Postprint: GIS-Based Study on Spatial Characteristics of Ningxia Road Network

Authors: Gao Yuxiang

Date: 2021-03-03T00:00:00+00:00

Abstract

As the only provincial-level Hui ethnic concentration area in China, the Ningxia Hui Autonomous Region constitutes a unique geographical-population-transportation unit and serves as a crucial node connecting North China and Northwest China. Based on Ningxia' s transportation network data, this study employs an impedance-modified network analysis method combined with cost-distance algorithms and GIS spatial analysis to calculate county (district) accessibility for 2011, 2017, and 2023, examines the spatial structural characteristics of the regional road network, and proposes policy recommendations for network development. The findings indicate that while Ningxia has established the main framework of its road network, development remains unbalanced, with superior construction in the northern region compared to the south; the average accessibility of counties (districts) decreased from 4.02 hours in 2011 to 3.75 hours in 2017, demonstrating rapid improvement in network accessibility and a significant spatiotemporal convergence effect; and the disparity in accessibility among counties (districts) has continuously diminished, with the equilibrium of the region' s road network spatial structure gradually strengthening. Ningxia should prioritize the development of transport corridors centered on Yinchuan, further optimize the regional network layout by accelerating railway construction in the southern region, and provide transportation support for the region' s socio-economic development and the Belt and Road Initiative.

Full Text

Spatial Features of Road Networks in Ningxia Based on GIS

GAO Yuxiang[1], **DONG Xiaofeng**[2], **LIANG Ying**[2] [1]College of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China
[2]College of Architecture and Design, Beijing Jiaotong University, Beijing 100044, China

Abstract

Ningxia Hui Autonomous Region serves as a crucial transportation node connecting northern and northwestern China. This study examines the spatial characteristics of Ningxia' s road network using an improved network analysis method, cost-distance algorithm, and ArcGIS spatial analysis to calculate county-level accessibility for 2011, 2017, and 2023 (projected). The analysis reveals several key findings: (1) The region has established a primary "cross-shaped" network framework, but development remains uneven, with superior infrastructure in the north compared to the south. (2) Average county accessibility improved dramatically from 4.02 h in 2011 to 3.75 h in 2017, demonstrating significant spatiotemporal convergence. (3) Disparities in county accessibility are gradually diminishing, indicating enhanced spatial equilibrium across the regional network. (4) Future development should prioritize Yinchuan-centered transportation corridors while accelerating railway construction in southern Ningxia to optimize overall network layout, thereby supporting regional socioeconomic development and the Belt and Road Initiative.

Keywords: road network; spatial feature; GIS; improved network analysis; Ningxia

1. Study Area Overview

Ningxia, one of China' s five autonomous regions, borders Shaanxi to the east, Inner Mongolia to the north, and Gansu to the south. Strategically positioned along the domestic segment of the New Eurasian Land Bridge, Ningxia possesses unique overland and air transport advantages, serving as China' s western gateway for opening up to Central and West Asia. The region's railway backbone consists of the Baotou-Lanzhou, Baoji-Zhongwei, and Taiyuan-Zhongwei-Yinchuan lines, while major expressways including the Fuzhou-Yinchuan, Beijing-Tibet, and Qingdao-Yinchuan highways traverse the region, connecting key node cities [Figure 1: see original paper].

The Hui population constitutes approximately 36% of Ningxia' s total population. Due to geographical and historical factors, the Hui nationality exhibits an uneven spatial distribution pattern of "more in the south, fewer in the north" [Figure 2: see original paper], which contrasts with the overall population distribution pattern in the region.

2. Methodology

2.1 Accessibility Metrics

Accessibility represents a critical attribute of road networks and constitutes a key consideration in network planning at all levels. Average accessibility is defined as the mean travel time from a given node to all other nodes within the study

area, reflecting the node' s transportation location advantage. Smaller values indicate better accessibility and closer spatial connections with other cities. The calculation formula is:

$$A_i = \frac{\sum_{j=1}^{n} T_{ij}}{n}$$

where A_i represents the average accessibility of node i, T_{ij} denotes the shortest travel time between nodes i and j, and n is the total number of nodes excluding the selected node.

2.2 Improved Network Analysis

Traditional network analysis methods widely used in accessibility calculations fail to consider transfer times between different transportation modes. To address this limitation, this study implements an improved approach by setting impedance values to account for time consumed during mode transfers, yielding more realistic results.

The Origin-Destination (OD) cost matrix utilizes a network dataset to calculate minimum travel costs from multiple origins to multiple destinations. During network vectorization, impedance segments are added at transfer points between transportation modes [Figure 3: see original paper]. When passengers transfer from train to automobile, they must wait, so the transfer time is added to the impedance cost attribute. Based on existing research regarding transfer and additional travel times, combined with Ningxia' s actual network conditions, railway-to-railway and railway-to-road transfer times are set at 1.0 h and 0.7 h, respectively. Road speeds are assigned according to established standards .

Since railways only interact with local areas at stations and expressways only connect with other roads at interchanges, 5 km buffers are established along railway and expressway lines. Non-station/non-interchange areas within these buffers are assigned extremely high time costs to represent prohibited access. The vector data is converted to 10 m × 10 m raster grids, with NoData values assigned. Water systems, slope, and relief are similarly incorporated as cost factors to create a comprehensive cost resistance surface.

2.3 Cost Distance Algorithm

The cost distance algorithm calculates the time cost distance from each grid cell to destination grid cells based on raster data. The travel cost for moving through a grid cell is calculated as:

$$c_i = \frac{1}{v} \times 60$$

where c_i represents the time cost for the i-th grid cell, and v is the assigned travel speed for the road or railway .

The total accessibility cost is computed as:

$$K_i = \sum_{i=1}^{n} c_i$$

where c_i is the time cost of the i-th grid cell, and n is the total number of grid cells traversed.

Based on the established cost raster layers, point objects are created for county centers and important towns. The cost distance method calculates time costs from each node, which are then extracted and spatialized using inverse distance weighting to generate accessibility surfaces for Ningxia.

3. Spatial Characteristics Analysis

3.1 2011 Network Characteristics

In 2011, Ningxia' s railway and highway totals were 1,029 km and 24,506 km, respectively. The northern region featured a well-developed network, with the Baotou-Lanzhou Railway and Beijing-Tibet Expressway connecting Yinchuan, Wuzhong, and Shizuishan—three prefecture-level cities with relatively rational road grade distributions. In contrast, southern areas exhibited a "single-line" pattern, with the Baoji-Zhongwei Railway and Fuzhou-Yinchuan Expressway linking Tongxin, Haiyuan, and Yuanzhou counties. Other counties in Guyuan City suffered from poor railway and expressway access, limiting the network' s contribution to regional economic development.

Using the improved network analysis method, inter-county travel times were calculated [Figure 4: see original paper]. Most county nodes could reach each other within 3.00–5.00 h, though travel times between southern and northern counties exceeded 3.00 h. The longest travel time was 9.47 h between Jingyuan and Huinong, while the shortest was between Jinfeng and Xingqing districts. Yinchuan and Wuzhong exhibited the best accessibility due to their status as major transportation hubs with converging routes.

The spatial accessibility analysis [Figure 5: see original paper] revealed that Yinchuan and Wuzhong had the best accessibility, with isochrones radiating outward from these centers. Approximately half of Guyuan City (Pengyang, Jingyuan, and Longde counties) showed the poorest accessibility, with nearly 50% of the area exceeding 4.40 h. This resulted from limited trunk transportation—only the Fuzhou-Yinchuan Expressway and the low-speed, single-track Baoji-Zhongwei Railway, which provided insufficient regional impetus. Eastern Yanchi County, as an isolated node without railway access, also demonstrated weak accessibility.

3.2 2017 Network Characteristics

By 2017, highway mileage had increased by 10,055 km to 52.05 km/100 km^2, representing a 41% expansion. The Guyuan-Xiji and Lijiazhuang-Jingyuan Expressways opened, enabling Guyuan City to achieve a "four counties, one district" 1-hour traffic circle. Ningxia became one of the few provinces where every county had expressway access, transforming the expressway layout from linear to network-based and gradually optimizing multi-grade road distributions, though railway mileage remained unchanged.

Inter-county travel times improved significantly [Figure 6: see original paper]. The number of counties reachable within 3.50 h increased substantially, with northern counties achieving 1.50 h connections and some southern counties reaching northern areas within 6.00 h. The Guyuan-Yinchuan travel time decreased from 6.50 h to 3.50 h, strengthening north-south spatial linkages .

Spatial accessibility improved markedly [Figure 7: see original paper], with Guyuan' s weak accessibility zone shrinking further. However, southern accessibility improvements outpaced those in the north. While the expressway network evolved toward a mesh structure, high-speed transport corridors remained limited. Among prefecture-level nodes, Yinchuan' s accessibility reached 2.68 h, while Guyuan' s was 3.56 h, reflecting the weakest network development.

Tourism represents a vital economic sector for Ningxia, yet major attractions cluster separately in north and south. Analysis of inter-attraction travel times [Figure 8: see original paper] revealed that most north-south connections exceed 7.00 h, creating weak linkages that hinder integrated tourism development. As a traditionally agricultural region with lagging economic development, Guyuan' s road network constraints limit growth. Accelerating internal and external transport connections would better serve local socioeconomic development and leverage tourism potential.

3.3 2023 Projected Network Characteristics

Based on ongoing railway and highway projects, the total operational mileage will reach 2,000 km by 2023, including over 800 km of high-speed rail, ushering most areas into the high-speed rail era. Assuming other transport conditions remain constant, the projected network data indicates that all prefecture-level cities except Guyuan will have high-speed rail access, with inter-city travel times within 1.50 h. The Yinchuan-Guyuan travel time will decrease from 6.50 h to 2.50 h, significantly facilitating personnel exchange and economic interaction between Guyuan and the capital.

County accessibility continues improving, with average accessibility decreasing from 4.02 h (2011) to 3.75 h (2017) and projected to reach 2.72 h (2023). Node accessibility disparities are diminishing, with the most significant improvements in Pengyang, Jingyuan, Longde, and Yuanzhou. By 2023, the projected mean county accessibility will be 3.00 h, with all Guyuan counties below 3.70 h [Figure

9: see original paper]. High-speed rail construction will substantially enhance regional accessibility, creating a belt-shaped high-quality accessibility zone (less than 2.72 h) across the northwest [Figure 10: see original paper]. This improvement will boost tourism development in Guyuan and promote coordinated socioeconomic development across the autonomous region [Figure 11: see original paper].

3.4 Recommendations for Ningxia' s Road Network Development

Based on these findings and the Western Land-Sea Corridor Master Plan, the following recommendations are proposed:

1. **Strengthen integrated transport corridor functions**: Establish freight corridors dominated by conventional railways and passenger corridors centered on high-speed railways. Enhance Yinchuan' s connectivity with surrounding provincial capitals to elevate its role as a comprehensive transportation hub.
2. **Prioritize railway-based regional backbone networks**: Develop a primary framework supported by railways and expressways to connect nodes beyond the current backbone' s influence, improving their accessibility. Use network development to drive economic growth and achieve balanced regional development.
3. **Accelerate Guyuan' s network development**: Guyuan remains Ningxia' s weakest network area, with only the Baoji-Zhongwei Railway and Fuzhou-Yinchuan Expressway providing limited external connections. Fast-track construction of links between Guyuan and Yinchuan, Pingliang, and Qingyang to strengthen regional integration.

4. Conclusions

This study analyzed Ningxia' s road network spatial characteristics using improved network analysis, cost-distance algorithms, and ArcGIS spatial analysis. Key conclusions include:

1. The regional network has formed a "cross-shaped" backbone with a "strong north, weak south" spatial pattern. Northern Ningxia has developed a mesh structure, while north-south county linkages remain weak, making Guyuan the priority area for future construction.
2. Average county accessibility improved from 4.02 h (2011) to 3.75 h (2017), with projected further improvement to 2.72 h (2023). Southern nodes show particularly notable accessibility gains. Compared with 2011, inter-county accessibility disparities are decreasing, gradually enhancing the spatial equilibrium of the regional network.
3. Ningxia' s network structure is shaped by both economic and natural factors. The north' s favorable economic conditions and flat terrain support

rational network layout, while southern construction remains constrained. The Belt and Road Initiative and Western Land-Sea Corridor development present important opportunities for optimizing the regional network structure to promote development.

References

[1] Givoni M. The development and impact of the modern High Speed Train[J]. Transport Reviews, 2014, 26(5): 593-612.

[2] Pan Jiajia. Analysis of the spatial relationship between traffic accessibility and tourism economic relationship: Taking 15 prefectures in Xinjiang as an example[D]. Urumqi: Xinjiang University, 2019.

[3] Zhong Yexi, Lu Yuqi. Urban accessibility and its structure evolution in Jiangsu Province[J]. Resources and Environment in the Yangtze Basin, 2011, 20(8): 903-910.

[4] Gao Yuxiang, Han Feng, Li Zeyu, et al. Study on coupling relations of the important tourism attractions and rail transit based on GIS: A case study of Tianshui[J]. Engineering of Surveying and Mapping, 2019, 28(3): 57-60, 65.

[5] Zhou Kai, Liu Chong. A new method to visualise the time-space compression effect in road network: A case study of Beijing-Tianjin-Hebei region[J]. Economic Geography, 2016, 36(7): 62-69.

[6] Mostafa M, Lei Z. Incorporating spatial equity into interurban road network design[J]. Journal of Transport Geography, 2014, 39(1): 59-68.

[7] Huang Xiaoyan, Zhang Shuang, Cao Xiaoshu. Spatial-temporal evolution of Guangzhou subway accessibility and its effects on the accessibility of public transportation services[J]. Progress in Geography, 2014, 33(8): 1078-1089.

[8] Gao Yuxiang, Han Feng, Yuan Feng. Study on temporal-spatial relations of railway network expansion in Belt and Road node province: A case study of Gansu Province[J]. Journal of Railway Science and Engineering, 2018, 15(8): 2172-2178.

[9] Wei Wei, Shi Peiji, Tuo Minyong, et al. The road network density and its spatial dependence in Gansu Province based on GIS[J]. Scientia Geographica Sinica, 2012, 32(11): 1297-1303.

[10] Yang Xiaomin, Li Lingqin, Fu Jianxin, et al. Pattern variation of accessibility and economic linkage at county scale in Qinghai Province from 1986 to 2016[J]. Arid Land Geography, 2018, 41(6): 1376-1387.

[11] Yao Zhaozhao, Cao Weidong, Yue Yang, et al. Study on the influence of high speed railway on the accessibility pattern in Pan Yangtze River Delta region[J]. Resources and Environment in the Yangtze Basin, 2018, 27(10): 2182-2193.

[12] Wang Xue, Bai Yongping, Wang Fan, et al. Characteristics of spatial distribution of basic education resources in Xi' an on street scale[J]. Arid Land Geography, 2019, 42(6): 1470-1477.

[13] Bao Chao, Zou Jianjun. Spatiotemporal variations of urbanization quality in northwest China[J]. Arid Land Geography, 2019, 42(5): 1141-1152.

[14] Pan Jinghu, LI Junfeng. Spatial distribution characteristics and accessibility of A-grade tourist attractions in China[J]. Journal of Natural Resources, 2014, 29(1): 55-66.

[15] Lu Qian. Analysis of accessibility change and urban location of expressway network in Yangtze River Delta[D]. Shanghai: Shanghai Normal University, 2011.

[16] Han Yanhong, Lu Yuqi. Analysis of accessibility and economic linkage spatial pattern evolution of Nanjing metroplitan area[J]. Resources and Environment in the Yangtze Basin, 2014, 23(12): 1641-1648.

[17] Xue Bingjie. Research on the rationality and development law of the scale of the road transportation network in the Pearl River Delta[D]. Xi' an: Chang' an University, 2011.

[18] Zhou Ruirui. Study on urbanization quality and spatial-temporal pattern evolution characteristics of Ningxia Urban Agglomeration along the Yellow River[D]. Yinchuan: Ningxia University, 2017.

[19] Cao Xiaoshu, Li Tao, Yang Wenyue, et al. Accessibility and urban spatial connections of cities in the Silk Road Economic Belt based on land transportation[J]. Progress in Geography, 2015, 34(6): 657-664.

[20] Yin C, He Q, Liu Y, et al. Inequality of public health and its role in spatial accessibility to medical facilities in China[J]. Applied Geography, 2018, 92(6): 50-62.

[21] Williams S, Wang F H. Disparities in accessibility of public high schools in Metropolitan Baton Rouge, Louisiana 1990–2010[J]. Urban Geography, 2014, 35(7): 1066-1083.

[22] Xiao Jixing, Wang Zhenbao. Accessibility analysis of medical service facilities in Handan based on GIS[J]. Geomatics & Spatial Information Technology, 2020, 43(1): 137-140, 144.

[23] Yu Ce, Li Yuanfu, Lin Fang, et al. Analysis on influence of Tianjin-Baoding Railway on accessibility of adjacent cities based on GIS[J]. Railway Transport and Economy, 2017, 39(5): 18-22.

[24] Gao Yuxiang, Han Feng, Ren Jie, et al. Study on the coupling relationship of Gansu railway network and regional development along the Belt and Road areas[J]. Railway Standard Design, 2019, 63(8): 46-52.

[25] Ma Hongwei. Research on targeted speed of Xi' an-Ankang high speed railway on newly built Baotou-Haikou Corridor[J]. Railway Standard Design, 2019, 63(3): 7-11.

[26] Wang Hui. Study on selection of target speed value for Jiamusi-Shenyang dedicated passenger railway[J]. Railway Standard Design, 2017, 61(9): 1-5.

[27] Mu Naixia, Liu Wenbao, Wang Haiyin, et al. ArcGIS geographic information system course: From beginning to proficiency[M]. Beijing: Surveying and Mapping Publishing House, 2012: 281-289.

[28] Statistics Bureau of Ningxia Hui Autonomous Region. Ningxia statistical yearbook 2018[M]. Beijing: China Statistical Publishing House, 2018: 26-28.

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