Postprint: Study on Spatial Linkage Intensity of Central Cities in Guanzhong Plain Urban Agglomeration

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Abstract

As the central city of the Guanzhong Plain urban agglomeration, Xi' an serves as an important engine driving the construction and development of Northwest China. By improving parameters such as mass, distance, and gravitational coefficient in the traditional gravity model, this study measures the spatial connection intensity between Xi' an and other cities within its urban agglomeration, as well as other national central cities in the central and western regions with their respective urban agglomerations, and comparatively analyzes the gaps and underlying causes for differences in spatial connection capabilities between Xi' an and other national central cities. The research results indicate: (1) The spatial connection intensity level of Xi' an, the central city of the Guanzhong Plain urban agglomeration, is relatively low. Within the urban agglomeration, the proportion of cities with strong or relatively strong connections to Xi' an is only 30%. In contrast, in the Chengdu-Chongqing urban agglomeration and the middle reaches of the Yangtze River urban agglomeration, the proportions of cities with strong or relatively strong connections to Chengdu and Wuhan are significantly higher, at 60% and 48.1%, respectively. (2) The comprehensive development level of Xi' an, the central city, and secondary cities such as Xianyang and Baoji within the Guanzhong Plain urban agglomeration is relatively low, hindering their effective performance of radiating and undertaking functions. Compared with other national central cities, Xi' an' s comprehensive quality is far lower than that of Chengdu and Wuhan, while Xi' an' s comprehensive quality exceeds that of secondary cities Baoji and Xianyang by approximately 3.4 times. (3) The comprehensive time distance between cities is an important factor affecting Xi' an' s spatial connection intensity. Compared with Chengdu, the comprehensive time distance between Xi' an and other cities within the Guanzhong Plain urban agglomeration remains relatively long despite geographical proximity, directly weakening Xi' an' s spatial connection capacity. Therefore, it is urgent to accelerate the construction of the Greater

Xi’ an metropolitan area, enhance the comprehensive strength of the central city, actively develop Baoji as a sub-central city, and simultaneously improve the urban agglomeration’ s transportation network system with Xi’ an as the hub, thereby enhancing its transportation efficiency.

Full Text

Spatial Connection Intensity of Central Cities in the Guanzhong Plain Urban Agglomeration

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Abstract

Xi’ an, as the central city of the Guanzhong Plain urban agglomeration and the only national central city in northwestern China, serves as a critical engine for regional development. This study improves upon the traditional gravity model by modifying parameters including mass, distance, and gravitational coefficients. Based on the revised gravity model, we measure the spatial connection intensity between Xi’ an and other cities within its urban agglomeration, comparing it with other national central cities in central and western China to identify gaps and underlying causes. The empirical results reveal three key findings: (1) Xi’ an exhibits relatively low spatial connection intensity, with only 30.0% of cities in the Guanzhong Plain urban agglomeration maintaining strong or relatively strong connections, compared to 60.0% for Chengdu in the Chengdu-Chongqing agglomeration and 48.1% for Wuhan in the middle Yangtze River agglomeration. (2) The comprehensive development level of Xi’ an and its secondary cities (Xianyang and Baoji) remains low, hindering their effective radiation and undertaking functions. Xi’ an’ s overall quality significantly lags behind Chengdu and Wuhan, while Baoji and Xianyang’ s comprehensive quality is approximately 3.4 times lower than Xi’ an’ s. (3) Inter-city comprehensive time distance constitutes a crucial factor affecting Xi’ an’ s spatial connection capacity. Despite geographical proximity, Xi’ an’ s comprehensive time distance to other cities in the agglomeration remains longer than that of comparable cities, directly weakening its spatial connectivity. Consequently, accelerating the development of the Greater Xi’ an metropolitan area, enhancing the central city’ s comprehensive strength, cultivating Baoji as a sub-central city, and improving Xi’ an’ s hub-based transportation network are essential for boosting connectivity efficiency.

Keywords: national central city; Guanzhong Plain urban agglomeration; urban spatial connection intensity; modified gravity model

1 Study Area Overview

This study focuses primarily on Xi' an and its Guanzhong Plain urban agglomeration, with comparative analysis of Chengdu, Wuhan, Zhengzhou, and their respective Chengdu-Chongqing, middle Yangtze River, and Central Plains agglomerations. Xi' an covers an area of 1.07×10^{4} km^2 with a permanent population of 12.9 million and GDP of 1.02×10^{12} yuan at year-end 2021. The Guanzhong Plain urban agglomeration encompasses 11 cities across three provinces: Xi' an, Xianyang, Weinan, Tongchuan, Baoji, and Shangluo in Shaanxi; Yuncheng and Linfen in Shanxi; and Tianshui, Qingyang, and Pingliang in Gansu. Chengdu, Wuhan, and Zhengzhou are all new first-tier cities and provincial capitals like Xi' an. Chongqing, a municipality directly under central government and the most populous city in China, serves as the economic center of southwestern China and the upper Yangtze region but operates at a different administrative level and was excluded from comparison. The four urban agglomerations collectively comprise 56 prefecture-level cities covering 90.52×10^{4} km^2 with a total population of 22.5 million and GDP of 4.2×10^{13} yuan.

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2 Methodology

2.1 Urban Quality Measurement Index System

Urban quality level reflects comprehensive urban strength. Drawing upon measurement indicators from the National Bureau of Statistics' Urban Socioeconomic Survey Team and referencing Li Boya' s and Fang Chao' s urban quality measurement systems, we constructed a comprehensive urban quality index system covering four dimensions: population development, economic development, social development, and ecological environmental protection. In the social development subsystem, we incorporated basic pension and medical insurance participation rates as they affect residents' quality of life. Urban external transport capacity constitutes another vital infrastructure component, so we included highway and railway passenger volumes. In the ecological subsystem, we used the number of days with air quality meeting Grade II standards as a key environmental indicator. Following data standardization using the extremum method, we applied the entropy weight method to calculate indicator weights, eliminating subjective factors and enhancing scientific rigor.

2.2 Modified Gravity Model

Derived from Newton' s law of universal gravitation, the gravity model serves as an important tool for measuring inter-city interaction intensity. This study modifies three parameters: mass, distance, and gravitational coefficient.

First, **urban mass**: Previous research used population or GDP as proxies, but given frequent flows of population, materials, capital, and information, single indicators cannot fully reflect comprehensive urban quality. We therefore use a four-dimensional composite index (population, economy, society, environment) to represent urban mass.

Second, **inter-city distance**: Traditional models use straight-line distance, but improved transportation has dramatically shortened actual travel time, making straight-line distance inadequate for capturing distance decay effects. We employ comprehensive time distance—the geometric mean of minimum commuting times via railway and highway.

Third, **gravitational coefficient**: Conventionally treated as constant K, we modify it based on Ullman' s complementarity principle, which posits that development gaps between cities generate interaction potential. In reality, higher GDP indicates stronger urban attractiveness. We therefore adjust K using cities' GDP proportions to represent interaction potential.

The modified gravity model is:

$$F_{ij} = K_{ij} \frac{Q_i Q_j}{D_{ij}^2}$$

where: - i = central city, j = non-central city - F_{ij} = gravitational force (connection intensity) between cities i and j - K_{ij} = gravitational coefficient - Q_i, Q_j = comprehensive quality scores of cities i and j - D_{ij} = comprehensive time distance between cities i and j

$$K_{ij} = \frac{GDP_i}{GDP_i + GDP_j}$$

$$D_{ij} = \sqrt{H_{ij} \times R_{ij}}$$

where H_{ij} = minimum highway travel time and R_{ij} = minimum railway travel time.

2.3 Data Sources

Data comprise two components: (1) Socioeconomic data from the *China City Statistical Yearbook 2021* and *China Urban Construction Statistical Yearbook 2021*; (2) Comprehensive time distance data from Baidu Maps (highway) and 12306.cn (railway).

3 Results

3.1 Urban Comprehensive Quality Assessment

3.1.1 Quality Scores and Classification Using the entropy method, we calculated comprehensive quality scores and applied hierarchical clustering to classify cities into four levels: central, secondary, tertiary, and quaternary. The spatial distribution reveals that the Guanzhong Plain urban agglomeration lags behind others in overall quality. Except for the Chengdu-Chongqing agglomeration' s dual-center structure (Chengdu and Chongqing), all others are monocentric. Central city rankings are: Chengdu, Wuhan, Xi' an, Zhengzhou, with Xi' an in the lowest position. Within the Guanzhong Plain, Xi' an scores highest (0.83), 3.4 times higher than secondary city Baoji (0.24) and 2.8 times higher than Xianyang (0.30). In contrast, Chengdu' s score (0.91) is only 2.1 times higher than Luzhou (0.43), and Wuhan' s gap with its secondary cities stays within 2 times. This indicates a weak sub-central city structure in the Guanzhong Plain.

[Figure 1: see original paper]

3.1.2 Central City Comparison Comparative analysis shows Xi' an holds advantages in education and scientific resources but lags in several areas. As of 2021, Xi' an' s permanent population (9.62 million) is the smallest among the four national central cities, and it' s the only one with GDP below one trillion yuan—mismatching its strategic status. A 1.5-fold economic gap widens disparities in living standards and infrastructure. Xi' an' s per capita disposable income is lower and unemployment higher than peers. Its transport capacity and drainage infrastructure also trail other central cities. Environmentally, Xi' an' s air quality—with fewer good-air days than Chengdu or Wuhan—further reveals weaknesses that may hinder its radiating effect.

[Figure 2: see original paper]

3.1.3 Secondary City Comparison Secondary cities should function as sub-centers bridging central and smaller cities. However, Xianyang and Baoji struggle to fulfill this role. By end-2021, neither exceeded 5 million residents—nearly 2 times fewer than Xi' an—creating a "discontinuous" urban hierarchy that impedes effective radiation. Both cities rely on technology-intensive industries while lagging in modern services and high-tech sectors, resulting in low industrial efficiency, weak market competitiveness, limited openness, and scarce growth drivers. Residents' low income and insufficient social insurance coverage further constrain quality of life. Consequently, Baoji and Xianyang' s underdevelopment weakens their undertaking and diffusion capacities, diminishing Xi' an' s radiating effect.

[Figure 3: see original paper]

3.2 Comprehensive Time Distance Measurement

Drawing on Guo Liang et al.' s "commuting circle" concept, we calculated geometric mean travel times via highway and railway, classifying them into <1-hour, 1-2 hour, 2-3 hour, and >3 hour commuting circles to analyze transport connectivity.

Results show most Guanzhong Plain cities are geographically close to Xi' an, with five cities (Xianyang, Weinan, Tongchuan, Baoji, Yuncheng) within the <1-hour circle—a proportion second only to Chengdu. However, Shangluo remains temporally distant despite proximity. Chengdu' s transport efficiency surpasses others, with only 3.7% of cities beyond 3 hours, compared to 25.9% for Xi' an, 10.7% for Wuhan, and 10.0% for Zhengzhou. The Guanzhong Plain' s transport network requires improvement; for instance, no direct railway connects Xi' an to Qingyang.

3.3 Spatial Connection Intensity Analysis

3.3.1 Calculation Results Substituting quality scores and time distances into the modified gravity model yields spatial connection intensities. Using standard deviation classification (mean ± SD), we categorize connections as strong, relatively strong, relatively weak, and weak.

In the Central Plains agglomeration, 20.0% of cities have strong/relatively strong ties with Zhengzhou, while the Guanzhong Plain shows the lowest proportion at 10.7%. Weak connections dominate Xi' an' s urban network.

3.3.2 Comparative Analysis Three key findings emerge: First, comprehensive time distance significantly impacts Xi' an' s connectivity, which weakens with longer commuting times. Compared to Chengdu and Wuhan, Xi' an and Zhengzhou face more substantial barriers—cities beyond 3 hours show markedly reduced strong/relatively strong ties. For example, Linfen' s long travel time diminishes Xi' an' s radiating capacity.

Second, Xi' an' s relatively weak comprehensive strength fails to overcome distance friction. Within the <1-hour circle, Xi' an has strong ties only with Xianyang (secondary) and Weinan (tertiary), while Chengdu and Wuhan connect strongly with quaternary cities. This reflects Xi' an' s quality gap and limited radiation capacity.

Third, the large quality disparity between Baoji and Xi' an results in only weak connection intensity. By contrast, other agglomerations' secondary cities like Changsha maintain relatively strong ties with Wuhan despite greater distance, demonstrating Baoji' s insufficient sub-center capacity.

4 Conclusions and Implications

Using 2021 data from 56 prefecture-level cities across four major agglomerations and a modified gravity model, we compared Xi' an' s spatial connection capacity with other national central cities. Key conclusions and policy implications follow:

Conclusion 1: Xi' an' s comprehensive quality is weak. Its quality score trails Chengdu' s by 1.5 times. Despite educational advantages, Xi' an' s economic scale—being the only national central city with GDP below one trillion yuan—constrains living standards, infrastructure, and population growth. Secondary cities Baoji and Xianyang lag significantly behind their peers, with quality gaps 3-4 times larger than those in other agglomerations.

Conclusion 2: Inter-city time distance critically affects connectivity. Although geographically proximate, Xi' an' s comprehensive time distances remain relatively long, as seen in weak connections with Linfen and Baoji. The Guanzhong Plain' s underdeveloped transport network and low density impede Xi' an' s radiating effect.

Conclusion 3: Xi'an's spatial connection pattern is unbalanced and dominated by weak ties. As the newest national central city, only 10.7% of its agglomeration has strong connections, while weak connections reach 67.9%—far exceeding Chengdu' s 25.9% and Wuhan' s 51.9%. This indicates substantial room for improving Xi' an' s radiating capacity.

Policy Implications:

1. **Enhance Xi'an's comprehensive strength:** Accelerate Xi'an-Xianyang integration to build the Greater Xi' an metropolitan area, enabling complementary industrial development. Implement targeted talent policies, establish income growth mechanisms synchronized with economic growth, expand social insurance coverage, and strengthen air quality monitoring with stricter penalties for polluters. Consider vehicle restrictions to reduce emissions.

2. **Cultivate Baoji as a sub-center:** Strengthen complementarity with Xi' an to create a robust secondary growth pole. Develop Baoji into China' s "Titanium Valley" through national torch program initiatives, advance equipment manufacturing clusters, and boost public services and infrastructure to improve living standards. Promote industry-university-research integration with Baoji University of Arts and Sciences to address talent shortages.

3. **Improve Xi' an-centered multi-node transport networks:** Develop intercity railways, provincial highways, and international aviation hubs to create an integrated multi-modal network. Enhance connectivity between main corridors, passenger hubs, and logistics centers to achieve seamless transfers and zero-distance connections. Launch civil feeder air-

port projects in Baoji, Tianshui, and Pingliang to establish a "trunk-feeder" airport system. Transform the single-center radial pattern into a multi-node network by establishing regional transport hubs in Baoji, Weinan, and Xianyang.

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5 Discussion

As the only national central city in northwest China and the newest among them, examining Xi' an' s radiating capacity and improvement strategies holds significant importance. While existing studies typically apply traditional gravity models to regional connectivity, few analyze national central cities' radiation capacity or conduct horizontal comparisons. This study measures Xi' an' s spatial connection capacity using a modified gravity model and compares it with peer cities.

However, limitations remain. The urban quality index system could be more comprehensive; data constraints prevented inclusion of smart city development indicators. Future research should leverage big data to incorporate contemporary metrics. Additionally, as this study focuses on inland western regions where transport relies primarily on highways and railways, the comprehensive time distance measurement may not apply to more developed coastal agglomerations like the Yangtze River Delta or Pearl River Delta where aviation plays a major role. Subsequent studies should adapt measurement approaches to specific contexts.

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