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Spatiotemporal evolution of China's railway network in the 20th century: An accessibility approach

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ABSTRACT

The interrelatedness of transportation development and economic growth has been a constant theme of geographic inquiries, particularly in economic and transportation geography. This paper analyzes the expansion of China's railway network, the evolution of its spatial accessibility, and the impacts on economic growth and urban systems over a time span of about one century (1906–2000). First, major historical events and policies and their effects on railway development in China are reviewed and grouped into four major eras: preliminary construction, network skeleton, corridor building, and deep intensification. All four eras followed a path of "inland expansion." Second, spatial distribution of accessibility and its evolution are analyzed. The spatial structure of China's railway network is characterized by "concentric rings" with its major axis in North China and the most accessible city gradually migrating from Tianjin to Zhengzhou. Finally, the study indicates that railway network expansion has significantly improved economic development and heavily influenced the formation of urban systems in China.

1. Introduction

Railways are an important component of transportation systems, and have played a key role in economic and social development in many countries since the 19th century. Taking the papers published in this journal as an example, much of the literature on railways has focused on their economic sustainability in the era of rising competition from air and highway transportation. Among others, Rühl (1991) proposed a financial management mechanism to improve the competitiveness of European railways' international services against other transportation modes; Blum et al. (1992) discussed the opportunities and challenges for high-speed railways in Europe; and Bharill and Rangaraj (2008) reported the revenue management practice in India's railway system in comparison with other modes. More recent work concerns the optimal railway network design in terms of transportation cost and quality. For instance, Jeong et al. (2007) addressed a hub-and-spoke network problem for the European freight railway system, and Kreutzberger (2008) examined the influence of some network design approaches on the performance of intermodal rail transportation in Europe. However, very little is reported in recent literature on railway network expansion and its impacts on economic development and urban growth. In order to properly examine railway expansion and evolution in China, it is necessary to revive what was once a tradition in transportation geography – spatiotemporal analysis.

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The presence of railways has important implications for improving accessibility, nurturing development, and driving population agglomeration and urban growth at regional and national scales. Accessibility is a popular measure for assessing the overall spatial structure of a transportation network, and also for evaluating a place's available opportunities. The latter is strongly correlative with economic development. Hansen (1959) defined accessibility as "the potential of opportunities for interaction," and suggested a method to measure it in metropolitan areas. Garrison (1960) introduced the graph theory to calibrate topological accessibility. Morris et al. (1979) and Pirie (1981) used the accessibility measure in transportation planning. Since then, accessibility has been a central theme in transportation studies (e.g., Keeble et al., 1981; Murayama, 1994; Spence and Linneker, 1994; Pooler, 1995; Gutiérrez et al., 1996; Royle and Scott, 1996; Li and Shum, 2001; Sohn, 2006). The research conducted here has also been inspired by the seminal work proposed by Taaffe et al. (1963), which was originally developed to describe the evolution of transportation networks of Ghana and Nigeria, but has been applied by others to many countries.

Since the 1950s, long-distance transportation of both mass freight and passengers in China has relied heavily on railway. Table 1 summarizes passenger and freight traffic volumes of various transportation modes since 1950, showing the significant role railway has played. Railway development once was the single most important force in the formation of transportation hubs and economic belts, and the growth of urban systems in China (Gu, 1992). In 2007, the length of operating railways reached 77,966 km, exceeding India and trailing only the US and Russia. China's unique history offers us a rare opportunity to examine an extensive railway network developed over a relatively short time span, and how it impacted economic development from its infancy to the 21st century. Have China's distinctions with the West resulted in significant differences in railway development, or has China simply been following in their footsteps? Does Taaffe's model apply to China? How has railway development in China impelled the growth of its economy and urban systems? These are the questions we hope to answer in this paper.

2. Methodology

2.1. Overall network connectivity

The following indices are often used for evaluating the overall network connectivity (Black, 2003):

(1) The *beta index* is the average number of edges (e) per vertex (v), i.e., $\beta = e/v$.
(2) The *cyclomatic number* measures the number of circuits, i.e., gap between e and v while accounting for the number of subnets p ($p = 1$ for a fully-connected network), written as $\mu = e - v + p$.
(3) The *alpha index* is the ratio of actual to maximal number of circuits in a fully-connected planar (e.g., railway) network, i.e., $\alpha = (e - v + p)/(2v - 5p)$, and thus $0 \leqslant \alpha \leqslant 1$.
(4) The *gamma index* is the ratio of actual to maximal number of edges, i.e., $\gamma = e/[3(v - 2)]$, and also $0 \leqslant \gamma \leqslant 1$.

The greater the values of the above indices, the better a network is connected.

2.2. Distance matrix

The above indices β, μ, α and γ only consider the topological properties of a network and do not concern actual distances between nodes in a network, and thus are primarily used to describe the overall connectivity of a network. These indices may be suitable for a telecommunications (Wheeler and O'Kelly, 1999) or airport network (Ivy, 1995), where the major concern is

Table 1
Percentage of passenger and freight traffic volumes among various transportation modes, 1950–2007.

Year	Passenger					Freight				
	Rail	Road	Water	Air	Total	Rail	Road	Water	Air	Total
1950	77.0	11.3	11.7	0.0	100	46.3	41.2	12.5	0.0	100
1955	56.6	28.0	15.4	0.0	100	34.1	45.3	20.6	0.0	100
1960	57.9	30.5	11.6	0.0	100	39.4	41.5	19.1	0.0	100
1965	42.8	45.4	11.8	0.0	100	40.6	40.5	19.0	0.0	100
1970	40.3	47.5	12.1	0.0	100	45.3	37.8	16.9	0.0	100
1975	36.5	52.5	10.9	0.1	100	45.3	36.9	17.8	0.0	100
1980	27.0	65.2	7.7	0.1	100	20.8	71.3	8.0	0.0	100
1985	18.1	76.8	5.0	0.1	100	17.9	73.5	8.6	0.0	100
1990	12.4	83.9	3.5	0.2	100	15.8	75.8	8.4	0.0	100
1995	8.8	88.8	2.0	0.4	100	13.6	77.1	9.3	0.0	100
2000	6.9	91.2	1.3	0.5	100	13.3	77.6	9.1	0.0	100
2005	6.3	91.9	1.1	0.7	100	14.7	73.3	12.0	0.0	100
2007	6.1	92.1	1.0	0.8	100	14.1	73.3	12.6	0.0	100

Data sources: Year book of China Transportation and Communications, 1980–2008.

how various nodes are connected to each other. For most transportation networks such as railway, actual travel distances between nodes through a network need to be considered. Also, variation of accessibility across different places should be evaluated.

The distance matrix L compensates for the shortcomings of the above indices. Each element l_{ij} (in the ith row and jth column) in L is the distance through the shortest path between an origin i and a destination j, defined as:

$$L = [l_{ij}]_{n\times n} \quad (i = 1, 2 \ldots, n;\; j = 1, 2, \ldots, n) \tag{1}$$

Note that $l_{ij} = 0$ when $i = j$, and $l_{ij} = l_{ij}^0$ when there is a direct link between nodes i and j (where the superscript 0 indicates the number of intermediate steps between nodes i and j through actual railway edges). l_{ij} is infinite if there is an absence of direct or indirect links between i and j. In all other cases, the distance between nodes i and j (l_{ij}) is computed by following the shortest path through multiple connections in the railway network.

Based on the matrix L, the total transportation distance from node i is defined as the ith row sum, written as:

$$D_i = \sum_j l_{ij} \quad (j = 1, 2, \ldots, n) \tag{2}$$

D_i is the minimum travel distance between i and all other nodes in the network. The smaller the D_i value, the more convenient it is to reach other nodes. Therefore, D_i can be used as a measure of nodal accessibility at i.

The total transportation distance of the network, another measure of overall network connectivity, is the sum of all row sums:

$$D = \sum D_i \quad (i = 1, 2, \ldots, n) \tag{3}$$

2.3. Nodal accessibility coefficient

Nodal accessibility coefficient is defined as the ratio of D_i at node i to the network average across all nodes ($i = 1, 2, \ldots, n$), and thus reflects its relative accessibility, given by:

$$A_i = D_i \Big/ \left(\sum D_i / n\right) \quad (i = 1, 2 \ldots, n) \tag{4}$$

If $A_i > 1$, its accessibility is below the network average. If $A_i < 1$, its accessibility is above the network average. A smaller A_i corresponds to a better accessibility. The index A_i tends to favor the nodes near the geometric center of a network.

3. Overview of railway network expansion

We selected the top 330 cities in terms of GDP and urban population as initial candidates for railway network nodes (not including Hainan, Taiwan, Hong Kong, and Macao). Tibet was not connected to the railway network until the operation of Qinghai–Tibet Railway in 2006, and thus is not included either. Table 2 sums up the increase of nodes and edges over time. There were only 35 nodes (vertices) in the railway network in 1906. More nodes were added as the network expanded over time, reaching 276 of the 330 nodes in 2000. According to the graph theory, an edge is defined as a direct link between two nodes. China's railway network had 43 edges in 1906 and extended to contain 638 edges by 2000. Given the data available from the Chinese government, the following years were selected to assess the railway network: 1906, 1911, 1925, 1937, 1949, 1957, 1965, 1974, 1981, 1988, and 2000.

Table 3 summarizes the major historical events and polices and their impacts on railway development. Accordingly, we divide China's railway network expansion during the last century into four eras – *preliminary construction, network skeleton,*

Table 2
Railway network expansion and linking units in selected years.

Year	Nodes	Percentage (%)	Edges	Percentage (%)	Mileage of railway* (km)
1906	35	12.7	43	6.7	5962
1911	62	22.5	73	11.4	9292
1925	78	28.3	96	15.0	12,302
1937	119	43.1	196	30.7	21,761
1949	131	47.5	234	36.7	21,810
1957	148	53.6	254	39.8	26,708
1965	177	64.1	309	48.4	36,406
1974	203	73.6	366	57.4	45,093
1981	217	78.6	438	68.7	50,181
1988	226	81.9	467	73.2	52,767
2000	276	100	638	100	68,656

* *Data sources*: History of railway construction in China, China Railway Publishing House, 2003.

Table 3
Significant events and policies and their impacts on railway development in China.

Time	Events/policies	Impacts on railway development
Before 1911	Qing Dynasty	The first railway in China was built by the British in 1876; the first railway built by the Chinese government was in 1881
1937–45	Second Sino–Japanese War	New lines were mainly built in Northeast China (Manchuria) occupied by Japan to exploit natural resources in the region
1945–49	Civil War	Few new railways were built
1949	P. R. C. ("New China") founded	The central government emphasized national integration by expanding the railway system, and established planning standards for railway construction
1953–1957	1st "Five-Year Plan"	Major railroads were constructed in the northwest and the southwest
1964–1978	Third-Line Development	More railways were constructed in the northwest and southwest with mountainous terrain, areas considered safe havens from foreign invasion (i.e., "Third-Line Defense")
1966–76	Cultural Revolution	Railway development was slow, adding only 8500-km of new lines
1978	Beginning of economic reform and open door policy	Transportation investment focus moved to the coastal region in the east. Railway development shifted from constructing new lines to increasing capacities of existing lines in the north and east
Mid-1980s	Uneven regional development	Railway development focused on the expansion and electrification of existing lines in the coastal areas. Funding sources for railways became more diversified
After mid-1990s	Towards balanced development	Railway development focused on constructing new lines and upgrading old lines in the Western, Northeastern, and Central Regions in order to reduce regional inequality. The railway network moved towards the mature stage

corridor building, and *deep intensification*. The following discusses the overall spatial pattern and changes of the network connectivity in each era.

3.1. Preliminary construction (before 1911)

At this early stage, railway construction was the central issue of national debate on the modernization of China. Advocates of the new technology argued that railways would improve living standards, but opponents countered that railways would be more likely to impoverish people. With nearly continuous violence and warfare in the decades before 1911, China's railway construction developed slowly.

In 1876, the British built and managed the first railway in China between Shanghai and Wusong for 15 km. However, one year later, the government of the Qing Dynasty demolished it. In 1881, the government built the Tangshan–Xugezhuang Route by itself, over 50 years after the world's first railway in Great Britain in 1825. After 1881, China focused on building the basic framework and forming a unified railway network. In the subsequent 20 years, Beijing–Hankou, Harbin–Dalian, Harbin–Suifenhe, Qingdao–Jinan, Beijing–Shenyang, and Beijing–Shanghai routes were constructed. From 1906 to 1911, the indices β, α, and γ changed little (Table 4), and the number of nodes and edges increased proportionally (Table 2). By 1911, the railways had a total length of 9292 km, with most being north of the Yangtze River and concentrated around Beijing. At the same time, 62 cities were connected to the network including Beijing, Shanghai, Tianjin, Shenyang, Wuhan, and Qingdao, with 38 of them located in North China and Northeast China. However, the majority of cities were not connected to the railways.

3.2. Network skeleton (1911–1949)

The second stage of railway development mainly focused on extending the existing railways and forming regional networks. During that time, China suffered from colonization and invasions by foreign powers and Civil War (also see Table 3).

Dr. Sun Yat-sen, widely regarded as the founding father of modern China, promoted railway construction starting in 1911. Afterwards, the railway network expanded comparatively fast until 1937, and achieved a total length of 21,761 km. Unfortunately, the second Sino–Japanese War broke out in 1937 and lasted for eight years. During this time new railway construction was mainly confined in the Northeastern Region occupied by Japan, and the purpose was to exploit natural resources in this region and beyond. Therefore, the length of railways in the northeast was close to 10,000 km in 1937, over 40% of the whole country and remained around that percentage until the early 1950s (Chen et al., 2007). Consequently, this stage is

Table 4
Accessibility indices of the railway network in China (1906–2000).

Index	Year										
	1906	1911	1925	1937	1949	1957	1965	1974	1981	1988	2000
β	1.23	1.18	1.23	1.65	1.79	1.72	1.75	1.80	2.02	2.07	2.31
μ	9	12	19	78	104	107	133	164	222	242	363
α	0.14	0.10	0.13	0.33	0.40	0.37	0.38	0.41	0.52	0.54	0.66
γ	0.43	0.41	0.42	0.56	0.60	0.58	0.59	0.61	0.68	0.69	0.78

characterized as the ‘‘Northeastern Region Period’’. As many existing railways were damaged and few new lines were built, the total length of railways in operation was only 21,810 km by 1949, almost no increase since 1937. The indices β, γ and α increased by 52%, 49% and 301%, respectively, from 1911 to 1949.

3.3. Corridor building (1950–early 1990s)

After the foundation of the People’s Republic of China in 1949, China’s economy stepped into the recovery period, and its railway development took significant strides forward.

In the earlier part of this period, the Chinese central government was the sole investor, owner, operator, and manager of the railway system, with a highly planned economy. In the first ‘‘Five-Year Plan’’ (1953–1957), the government emphasized expanding the transportation system to include coal, grain, and timber, and over 60% of the infrastructural investment (9.015 billion RMB) was used for railway construction. Railways soon became the most important transportation mode in China, with new lines concentrated in mining districts and forest areas. In the early 1960s, as China broke the diplomatic relationship with the Soviet Union and the US was engaged in the Vietnam War, the government made national security a priority in railway development. As a result, the major investment for transportation was focused in the mountainous west such as Sichuan, Guizhou, south of Shanxi, and west of Henan, Hubei, and Hunan Provinces, namely ‘‘Third-Line Development’’ areas. Meanwhile, the proportion of total railway length in the hinterland began to increase and continued until 1975 (Comtois, 1990). Afterwards, the Cultural Revolution (1966–1976) shifted economic development strategy, and only a few new lines such as Guiyang–Kunming, Chengdu–Kunming, Changsha–Kunming, and Beijing–Taiyuan were built.

Since the late 1970s, China has entered a new era of ‘‘Economic Reform and Open Door Policy.’’ In the mid-1980s, the central government implemented the strategy of developing the Eastern Coastal Region first and shifted the focus of railway development to stimulating economic development. In this transitional stage, several lines were constructed and upgraded. For example, the Hengyang–Guangzhou Stretch (part of the Beijing–Guangzhou Route) was rebuilt as a double track, and the Datong–Qinghuangdao Line was built and electrified. Meanwhile, the funding sources became more diversified to include local governments, loans from international organizations, and foreign capital. While the majority of joint funding came from local governments, several rail lines were partially funded by foreign capital in the 1980s. For example, the first joint-venture railway was the Sanshui–Maoming Route, co-funded by the Ministry of Railway, Guangdong Province and the Asian Development Bank, managed by the Guangzhou Railroad Bureau. In 2005, the joint funded railways in China only accounted for 1.13% of the total passenger-kilometers and 1.4% of the whole freight ton-kilometers. The economic restructuring resulted in quick economic growth, but also widened regional inequality.

Therefore, factors such as exploring resources, economic development and national security, played important roles in railway development in this stage. The railway network coverage gradually expanded towards the Southeastern Coastal Area, Southwestern and Northwestern Regions. The total length of railway reached 53,378 km in 1990, with an increment of 770 km per year during 1950–1990, but the indices β, γ and α changed little in the corresponding time. By the early 1990s, China had formed a relatively integrated railway network, with two-thirds of cities connected by railway.

3.4. Deep intensification (since mid-1990s)

After the mid-1990s, China mainly focused on strengthening railway corridors and expanding the network, referred to as the ‘‘corridor-building stage.’’ In order to reduce regional disparity, the central government adopted a balanced development strategy, and shifted its investment focus from the Eastern Region to the less-developed Western, Northeastern and Central Regions accordingly. The network expansion continued on a fast pace with over 1500 km of new lines constructed each year. The Beijing–Jiujiang, Lanzhou–Urumchi, Baoji–Zhongwei and Houma–Yueshan stretches appeared in this period. Meanwhile, fast economic development resulted in transportation demands over its capacity. The central government emphasized upgrading old rail lines along with building new rail lines. In the Eastern Region, three key transportation corridors were formed, Beijing–Guangzhou, Beijing–Shanghai, and Beijing–Shenyang, thus the railways there entered a new era and the railway hierarchical system in China began to take shape. This period also marked the highest return on transportation investment, as every 1.25% of GDP growth corresponded with 1% increase in transportation investment (Jin et al., 2005).

4. Spatial patterns of railway accessibility

The railway network expansion has significantly improved the accessibility of cities in China. By the end of 2000, 83.6% of all major cities (330 in total) were connected to the railway network, and the number of edges rose to 638. The β index rose from 1.23 in 1906 to 2.31 in 2000 with an increase of 88%, and the μ index increased from 9 to 363 accordingly (Table 4). Finally, China’s railway network developed into a grid network, and ensured an effective integration with the national economy.

4.1. Expansion and optimization of the railway network

The railway network in China was not only extended but also became better connected over time. On one hand, the total length of the railway network D (or $\sum D_i$) according to the Eq. (3) increased from 1.32×10^6 km in 1906 to 1.45×10^8 km in

2000, as more nodes were connected. On the other hand, the D value among the same nodes decreased gradually. For example, the sum of transportation distance among the 62 nodes in 1911 was 4.82×10^6 km, and then declined to 4.00×10^6 km in 2000, a reduction of 0.82×10^6 km or 17%. The reasons are more alternatives and shorter routes became available for traveling from one node to another in the network, which is commonly referred to as the "Temporal-Spatial Convergence" phenomenon.

The most significant increase of railway lengths occurred in the periods of 1925–1937, 1957–1974 and 1988–2000, when the number of new nodes increased noticeably. During 1965–1981, the largest drop in D among the same nodes occurred with a 5.13% decline. The change was minimal during 1981–1988 and became noteworthy again with a 2.75% drop during 1988–2000.

4.2. Spatial structure of accessibility

Based on Eq. (4), the nodal accessibility coefficient A_i is computed in this study. The index A_i reflects a node's accessibility relative to the others. Figs. 1a–1d show the contours of nodal accessibility coefficients of China's railway network in 1911, 1949, 1965 and 2000, respectively. The findings are summarized as follows.

(1) The area coverage of the railway network consistently expanded over time. As shown by the contours from 1906 to 2000, the railway network stretched along the direction of Northeast China → East China → South China → Southwest China → Northwest China. Also, the contour lines of accessibility coefficient became smoother gradually, and thus formed a more compact network. The number of provincial units (including provinces, municipalities under the central government and autonomous regions) covered by railways increased from 9 to 29.
(2) Accessibility improvement spread to more areas. Areas with accessibility above the national average increasingly expanded from North China to East China and South China. In 1906, only Beijing, Tianjin, Hebei, and parts of Liaoning, Inner Mongolia and Henan, had accessibility over the average. In 1949, Shandong, Jiangsu, Anhui, Hubei and Shanxi Provinces joined the list and in 2000, Guangxi, Sichuan and Gansu Provinces also joined.
(3) Accessibility contours showed a concentric pattern around North China. Zhengzhou, the capital city of Henan Province, located almost in the geometric center of China's railway network, has been the top ranked city in accessibility since 1957. Interestingly, Zhengzhou was also the geometric center of China's urban systems (Ye et al., 2001). In 2000, there was a major gap between Eastern and Western Regions in railway accessibility. Most places in the Eastern Region had accessibility above the average, but conversely the Western Region was mostly below it, except for Sichuan, Gansu and Shanxi Provinces. Lhasa is the latest capital city connected to the railway network with the operation of Qinghai–Tibet Route in 2006.

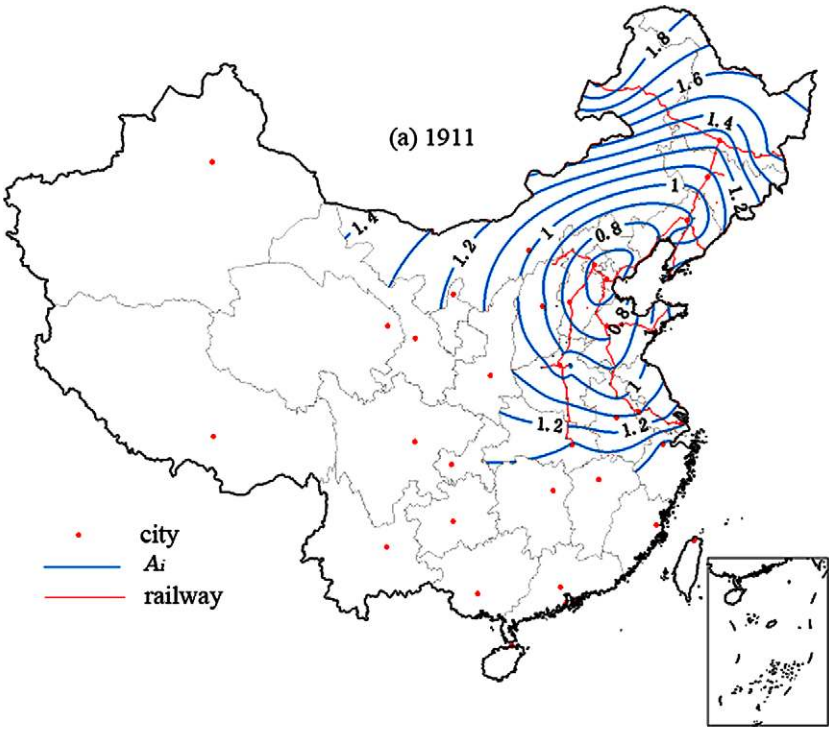

Fig. 1a. The accessibility coefficient of railway network in China, 1911.

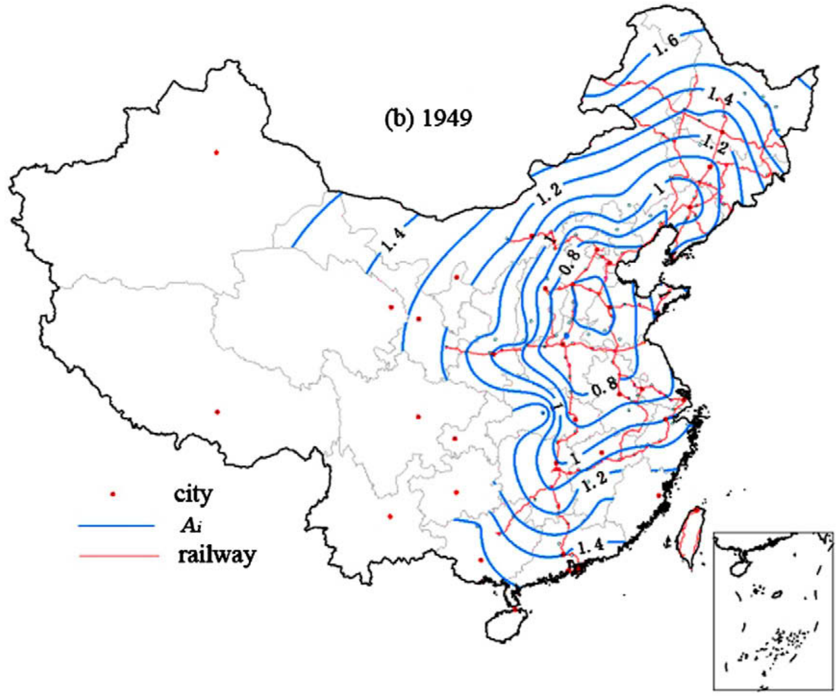

Fig. 1b. The accessibility coefficient of railway network in China, 1949.

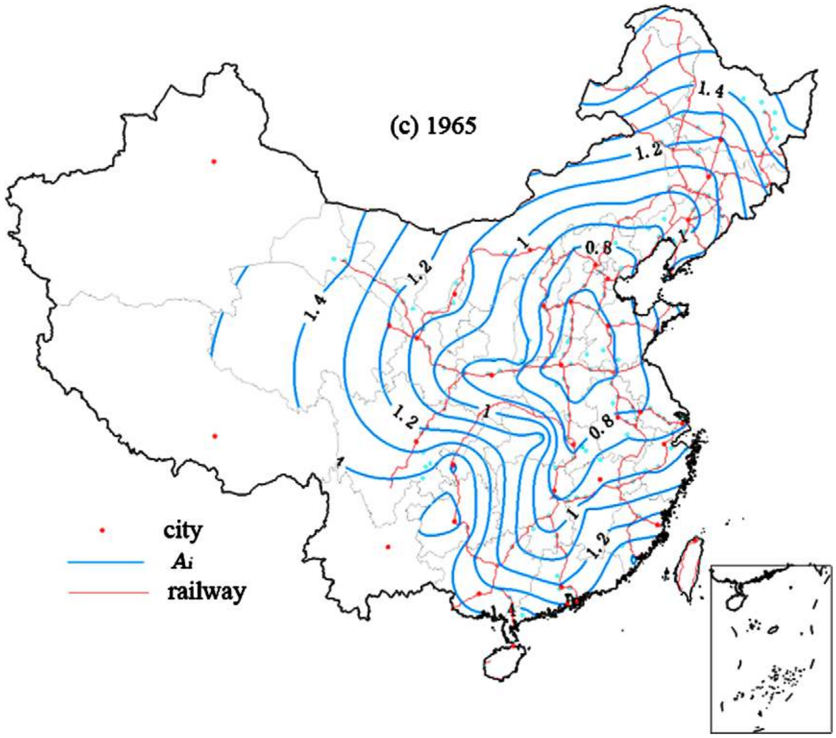

Fig. 1c. The accessibility coefficient of railway network in China, 1965.

(4) Since the early stages of Economic Reform in the mid-1980s, China emphasized the development of the Eastern Region, leading to considerable regional disparity. With the railway investment focus shifting from north to south, the node with the best accessibility gradually migrated from Tianjin to Zhengzhou. In 1906, Tianjin's accessibility coefficient ranked at the top with $A_i = 0.75$. In 1937, Xinxiang in Henan Province and Jining in Shandong Province had the

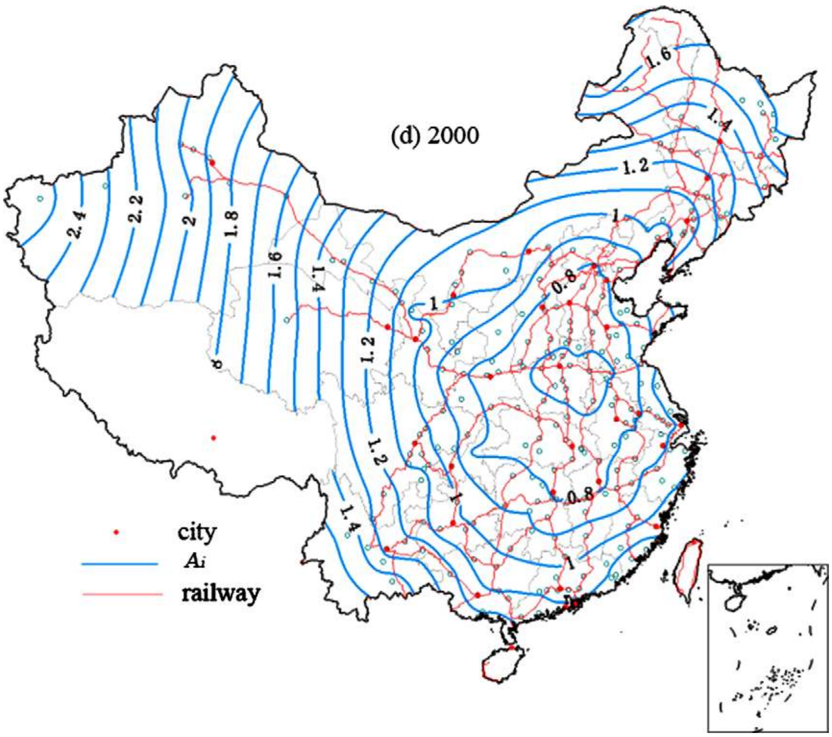

Fig. 1d. The accessibility coefficient of railway network in China, 2000.

best (lowest) accessibility coefficient with $A_i = 0.70$. In 1949, Dezhou and Tai'an in Shandong Province and Shijiazhuang in Hebei Province shared the best value with $A_i = 0.69$. Zhengzhou became the most easily accessible city with $A_i = 0.66$ in 1957 and kept the status ever since. Therefore, the A_i of the easiest accessible node declined slightly, which means the aggregation of the railway network was increasing. Meanwhile, areas with accessibility above the average were still in the Northern Region, but moved clearly towards the Central Region.

(5) After the 1970s, areas with greater improvement in accessibility shifted gradually from the Central Region to the Eastern Region. Figs. 2a and 2b show that the percentage of transportation distance declined across various nodes in the past few decades. During 1974–1981, the areas located in the Central Region extending towards the Southwestern Region, where the "Third-Line Development" was concentrated, and transportation distances among the nodes (excluding newly connected nodes) in Hubei, Hunan, and Guizhou Provinces were shortened remarkably. During 1981–2000, the areas transferred towards the Southeastern Region (Fig. 2b). In the latter case, when the Beijing–Jiujiang Line became operational in 1996, the accessibility for cities along this line was greatly improved, with a decline of transportation distances to each other by over 10%.

5. Impacts on economic development and urban systems

5.1. Parallel development between railway and economy

Over the past 100 years, China's railway network expanded bit by bit, and the process paralleled closely with economic development in spatial patterns. In the first half of the 20th century, railway development may be described as "the Northern-Northeastern period" to reflect its relatively fast expansion in these areas. During that time, China built 35 major railway lines, with 22 of them located in North China and Northeast China, accounting for 70% of the total length. Since the 1911 Revolution War, railways in North China and Northeast China already formed a primitive network, and then developed into an integral network step by step in the following 30 years. Railways provided much needed infrastructure and helped to exploit natural resources, cultivate major heavy industries, and impel economic development in these areas (Li, 1990). For example, economic agglomeration began to occur around the center of Liaoning Province, the Beijing–Tianjin–Tangshan area, the Shangdong Peninsula, etc. All of these revealed the interaction between railway network expansion and economic development. In the second half of the 20th century, the railway network steadily extended to the Southeastern, Southwestern, and Northwestern Regions to shift economic center toward south, confirmed by the two areas with the fastest economic growth: the Yangtze River Delta around Shanghai and the Pearl River Delta around Guangzhou.

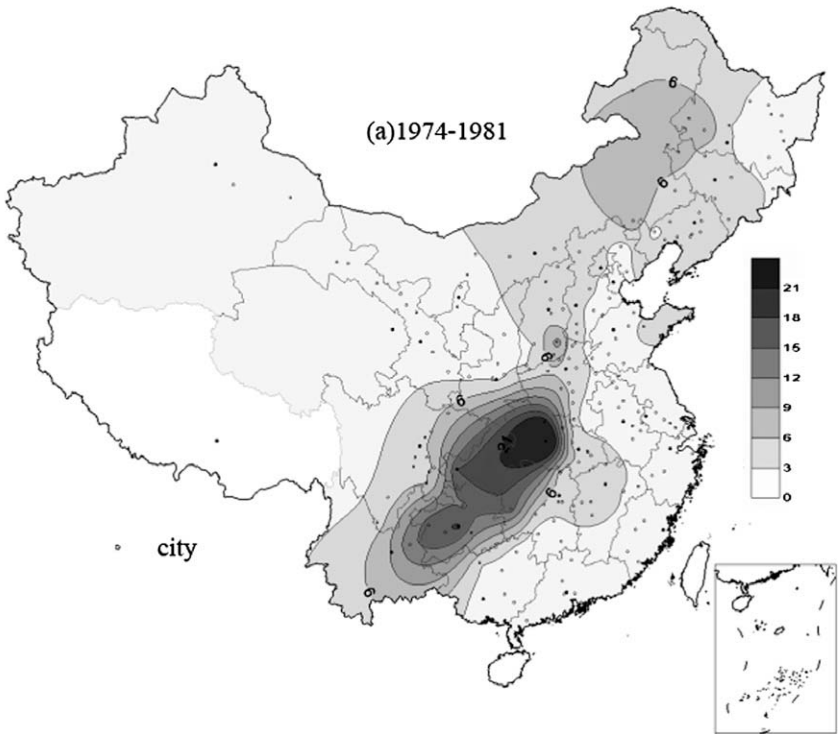

Fig. 2a. The change of railway network accessibility in China, 1974–1981.

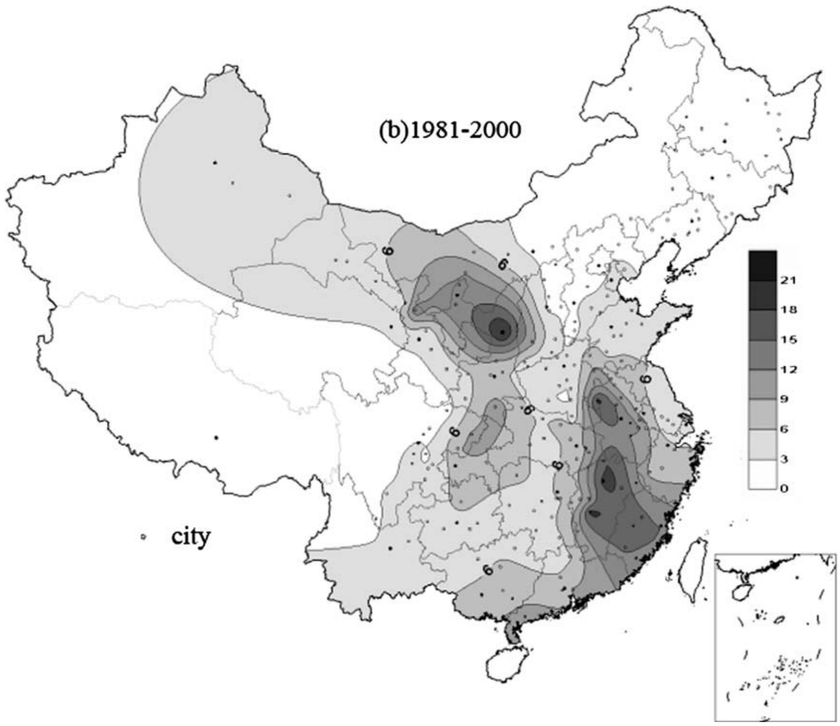

Fig. 2b. The change of railway network accessibility in China, 1981–2000.

5.2. Economic belts along railways

As railway transportation gained an important role in China during the last century, economic belts along railways replaced economic agglomerations along rivers or canals. Double-track railways have become major arteries in the transportation system, and have formed the axes for urban growth and economic development. Table 5 summarizes the number of cities in various categories and related economic indices along the key railway corridors. In 2000, there were 163 cities along the railway corridors, with 28 of them having nonagricultural population over 1 million and 13 of them with over 2 million. These corridors generated a GDP of 2269.5 billion RMB in 2000, taking 25.36% of the entire country, with the Beijing–Shanghai and Beijing–Guangzhou corridors among the most important contributors. Also, these corridors form the economic backbones of China, and all major economic centers are the pivotal nodes in the railway network.

5.3. Railway construction and growth of cities

Although China's railway development in the last century was not a smooth process, its contribution to the growth of cities was evident. Figs. 3a–3d illustrate the interaction between railway network expansion and the growth of cities with a non-agriculture population over 100,000 from 1936 to 2000. Among the top 20 cities in 1950, there were six near major rivers, four on the eastern coastline and 16 near railways (allowing overlapping categories) (Zhou, 1995). The large percentage of major cities near railways demonstrates the importance of railways in urban development at the onset of "new" China. By the end of 2000, all the top 20 cities in China were connected to the railway network, indicating an increasing role and prevalence of railways. There were two reasons for the increase of cities in the network. First, new rail lines were built to connect major cities. Second, the presence of new railways benefited the growth of many cities. For example, the quick rises of Zhengzhou, Lanzhou, Taiyuan and Zibo (i.e., four new cities on the top 20 list) were mostly attributed to their important roles in an expanded railway network. In particular, railway construction directly resulted in the emergence of some cities,

Table 5
Basic facts of key railway transportation corridors in China, 2000.

Transportation corridor	I_1	I_2	I_3	I_4	I_5	I_6	I_7	I_8
Longhai–Lanxin	37	8	4	13	6	5	273.84	3.06
Beijing–Guangzhou	41	13	6	19	8	2	846.82	9.47
Beijing–Shanghai	29	13	5	14	8	2	1144.09	12.80
Harbin–Dalian	17	7	3	6	5	5	344.88	3.86
Jinan–Qingdao	10	4	1	3	3	1	199.63	2.23
Zhegan–Xiangqian	28	5	3	13	7	2	198.86	2.22
Chengdu–Chongqing	7	2	2	2	3	2	155.14	1.74

Note: I_1, number of cities. I_2, number of cities with population over 500,000. I_3, number of provincial capitals and the municipalities directly under the central government. I_4, number of municipalities. I_5, number of National Hi-tech Development Zones, I_6, number of National Economical and Technological development Zones. I_7, GDP/billion Yuan, in 2000, I_8, proportion of the whole country (%).
Data sources: China Statistical Year book, 2001.

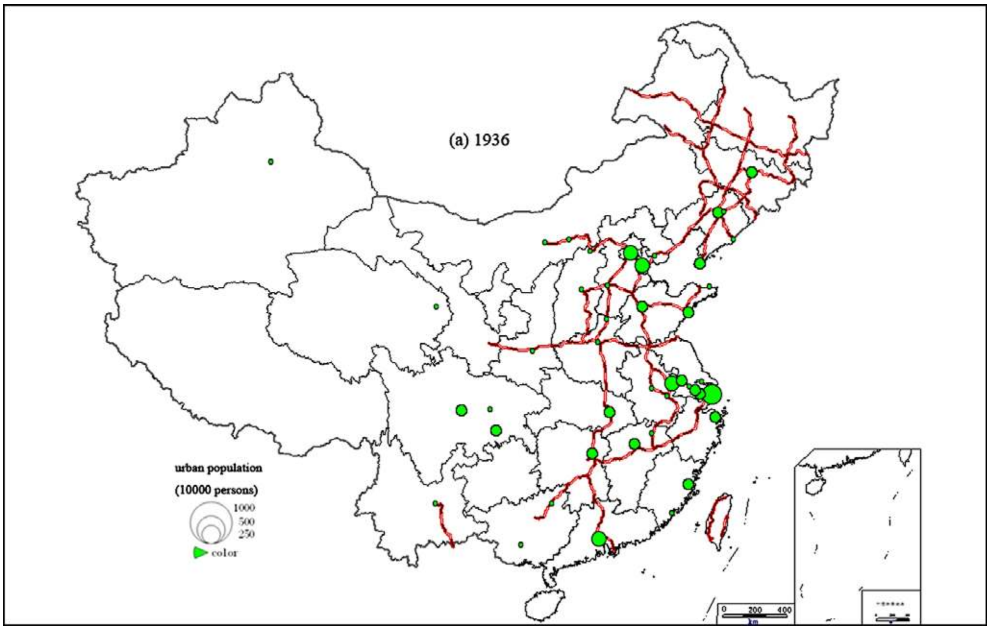

Fig. 3a. Development of railway network and growth of cities in China, 1936.

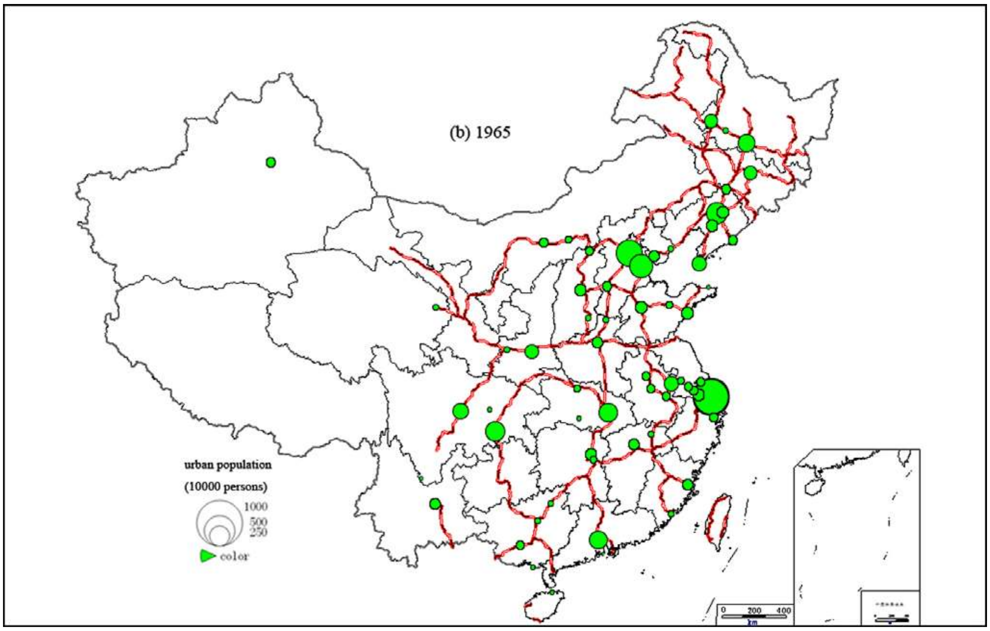

Fig. 3b. Development of railway network and growth of cities in China, 1965.

such as Shijiazhuang in Hebei, Zhuzhou in Hunan, Yingtan in Fujian etc. Therefore, urban growth in China has been strongly related to the railway network development.

6. Summary

6.1. Slow expansion

The total length of railways in China was only 467 km in 1895, reached up to 68,656 km by 2000, and made great progress in the last century, but the growth rate was slow. In the 55 years from 1894 to 1949, China only constructed 389 km of railways per year. From 1950 to 2000 under the People's Republic of China, that number was more than doubled to 936 km per year. However, the growth was not as high as some other countries' during the years of their most rapid development. For example, the US averaged 4000 km per year from 1850 to 1890, more than four times the rate of China's contemporary development.

6.2. Maturing network structure

In 2000, the indices α and γ attained 0.66 and 0.78, respectively, implying that the railway network was approaching a mature stage. In the last century, railway development expanded gradually from the Northern and Northeastern to other regions. The network center had shifted from Tianjin to Zhengzhou by 1957 and has stayed there ever since. Also, the improvement of accessibility for most cities has helped to pave the way for economic growth in those areas. Thus, the spatial hierarchy of the railway network in this maturing stage closely reflects what is characterized as the final stage in Taaffe's model.

6.3. Inland expansion pattern

Taaffe et al. (1963) developed a model to illustrate the evolution of transportation networks and economic development, particularly in developing and colonial countries. The model emphasizes coastal ports as beginning points of a network that gradually expands inland. Based on our analysis, China followed this evolution model in some ways, but also showed three unique characteristics. (1) At the initial stage, connecting the administrative center and its surrounding areas was a priority rivaling the need of linking ports and their hinterlands. The former was probably stronger than the latter as the central government stressed communication between Beijing and the rest of the country. Furthermore, this strategy did not change until the late 20th century when the export-oriented economy and port city development gained more attention. (2) An important deviation from Taaffe's model is that many inland cities developed prior to port cities in China, reflecting the strong political influence on railway construction. (3) China's railway network expansion followed the strategy of connecting inland cities with political and economic centers. Most railways did not stretch from port cities toward the hinterland, but

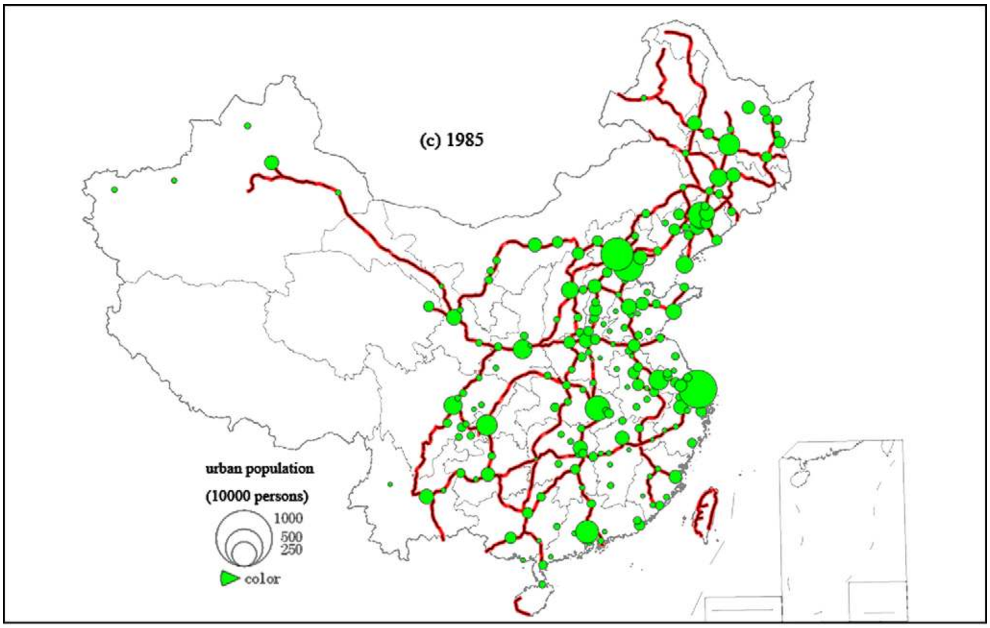

Fig. 3c. Development of railway network and growth of cities in China, 1985.

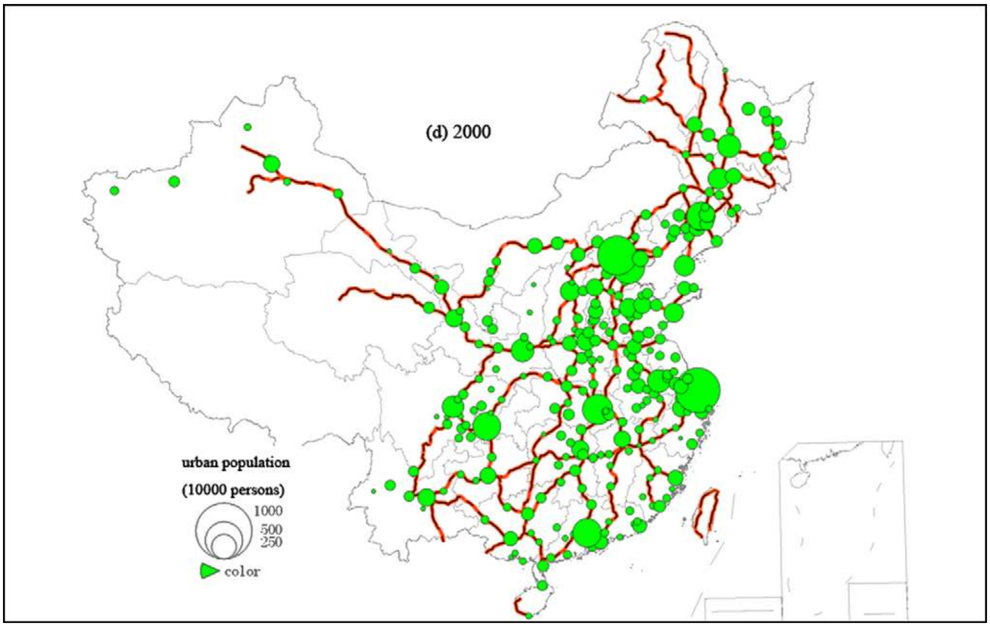

Fig. 3d. Development of railway network and growth of cities in China, 2000.

rather from the hinterland toward port cities. Therefore, we summarize the evolution of China's railway network and its impacts on economic development and urban systems as a four-stage model (Fig. 4), which may be termed as the "Inland Expansion Model" in contrast to Taaffe's "Port Penetration Model."

6.4. Correlation with economic and urban development

Railway construction profoundly affected economic development and urban growth in China, as evidenced by their spatiotemporal couplings. All major economic corridors and urban systems were formed with close relation to railway development. The areas along major railways (e.g., Beijing–Guangzhou, Beijing–Harbin, Beijing–Shanghai and

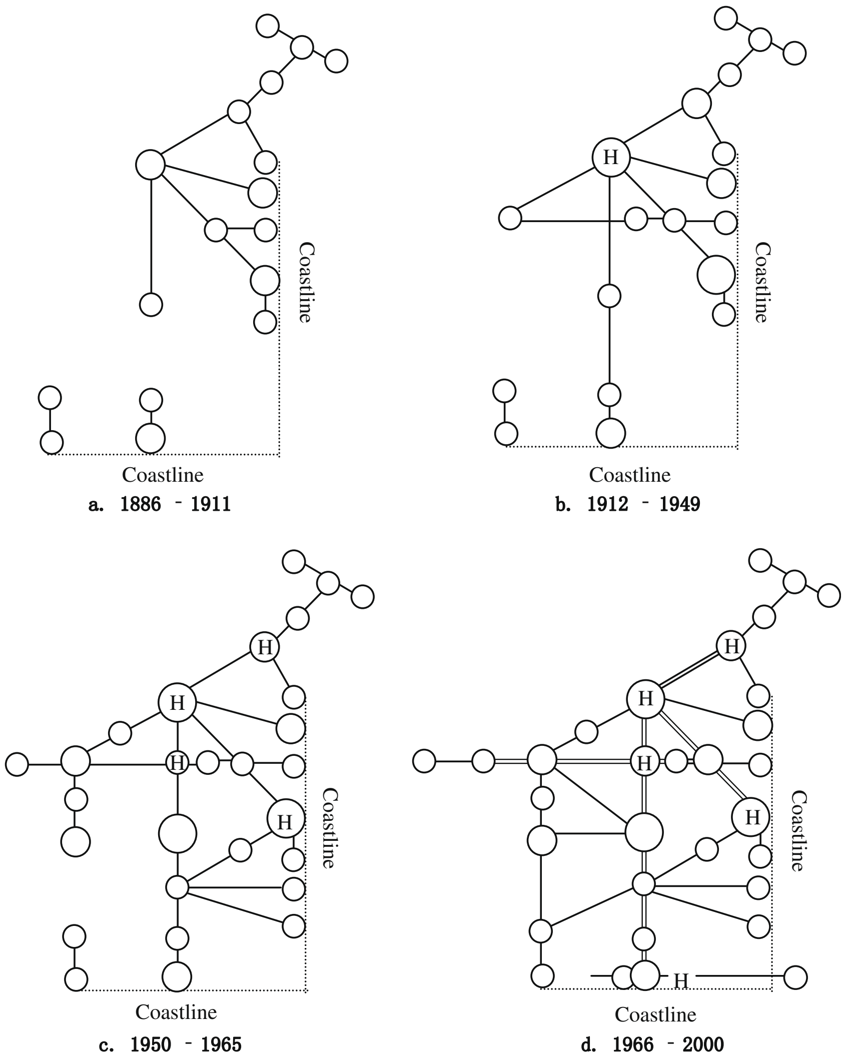

Fig. 4. Spatial patterns of railway network expansion in China, 1886–2000 (H for Hub).

Lianyungang–Lanzhou Routes) were the best served by the railway system in terms of service capacity, quality, and time efficiency. These areas will undoubtedly remain the major economic belts, urban agglomerations, and metropolitan areas of China in the foreseeable future.

6.5. Uneven railway distribution shaped by central government policies

Since the communist takeover in 1949 and ensuing implementation of a planned economy, the central government's policies have been by far the most influential factor in shaping the uneven spatial distribution of China's railways. The central government changed the focus of its regional development several times, leading to unequal investment spatially in railway construction. For example, in the post-reform era after 1978, development policies favored the Eastern Region because of its advantage location and advanced industrial base. Meanwhile, the rapid economic growth there generated revenues needed for improving its transportation system, which in turn supported further economic development and reinforced regional inequalities. Therefore, the Eastern Region's economic development significantly outpaced the Central and Western Regions. Since the mid-1990s, the shift in national development strategies towards the Western, Northeastern, and Central Regions has provided an opportunity for balanced development.

6.6. New challenges

After three decades of rapid economic growth, both freight and passenger traffic volumes increased significantly and reached or exceeded the designed capacity of the railway network. The relative importance of rail travel has declined over time. Specifically, the percentage of railway passengers among all transportation modes in China declined from 77% in 1950 to 6.1% in 2007, whereas the percentage of road and air passengers increased from 11.3% to 92.1%, and 0.005% to 0.83%, respectively (Table 1). The railway administration is more centralized and strictly controlled by the state than other transportation systems, and faces increasing pressure from market-oriented reforms and decentralization. High-speed railway development and railway deregulation have been proposed as possible remedies to improve its competitiveness. Given the advantages in energy efficiency and environmental impact, railways should receive favorable governmental attention over air and highway transportation.

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