Analysis of Railway Accessibility and Spatial Interaction Pattern Changes in Northwest China in the Context of High-Speed Railway: Postprint

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Abstract

Northwest China serves as a crucial domestic and international junction in the construction of the Silk Road Economic Belt. By considering the heterogeneity of railway traffic flows among cities, this study takes major cities in northwestern prefecture-level cities as research units, uses the opening times of important high-speed rail lines as cross-sections, and selects 2011, 2015, and 2019 as time nodes to analyze railway accessibility and urban spatial interactions using train frequency-based accessibility measurement methods and the standard gravity model, employing indicators such as train frequency-weighted average travel time, total economic linkage, and economic linkage intensity. The results indicate: (1) Railway accessibility and inter-city economic linkage intensity have improved significantly overall, with more pronounced enhancements along high-speed rail lines, largely influenced by train frequency. (2) The region' s railway accessibility exhibits significant east-west gradient differences overall, gradually decreasing toward the northwest. At the provincial (autonomous region) level, local patterns display a circle-layer structure centered on provincial capitals and sub-centered on railway hub cities. (3) The region' s spatial interaction has transformed from the traditional "polar-core" pattern to a "point-axis" pattern with hub cities as nodes and main railway lines such as the Longhai, Baolan, and Lanxin lines as axes extending longitudinally, initially forming a certain "network" pattern. Within each province (autonomous region), the gradient structure of total economic linkage is evident in the "regional central city —peripheral city—marginal city" hierarchy. Based on an in-depth analysis of the regional accessibility and economic linkage distribution patterns, it is recommended that railway construction be further strengthened, particularly by expanding railway network coverage in marginal areas, coordinating east-west gradient development, and that cities not along high-speed rail lines should enhance transportation connectivity with cities along the lines to actively integrate into the high-speed rail network.

Full Text

Analysis of Railway Accessibility and Spatial Interaction Pattern Changes in Northwest China in the Context of High-Speed Rail

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Abstract

Northwest China is an important juncture connecting domestic and international segments of the Silk Road Economic Belt. Considering the heterogeneity of railway traffic flow across cities, this study takes major cities in northwestern prefectures as research units, uses the opening times of important high-speed rail lines as cross-sections, and employs 2011, 2015, and 2019 as time nodes. Using train frequency-based accessibility measurement methods and the standard gravity model, with indicators such as frequency-weighted average travel time, total economic linkages, and economic linkage intensity, we analyze railway accessibility and urban spatial interactions. The results indicate: (1) Railway accessibility and intercity economic linkage intensity have improved significantly overall, with more pronounced improvements along high-speed rail lines, strongly influenced by train frequency. (2) Regional railway accessibility exhibits a distinct east-west gradient, gradually decreasing toward the northwest. Within each province (autonomous region), a circular structure is evident, centered on provincial capitals with railway hub cities as sub-centers. (3) The region' s spatial interaction has shifted from the traditional "polar-core" pattern to a "point-axis" pattern, with hub cities as nodes and main railway lines such as the Longhai, Baoji-Lanzhou, and Lanzhou-Xinjiang lines as longitudinal axes, initially forming a certain "network" pattern. Within provinces (autonomous regions), the "regional central city-peripheral city-marginal city" economic linkage gradient structure is pronounced. Based on this in-depth analysis of regional accessibility and economic linkage distribution patterns, we recommend further strengthening railway construction, particularly expanding railway network coverage in marginal areas, coordinating east-west gradient development, and requiring non-high-speed rail cities to enhance transportation connections with cities along high-speed lines to actively integrate into the high-speed rail network.

Keywords: high-speed railway; railway accessibility; spatial interaction; northwest China

Introduction

As the backbone of the transportation network, rail transit—especially high-speed railway—enhances the accessibility of cities along its routes with its rapid and convenient spatiotemporal connectivity, significantly influencing regional

economic spatial distribution patterns. However, traditional accessibility measurement methods fail to consider differences in urban railway traffic volume, making it difficult to accurately reflect accessibility levels. In studying the spillover effects of accessibility on regional economic and social development, Ye Yanxia [citation] found significant positive correlations with tertiary industry output value and tourism revenue. In recent years, scholars have conducted research at macro scales and micro scales such as within cities [citation] on the close synergistic relationship between accessibility and economic linkage intensity, covering topics including economic linkage structure evolution [citation], accessibility and economic linkage patterns [citation], and urban spatial interaction [citation]. In terms of accessibility research methods, traditional models based on spatial and temporal distances are primarily used. Spatial distance ignores factors such as road grade and vehicle speed, while temporal distance-based weighted average travel time is currently widely applied in land accessibility measurement. Qin Chenglin et al. [citation], when analyzing the impact of China' s railway transportation development on economic growth convergence in cities along railways, argued that traditional accessibility measurement methods fail to account for urban railway traffic volume differences. Zhou Qian et al. [citation], when studying the spatial coupling coordination between road network accessibility and economic development level distribution in the Changsha-Zhuzhou-Xiangtan urban agglomeration, found that the transportation system significantly influences their coordinated development. Additionally, Yan Huili et al. [citation], when studying the impact of China' s "Four Vertical and Four Horizontal" high-speed rail network on accessibility and economic linkages of cities along the lines, similarly verified that accessibility changes brought by high-speed rail opening can significantly improve economic linkages among station cities. In terms of research regions, some scholars have conducted in-depth studies on transportation networks and economic linkages in western regions, though such research remains limited. For example, Xiao Rui et al. [citation] used models such as weighted average travel time, isochrone maps, economic potential, and spatial variogram functions to comprehensively analyze the spatiotemporal convergence effects and economic potential characteristic changes in counties along the Lanzhou-Xinjiang high-speed railway before and after its operation. Gao Yuxiang et al. [citation], based on road network data in Ningxia, studied the spatial characteristics of the regional road network through an improved network analysis method with impedance settings.

By the end of 2014, the Lanzhou-Xinjiang high-speed railway was officially opened, marking the true arrival of the high-speed rail era in Northwest China. Subsequently, the Zhongchuan intercity railway, Baoji-Lanzhou passenger dedicated line, Xi' an-Chengdu passenger dedicated line, and the Yinchuan-Lanzhou passenger dedicated line (Yinchuan-Zhongwei section) were opened to traffic, further increasing the density of the high-speed rail network in Northwest China. Therefore, this study, based on traditional accessibility metrics and drawing on the research of scholars such as Tang Enbin et al. [citation], considers the heterogeneity of railway traffic volume across cities, incorporates station scale factors,

and uses changes in train frequency as a quantitative reference indicator to analyze railway accessibility and spatial interaction patterns in Northwest China against the backdrop of high-speed rail, aiming to provide references for optimizing transportation network structure and layout.

1. Methodology

1.1 Railway Accessibility Models

1.1.1 Railway Weighted Average Travel Time Accessibility is closely related to urban geographic location, economic development level, and city size. This study selects railway weighted average travel time, which assigns economic weights to shortest travel times to strengthen the connection between economic development and accessibility, providing a more objective reflection of urban accessibility levels. A larger value indicates lower accessibility [7,14-15].

The formula is:

$$M_i = \frac{\sum_{j=1}^{n} T_{ij} \times P_j}{\sum_{j=1}^{n} P_j}$$

where M_i is the railway weighted average travel time for city i (minutes); n is the number of nodes in the network; P_j is the city mass of city j, reflecting its economic radiation capacity and attractiveness, constructed using GDP and permanent population ($P_j = \mathrm{GDP}_j \times \mathrm{POP}_j$); and T_{ij} is the shortest railway travel time between city i and city j (minutes).

1.1.2 Spatial Economic Structure Model (1) Gravity Model

This study applies the gravity model to calculate economic linkage intensity between cities to characterize intercity interactions. It reflects both the radiation capacity of economic centers on surrounding areas and the surrounding areas' ability to accept this radiation [citation].

The formula is:

$$L_{ij} = \frac{P_i \times P_j}{T_{ij}^2}$$

where L_{ij} is the economic linkage intensity between city i and city j; P_i and P_j are the city masses of city i and city j, respectively; and T_{ij} is the shortest railway travel time between city i and city j (minutes).

(2) Total Economic Linkages

The total external economic linkages of a city reflect the sum of its outward flows. This study calculates the total economic linkages L_i for city i to characterize its position in the regional economic network. A larger value indicates greater total external economic linkages and higher economic status.

The formula is:

$$L_i = \sum_{j=1}^{n} L_{ij}$$

where L_i is the total economic linkages of city i; n is the number of sample cities; and L_{ij} is the economic linkage intensity between city i and city j.

1.2 Data Sources

This study focuses on Gansu Province, Qinghai Province, Shaanxi Province, Xinjiang Uygur Autonomous Region, and Ningxia Hui Autonomous Region in Northwest China. Railway shortest travel times between major cities (prefectures, autonomous prefectures) and train frequencies at each station were obtained from the China Railway Timetable Software (2019 version) and Shengming Timetable Software. Permanent population and GDP data for each city were sourced from corresponding years' Statistical Yearbooks or Government Statistical Bulletins. The selected GDP and permanent population data are for municipal districts rather than entire cities. Train station frequency data are for stations within municipal districts. The study area is shown in [Figure 1: see original paper].

2. Railway Accessibility Analysis in Northwest China

Based on the improved accessibility model, we apply the formulas to measure the railway frequency-weighted average travel time N_i and its changes for major cities. To enhance comparability when comparing changes in railway accessibility and train frequency n_i, we list cities with train stations in all three time cross-sections (2011, 2015, 2019), as shown in . The symbols in the table correspond to those in the models, with Δ indicating change rates for each indicator.

2.1 Overall Railway Accessibility Pattern

The overall railway accessibility across the five northwestern provinces (autonomous regions) exhibits a clear east-west gradient, with each province (autonomous region) locally showing a "circle-layer"structure centered on provincial capitals and sub-centered on railway hub cities. Since entering the high-speed rail era, regional railway accessibility has continuously improved, though some cities experienced decreased accessibility during certain periods. Accessibility improvements are strongly correlated with train frequency. In 2011, the total train frequency in Northwest China increased from [original value] to [new value] with a growth rate of 146.56%, and the frequency-weighted average travel time decreased from 4579 $\text{min} \cdot \text{trip}^{-1}$ to 2475 $\text{min} \cdot \text{trip}^{-1}$, representing an accessibility improvement rate of 45.95%. By 2019, the regional frequency-weighted average travel time further decreased to 2475 $\text{min} \cdot \text{trip}^{-1}$, with an accessibility improvement rate of 78.88%.

2.2 Characteristics of Accessibility Changes

2.2.1 Significant East-West Gradient Differences The Guanzhong Plain urban agglomeration centered on Xi'an and the Lanzhou-Xining urban agglomeration with Lanzhou and Xining as dual cores demonstrate significant high-speed rail network effects, with railway accessibility becoming more balanced. Along the Hexi Corridor, areas west of Lanzhou show substantial gaps compared to the Guanzhong region in both network coverage and network functional structure. In 2011, the top 10 cities for railway accessibility were mostly located in central and eastern Shaanxi and eastern Gansu, while most cities in western border areas had lower accessibility. By 2019, the east-west gradient pattern remained largely unchanged, but some western cities along high-speed rail lines, such as Jiayuguan, Zhangye, and Urumqi, entered the top 10.

2.2.2 Limited Impact Range of High-Speed Railway with Strong Corridor Effects Before the Lanzhou-Xinjiang high-speed rail opened, overall railway accessibility values were relatively high. After its opening, all cities showed significant accessibility improvements, but clear differences existed among them. Due to the limited influence range of high-speed rail, while accessibility levels among cities along the line became more balanced, the gap between cities along and away from the line widened. Cities with small changes were mainly concentrated in western and southern Xinjiang and parts of Qinghai, risking further marginalization in the future. In 2015, the best accessibility was in Xi' an ($1.22\ \text{min} \cdot \text{trip}^{-1}$) and the worst in Hotan ($1010.85\ \text{min} \cdot \text{trip}^{-1}$). The improvement in accessibility shows clear transportation orientation, with the largest changes concentrated near high-speed rail lines. Cities along the Lanzhou-Xinjiang high-speed rail line achieved accessibility improvement rates above 68.20%, far exceeding the regional average.

2.2.3 Strong Correlation Between Accessibility Improvement and Train Frequency Increases Station scale is also an important factor affecting urban railway accessibility. Based on the measurement results of railway accessibility in Northwest China, accessibility changes show strong correlations with train frequency changes both overall and across time periods. Cities with top accessibility improvement rates also have top train frequency change rates, while most cities with decreased accessibility levels experienced negative train frequency growth. For example, Hanzhong, with the highest train frequency growth rate, increased from [original] to [new] $\text{trips} \cdot \text{day}^{-1}$, with a frequency growth rate of nearly 10 times and an accessibility improvement rate of 92.91%. Meanwhile, Jiuquan and Pingliang experienced train frequency decreases, but while Pingliang' s accessibility decreased by 20.72%, Jiuquan' s accessibility actually improved by 12.62%, indicating that urban railway accessibility is also related to city development scale and geographic location.

3. Spatial Interaction Analysis Based on Railway Accessibility

Using formulas to calculate intercity economic linkage intensity L_{ij} (expanded 10^6 times) and total economic linkages L_i, we rank the top 30 city pairs by economic linkage intensity, as shown in .

3.1 Overall Spatial Interaction Pattern Transformation

3.1.1 Transformation of Overall Spatial Interaction Pattern in Northwest China Changes in transportation conditions not only alter urban railway accessibility but also influence intercity interaction patterns. Around 2011, economic linkages among cities in Northwest China generally showed a "polar-core"pattern. With railway construction and economic development, the pattern gradually transformed to a "point-axis" model, with hub cities such as Lanzhou, Xi' an, Yinchuan, Xining, and Urumqi as nodes radiating to surrounding areas, and main railways like the Longhai, Lanzhou-Xinjiang lines as longitudinal axes. By the end of 2019, Northwest China had initially formed a certain "network" pattern. The total regional economic linkages increased by 171.33% from 2011 to 2019, with a growth rate of 40.33%. Marginal areas and contiguous autonomous prefectures have consistently weak accessibility and receive limited radiation from core cities, ranking low in economic potential.

3.1.2 Provincial (Autonomous Region) Spatial Interaction Analysis Gansu Province: Located in the center of Northwest China, Gansu has basically formed a "dumbbell-shaped" network skeleton centered on Lanzhou, with the Longhai and Lanzhou-Xinjiang lines as main axes and supported by lines such as the Xi' an-Pingliang and Ganzhou-Wuwei lines. Lanzhou, at the network center, ranks first in the province in total economic linkages due to its convenient accessibility. Before the Lanzhou-Xinjiang high-speed rail opened in 2011, eastern cities like Tianshui and Baiyin had greater total economic linkages than western cities. After the high-speed rail opening, Jiayuguan, Zhangye, and other cities along the line generally surpassed eastern cities in total economic linkages. In 2019, with the opening of the Baoji-Lanzhou passenger dedicated line and Zhongchuan intercity railway, cities along the line like Tianshui and Dingxi achieved total economic linkage improvement rates above 2.64 times. However, Longnan, Pingliang, and Gannan, which lack high-speed rail connections, remain ranked low in economic linkages.

Shaanxi Province: With a relatively dense high-speed rail network and the powerful economic radiation capacity of the megacity Xi' an, Shaanxi has built a "one core, multiple poles" comprehensive transportation system centered on Xi' an with nodes in Yulin, Yan' an, Ankang, Hanzhong, and Baoji. In 2011, Xi' an' s total economic linkages accounted for 45.44% of the regional total, with Xianyang and Weinan accounting for 25.65% and 15.96% respectively. Cities near Xi' an like Baoji, Xianyang, and Weinan benefit from strong central radia-

tion. Additionally, thanks to the Xi' an-Chengdu and Baoji-Lanzhou passenger dedicated lines, Baoji and Xianyang' s total economic linkages reached 157.99% and 120.86% of their 2011 levels, ranking among the top in the province.

Xinjiang Uygur Autonomous Region and Ningxia Hui Autonomous Region: These regions show a clear "regional central city-peripheral city-marginal city" gradient structure in total economic linkages. Provincial capitals and some railway hub cities, as important central nodes or high-speed rail intersections, have strong radiation capacity. In 2011, Urumqi and Yinchuan' s total economic linkages exceeded 10^6. Under the radiation of core areas, peripheral cities like Hami, Turpan, Wuzhong, and Zhongwei have also seen increasing economic linkages. However, due to typical east-west gradient differences, border areas have low accessibility, and even Urumqi, as a provincial capital, ranks low in total economic linkages, accounting for only 0.64% of the regional total.

3.2 Analysis of Economic Linkage Intensity and Direction

3.2.1 Analysis of Total Economic Linkages The overall intercity economic linkages in the region show a significant east-west gradient, with cities having larger economic totals concentrated along the Silk Road Economic Belt and in the Lanzhou-Xining and Guanzhong urban agglomerations, showing a "belt-shaped" distribution. Qinghai Province shows poor balance in internal economic linkages, with significant gradient differences between eastern and western areas. In 2011, Xining' s total economic linkages were [value]. By 2019, thanks to the Lanzhou-Xinjiang high-speed rail, Xining' s total economic linkages increased by nearly 10 times. Eastern Qinghai cities rank high in the province, while western areas with contiguous autonomous prefectures have low railway accessibility and limited economic radiation from core cities, remaining in disadvantaged positions.

3.2.2 Analysis of Economic Linkage Intensity Direction To further analyze intercity interaction patterns, we use ArcGIS software to map economic linkage intensity, showing only linkages above certain thresholds. In 2011, strong economic linkages were mainly within provinces (autonomous regions), with relatively weak cross-provincial linkages. The top linkages were Xi' an-Xianyang, Xi' an-Weinan, Xi' an-Baoji, Baoji-Xianyang, and Xianyang-Weinan. After the Lanzhou-Xinjiang high-speed rail opened in 2015, cross-provincial linkages significantly strengthened. Economic linkages no longer confined to intra-provincial cities but gradually spread to extra-provincial cities, showing "corridor-style" distribution. Linkages between high-speed rail cities like Xining-Haidong, Lanzhou-Xining, Jiayuguan-Jiayuguan, and Lanzhou-Haidong all increased substantially, with intensities above [threshold]. By 2019, this pattern further changed, with Xi' an-Lanzhou linkage intensity reaching [value], rising to 4th place. Xi' an-Tianshui, Tianshui-Baoji, Lanzhou-Tianshui, and Lanzhou-Dingxi benefited from the Zhongchuan intercity and Baoji-Lanzhou passenger dedicated lines, with their linkage intensities increasing significantly.

4. Conclusions and Discussion

In recent years, with the addition of high-speed railways in Northwest China and increased train frequency density, urban railway accessibility and spatial interaction patterns have shown clear overall characteristics and spatiotemporal differentiation.

(1) **Significant east-west "gradient" difference in railway accessibility.** Regional railway accessibility has improved markedly overall, but shows a clear east-west gradient. Along the Hexi Corridor, areas west of Lanzhou have substantial gaps compared to the Guanzhong region in both railway network coverage and functional structure. Within provinces (autonomous regions), areas with better railway accessibility are mainly concentrated in economically developed provincial capitals and their surroundings, forming a "core-subcore" circular structure based on distance decay principles.

(2) **Obvious "corridor" effect in high-speed rail impact range.** Cities along high-speed rail lines have better railway accessibility. In 2019, Urumqi and Zhangye along the line achieved accessibility improvement rates of 81.28% and 83.13% respectively, both exceeding the regional average. The operation of the Baoji-Lanzhou passenger dedicated line strengthened linkages between Lanzhou and cities like Tianshui, Dingxi, Xi' an, and Baoji, with some cities' accessibility improvement rates reaching 5 times. Marginal cities like Yushu, Gannan, and Guoluo that have not yet integrated into the high-speed rail network risk being marginalized, with a "core-periphery" pattern in railway accessibility becoming increasingly pronounced. Additionally, railway accessibility changes show strong correlation with train frequency.

(3) **Transformation of economic linkage pattern from "point-axis" to "network."** The spatial interaction pattern has generally shifted from the traditional "polar-core" model to a "point-axis" model, with central cities or high-speed rail intersection cities as nodes radiating to surrounding areas, and main railways like the Longhai, Lanzhou-Xinjiang, and Baoji-Lanzhou lines as longitudinal axes, initially forming a "network" pattern. Regional overall economic linkage intensity has grown increasingly stronger. The original intra-provincial linkage pattern has gradually changed, spreading to extra-provincial cities. Hami, Turpan, Karamay, and Shihezi have also become core cities with significantly increased external radiation, though clear variation differences exist within the region.

Given Northwest China' s typical east-west gradient differences, we recommend further strengthening railway construction, particularly expanding railway network coverage in marginal areas, coordinating east-west gradient development, and promoting balanced and integrated intercity development. Some non-high-speed rail cities that have been marginalized by high-speed rail need to strengthen transportation connections with cities along the lines and actively in-

tegrate into the high-speed rail network to leverage its convenience for improving their own railway accessibility levels and spatial interaction capacity. Additionally, since railway accessibility strongly correlates with train frequency, railway station scales and intercity train frequencies should be rationally planned and allocated according to different regional and urban conditions.

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Note: Figure translations are in progress. See original paper for figures.