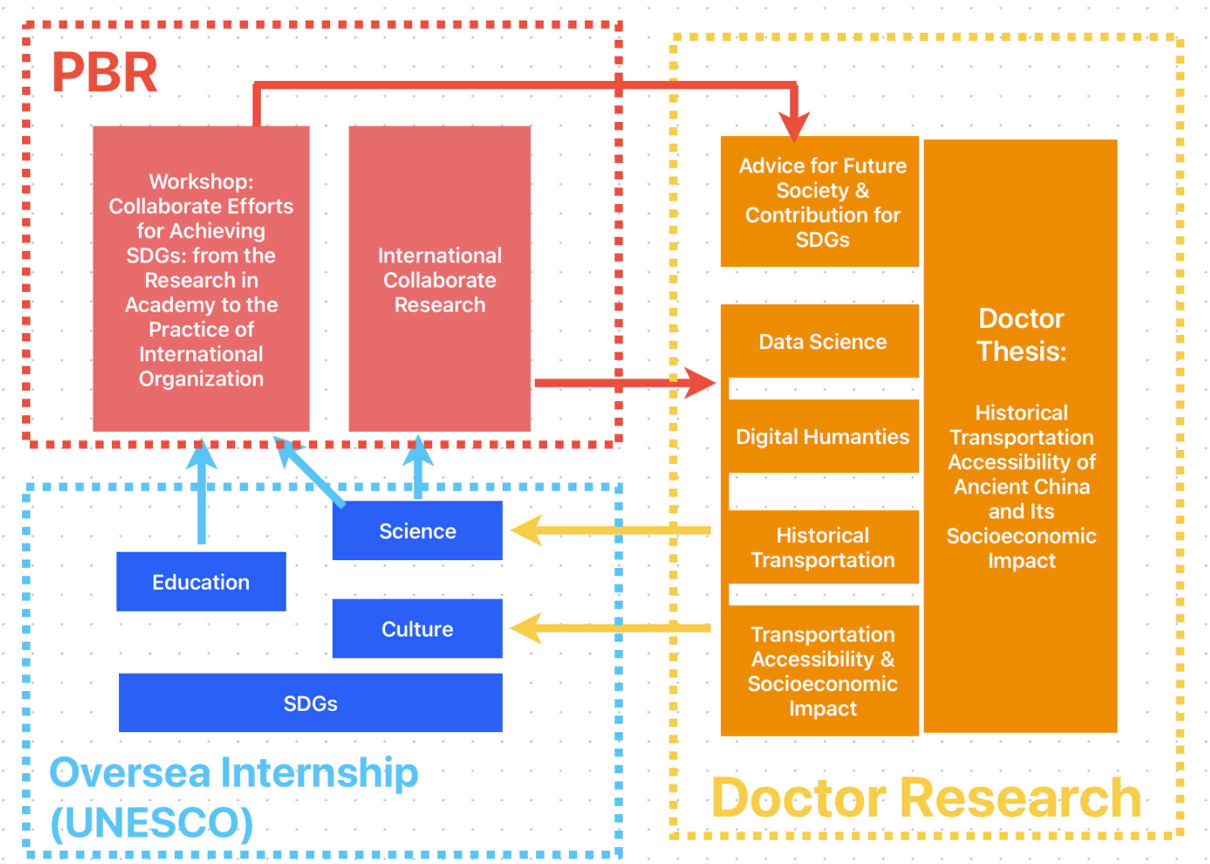

Figure 19. The Contributions of This Research to the Doctoral Dissertation

Here, I state the specific contributions:

1. Through an internship at the UNESCO Beijing Office, involvement in regional projects such as MAB,

IHP, EABRN, etc., in East Asia deepened my understanding of regional programs related to the SDGs. These experiences demonstrated how doctoral dissertation theoretical research can provide insight into future societal development and the achievement of SDGs.

2. In the seminar held at Kyoto University, "Collaboration towards the Achievement of SDGs: From Academic Research to Practice in International Institutions," connecting academic research with the practice of international institutions provided opportunities for students and researchers to gain a deeper understanding of UNESCO and its projects. This contributed to the formation of the theoretical framework for the doctoral dissertation.

3. In joint research with Taiwan's Academia Sinica, the Chinese Academy of Sciences' Institute of Geographic Sciences and Natural Resources Research, and the Medical Geography Research Laboratory of Central China Normal University, studies were conducted on the digitalization of Tang Dynasty transportation, the digitalization of ancient Chinese population distribution, and research on epidemics during the Sui and Tang dynasties. The results of these investigations were significant in elucidating the relationship between the socio-economic conditions and transportation accessibility of ancient China. Those joint research efforts-built part of the main data sources and methodologies for the doctoral dissertation, allowing for a detailed analysis of the historical transportation accessibility in ancient China and its socio-economic impact.

These activities significantly contributed to data source collection, theoretical framework construction, and research methodology selection for the doctoral dissertation. They are positioned as part of the main chapters of the doctoral dissertation, clearly indicating the flow and formation of conclusions of the research. These outcomes enhanced the overall quality and completeness of the doctoral research and were significant in deepening the overall understanding of the historical transportation accessibility of ancient China and its socio-economic impact.