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A Study on the Coupled Characteristics of Transportation Accessibility and Spatial Distribution in Traditional Villages of Jincheng City

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Abstract: *Traditional villages are key repositories of agrarian civilization, and transportation accessibility critically affects their preservation. Most existing accessibility studies on northern China's Taihang Mountains neglect slope as a mobility barrier. This study examines 186 national-level traditional villages in Jincheng City, integrates multi-source data (road networks, land use, DEMs), and constructs a grid-based cost-distance accessibility model with terrain correction. Results show: villages are highly clustered along the Qinhe and Danhe River valleys, forming three high-density clusters; travel times range from 0.23 to 166.86 min (mean 13.88 min), with accessibility higher in central river valleys and lower in east/west/mountains; 89.8% of villages lie within the 30-min high-accessibility zone, which fully overlaps with high-density clusters. This research provides a scientific basis for tiered protection and road network optimization of traditional mountain villages.*

Keywords: *Traditional villages; Transportation accessibility; Taihang Mountains; Jincheng City*

1. Introduction

Traditional villages serve as vital repositories of China's agrarian civilization, preserving centuries-old ways of life and local cultural heritage [1]. In recent years, with the comprehensive advancement of the rural revitalization strategy and the continuous improvement of the cultural heritage protection system, the revitalization and sustainable development of traditional villages have become focal points of scholarly attention [2]. However, the rapid pace of urbanization has left a large number of traditional villages facing crises of population hollowing out, spatial marginalization, and even accelerated disappearance [3]. Resolving the dilemma of balancing protection and development, and reversing the decline of traditional villages, has become an urgent challenge.

Transportation infrastructure constitutes a key channel for the exchange of material resources and energy between urban and rural areas. The level of development of regional transportation networks directly affects a village's capacity for resource spillover, potential for tourism development, residents' quality of life, and the efficiency of cultural dissemination [4,5]. High levels of accessibility accelerate the flow of information, people, and goods, injecting developmental momentum into villages; conversely, low accessibility makes villages highly susceptible to marginalization by external development processes, leading to decay despite preservation efforts [6]. In 2023, the General Offices of the Ministry of Transport and the Ministry of Culture and Tourism jointly issued the "Notice on Accelerating the Integrated Development of Urban–Rural Road Passenger Transport and Tourism," explicitly calling for improved accessibility to rural tourism resources such as ethnic villages, ancient villages and towns, and key rural tourism towns and villages. The United Nations Educational, Scientific and Cultural Organization (UNESCO) explicitly states in its guidelines for the protection of rural heritage that transportation accessibility is a core variable in balancing the preservation of heritage authenticity with sustainable revitalization; rural heritage in mountainous regions worldwide faces the common challenge of transportation constraints and developmental marginalization. These policy directions highlight the crucial role of transportation in rural revitalization and the development of traditional villages.

Existing research on traditional villages has largely focused on architectural heritage conservation [7], spatial evolution [8], and tourism development [9]. Some scholars have attempted to establish correlations between regional transportation networks and village distribution. Studies have begun to utilize the Amap API to obtain actual travel times or employ geographically weighted regression models to account for spatial heterogeneity [10], providing methodological insights for refined accessibility analysis. However, these studies often simplify the representation of village transportation conditions using straight-line or administrative distances and fail to fully incorporate real-world resistance factors such as actual road classifications, travel time costs, and topographic undulation. Consequently, the evaluation results struggle to accurately reflect the relative advantages or disadvantages of a village's transportation location [11–13]. Existing raster cost models mostly set slope correction coefficients for the hilly terrain of southern China and lack specialized corrections adapted to the steep terrain of the Taihang Mountains. Furthermore, they often calculate accessibility using a single-road network without integrating multisource resistance factors such as land use and topography, resulting in distorted accessibility measurement results in mountainous areas.

This study focuses on 186 national-level traditional villages in Jincheng City. Using GIS spatial analysis and a grid-based cost-distance method with terrain correction, we evaluate transportation accessibility and its coupling with village distribution. The findings provide a scientific basis for road network optimization and graded protection of traditional mountain villages.

2. Overview of the Study Area and Data Sources

2.1. Study Area Overview

Jincheng City is located in southeastern Shanxi Province (111°55′–113°37′E, 35°12′–36°00′N), with a total area of 9,490 km² and six county-level administrative divisions under its jurisdiction (Figure 1). The study area is located in the southern section of the Taihang Mountains. Its topography is predominantly mountainous and hilly, with significant elevation variations. The Qinhe River and Danhe River systems traverse the entire region, making it a typical concentration area for traditional mountain villages in northern China. To date, the city of Jincheng has a total of 186 national-level traditional villages, accounting for 30% of Shanxi Province's total. As a region with a high concentration of traditional northern mountainous villages—many of which are distributed along the Qinhe and Danhe River valleys—the area features architecture dominated by northern-style Siheyuan courtyards and fortress-style dwellings. With its outstanding historical and cultural value, this region serves as the core subject of this study.

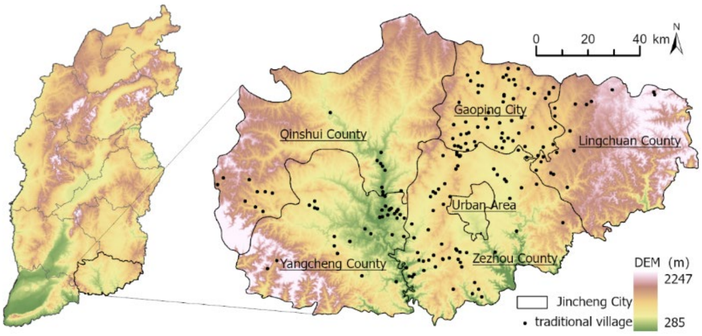

Figure 1: Location of the study area

2.2. Data Sources

The data used in this paper include traditional village data (https://www.dmctv.cn/): sourced from the first through sixth batches of the National List of Traditional Villages published by the Ministry of Housing and Urban–Rural Development; coordinates were extracted via the Baidu Maps API and converted to point vector data after correction to the WGS84 coordinate system; Road network and administrative boundary data (https://www.openstreetmap.org/): 2024 OpenStreetMap (OSM) vector data, including roads of all levels, township government seats, and administrative boundaries; Land use data (https://zenodo.org/records/12779975): 2024 China Annual Land Cover dataset (30 m resolution); and DEM Data (http://www.gscloud.cn): GDEMV3 dataset from the Geospatial Data Cloud Platform (30 m resolution). All the data are uniformly projected to the WGS 1984 UTM Zone 49 N coordinate system, with a consistent raster resolution of 30 m, to ensure spatial alignment.

3. Research Methods

3.1. Average Nearest Neighbor Index

The average nearest neighbor (ANN) index is used to evaluate the spatial distribution patterns of point features and determine whether they exhibit clustered, random, or uniform distribution patterns [12]. The specific formula is as follows:

$$ANN = \frac{\gamma_\alpha}{\gamma_\beta} = \frac{\sum \frac{d_{min}}{n}}{\frac{\sqrt{n/A}}{2}} = \frac{2\sqrt{\lambda}}{n}\sum d_{min} \tag{1}$$

where *ANN* represents the average nearest-neighbor index, $\gamma\alpha$ is the average distance to the nearest traditional village, $\gamma\beta$ is the theoretical average under the spatial random distribution of traditional villages, d_{min} is the distance between any traditional village and its nearest neighbor, n is the number of traditional villages in the study area, A is the total area of the study region, and λ is the distribution density of traditional villages.

3.2. Kernel Density Estimation

To identify the spatial agglomeration areas of traditional villages, kernel density estimation (KDE) was employed to calculate the sample density distribution across the entire region on the basis of the input point elements and their distribution values. The bandwidth was set to 10 km to generate a continuous density raster map, which was used to identify spatial agglomeration areas of traditional villages and produce a continuous density surface [13]. The specific formula is as follows:

$$f(x)=\frac{1}{nh}\sum_{i=1}^{n} k\left(\frac{x-X_i}{h}\right) \tag{2}$$

In the formula, $k\left(\frac{x-X_i}{h}\right)$ denotes the kernel function, h is the bandwidth, n represents the number of traditional village points in the study area, and $x-X_i$ is the distance from the estimation point x to the event point X_i in the kernel density estimation.

3.3. Raster Cost Distance Method

The raster cost distance method calculates the minimum cumulative travel time from each cell to the nearest source point (here, 83 township seats) using a comprehensive cost raster that integrates multiple factors (Table 1) [14,15]. Slope correction coefficients are applied to passable areas without road coverage (Table 2), referencing Tobler's hiking function [16]. The cost raster follows a priority order: roads > railways > expressway buffers (100 m, set as impassable) > land use > slope correction. All data were projected to WGS 1984 UTM Zone 49 N with 30 m resolution. Detailed construction steps follow standard GIS procedures [15].

Table 1: Accessibility Assignment Criteria.

Factor Category	Secondary Classification	Travel Speed (km/h)	Unit Time Cost (min/m)	Remarks
Land Use	Arable land	3.24	0.0185	Assigned for areas without road coverage
	Forestland	1.62	0.0370	Assigned for areas without road coverage
	Shrubland	4.20	0.0143	Assigned for areas without road coverage
	Grassland	4.86	0.0123	Assigned for areas without road coverage
	Water body	9999	-	Completely impassable area
	Bare land	3.00	0.0200	Assigned for areas without road coverage

Table 1 (continued)

Factor Category	Secondary Classification	Travel Speed (km/h)	Unit Time Cost (min/m)	Remarks
Land Use	Urban land	5.00	0.0120	Assigned for areas without road coverage
	Wetland	2.00	0.0300	Assigned for areas without road coverage
	Others	3.00	0.0200	Assigned for areas without road coverage
	Railway	120	0.00050	Priority assignment for full line coverage
Transportation Routes	Expressway	120	0.00050	100 m buffer zones on both sides assigned as 9999 (impassable)
	Main road	80	0.00075	Including national and provincial highways
	Ordinary highway	50	0.00120	Including county and township roads
	Rural road	30	0.00200	Paved village-level roads
	Dirt road	15	0.00400	Unpaved agricultural roads
	Footpath	5	0.01200	Mountain pedestrian trails

Table 2: Slope grading correction coefficients.

Slope	0-10°	10-20°	20-30°	＞30°
Correction Coefficient	1.0	1.5	2.0	3.0
Note: Correction is only applied to passable areas without road coverage.				

3.4. Bivariate Spatial Autocorrelation

The bivariate spatial autocorrelation model can be applied to identify the correlation between the spatial distribution characteristics of geographic elements and the differentiation characteristics of accessibility. In this study, a systematic analysis was performed using the bivariate Moran's I index method based on the GeoDa platform, and the specific formula is shown below [17]:

$$I = \frac{n\sum_{i=1} n\sum_{j=1} nW_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1} n\sum_{j=1} nW_{ij}\sum_{i=1} n\,(x_i - \bar{x})^2} \tag{3}$$

In the formula, I denotes the global Moran's I index; n denotes the total number of spatial units; x_i and x_j represent the attribute values of the i-th and j-th spatial units, respectively; $\bar{x}$ denotes the mean value of attribute values across all spatial units; and W_{ij} denotes the spatial weight matrix between spatial unit i and spatial unit j.

4. Results Analysis

4.1. Spatial Distribution Pattern Characteristics of Traditional Villages

Based on the average nearest neighbor (ANN) index analysis, the ANN value of the 186 national-level traditional villages in Jincheng City is 0.6731, with a z-score of -8.5280 and a p-value < 0.01, passing the significance test at the 1% level. This indicates that the villages as a whole exhibit an extremely significant clustered spatial distribution pattern, rather than a random or uniform distribution.

From the perspective of the overall spatial pattern, traditional villages in Jincheng are distinctly unevenly distributed and are characterized by a dense pattern in the center, a sparse pattern in the east and west, dense in the north and sparse in the south. With cross-validation combined with the average township spacing in the study area, the search radius for kernel density estimation was determined to be 10 km, and a kernel density distribution map was generated (Figure 2). The results show that a continuous high-density agglomeration belt running northeast–southwest has formed in the central part of the city, spanning the contiguous areas of Gaoping city, Zezhou County and Yangcheng County. The kernel density ranges from 0.001 to 0.156 units/km^2, with an average city-wide density of 0.0196 units/km^2.

The peak density is approximately 8 times the average, revealing extremely prominent regional differences in spatial agglomeration. In the deep mountainous areas of the Taihang and Taiyue Mountains on the eastern and western sides of the city, as well as in the southern marginal zones, kernel density values decrease significantly, and villages are mostly scattered as isolated points without large-scale agglomeration.

At the county level, the number and agglomeration density of traditional villages show significant hierarchical differentiation along the gradient. Gaoping city acts as the core high-density cluster of traditional villages in the city, with the greatest number of villages and the highest degree of agglomeration, and the entire area falls within the medium- to high-density range. Zezhou County and Yangcheng County form the sub-dense distribution area, with the number of villages second only to Gaoping. Continuous agglomeration belts mainly occur in areas bordering Gaoping, while scattered small clusters dominate elsewhere. Lingchuan County and Qinshui County are low-density areas, with relatively few villages. Small agglomeration groups only appear in individual townships, leaving most of the region as low-density blank areas.

KDE accurately identifies three gradient high-density agglomeration groups of traditional villages in Jincheng, with strong spatial linkages between groups, forming an overall agglomeration structure of “one main core and two secondary cores”. The primary main core is located in the south-central part of Gaoping city, centered on Hexi Town, Macun Town, Mishan Town, Nancheng Subdistrict and Shimo Township. It has the highest kernel density values in the city, with highly concentrated and spatially contiguous villages, representing the most central preservation and agglomeration area of traditional villages in Jincheng. The secondary subcore is located in the junction zone between northwestern Zezhou County and southeastern Gaoping city, centered on Dayang town, Dadonggou town and Beiyicheng town. It connects with the main core of Gaoping to form the central agglomeration belt, constituting the second major high-density cluster in the city. The tertiary southern core is located in the junction area of northern Yangcheng County and southwestern Zezhou County and is centered on the towns of Beiliu, Runcheng and Nancun. It forms a southern high-density agglomeration group that spatially corresponds to the central core area.

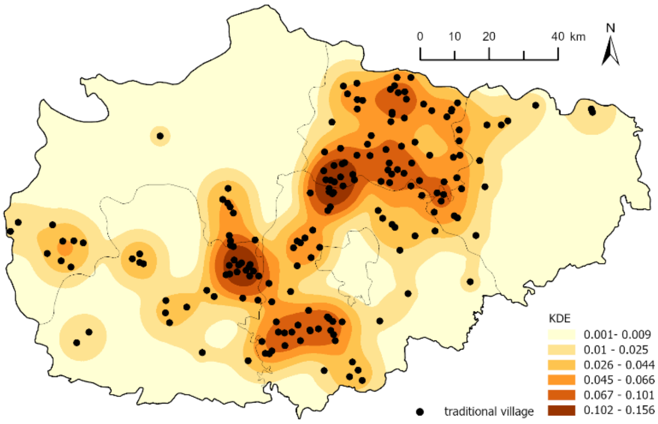

Figure 2: Kernel Density Spatial Distribution Map of Traditional Villages in Jincheng

4.2. Differentiation Characteristics of Traffic Accessibility of Traditional Villages

Taking 83 township government seats in Jincheng City as source points, distance accumulation was performed on the basis of the comprehensive cost raster. The cumulative travel time from 186 national-level traditional villages to their nearest townships was extracted, yielding accessibility statistics (Table 3). Overall, the travel time for traditional villages in Jincheng ranges from 0.23 to 166.86 minutes, with a mean of 13.88 minutes and a median of 7.44 minutes, indicating favorable overall accessibility and strong service coverage from grassroots townships to villages. However, the range of travel time is extremely large, with a skewness of 4.18, indicating a highly positively skewed distribution. This suggests that only a small number of remote villages significantly increase the mean value and that the spatial differentiation of accessibility is highly pronounced.

Table 3: Statistical Characteristics of Traffic Accessibility of Traditional Villages

Indicator	Minimum	Maximum	Mean	Median	Standard Deviation	Skewness
Access Time (min)	0.23	166.86	13.88	7.44	22.07	4.18

From the perspective of spatial patterns (Figure 3), the accessibility of traditional villages in Jincheng shows a continuous gradient differentiation characterized by superior accessibility in the central area and inferior accessibility in the east and west, as well as being superior in river valleys and inferior in mountainous areas.

Areas with high accessibility (<30 min) are continuously distributed around the urban areas of Jincheng, western Gaoping, central and western Zezhou County, and the Qinhe and Danhe River valleys. The Qinhe and Danhe River valleys in the central part of the city, together with the periphery of the Jincheng urban area, central and western Gaoping, and central and western Zezhou County, constitute the low-value concentration zone of travel time. This region features a gentle terrain, dense road networks and evenly distributed townships. The travel time of the vast majority of the villages is less than 30 min, accounting for 89.8% of the total villages, among which 64.5% have a travel time of less than 10 min.

With the transition to peripheral areas of the city, topographic relief gradually increases, road extension is more constrained by terrain, and township spacing widens, leading to an obvious gradient increase in travel time for traditional villages. In western Qinshui County, the eastern edge of Yangcheng County, central Lingchuan County, and the low hilly areas in southern Zezhou County, the village travel time mostly ranged from 30 to 90 min, indicating a significant decline in traffic efficiency compared with that in the river valley areas. For instance, travel times within the same township can vary by an order of magnitude (e.g., from 2.45 min to 29.51 min in Henghe town) due to topographic differences.

The deep mountainous area of the Taihang Mountains in the southern part of the city is the high-value concentration zone of travel time. In this region, slopes mostly exceed 20°, and road networks are sparse. Despite short straight-line distances between villages and township seats, the actual travel times in the city are concentrated here, namely, Nanzhuang Village in Liushukou Town (124.71 min), Songquan Village in Nanling Township (114.97 min), Huangshadi Village in Nanling Township (111.99 min), Mayu Village in Liushukou Town (102.35 min), and Heishiling Village in Jinmiaopu Town (98.62 min), all in Zezhou County. Such villages have extremely poor traffic conditions, with accessibility levels significantly below the city average.

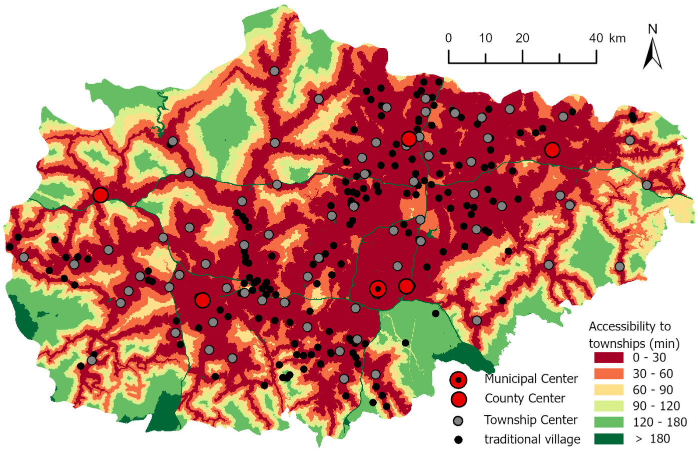

Figure 3: Spatial Distribution Map of Township Accessibility of Traditional Villages in Jincheng

4.3. Coupling Relationships between the Spatial Distribution and Traffic Accessibility of Traditional Villages

To quantitatively verify the spatial correlation between the kernel density of traditional villages and township accessibility, this study adopted a 1 km×1 km grid as the analysis unit and used bivariate global spatial autocorrelation analysis. The results show that the bivariate Moran's I index is 0.0854, with a pseudo p-value of 0.001 (based on 999 permutations), passing the significance test at the 1% level. The z-value is 29.99, which is much larger than 2.58, indicating that the spatial clustering pattern is not randomly generated. These results confirm that there is an extremely significant positive spatial autocorrelation between the kernel density of traditional villages and township accessibility in Jincheng; that is, high-kernel-density areas tend to spatially cluster with high-accessibility areas. Statistically, this finding verifies the strong directional effect of traffic accessibility on the spatial pattern of traditional villages.

In terms of overall spatial matching, the spatial agglomeration pattern and traffic accessibility of traditional villages in Jincheng show a core feature: high-accessibility zones highly coincide with high-density village clusters, and low-accessibility zones strictly correspond to sparsely distributed village areas. Traffic accessibility strongly influences the site selection, development and preservation of traditional villages and serves as a core factor in shaping the spatial differentiation pattern of traditional villages in a city. The coupling pattern of the two is highly consistent with the city's physical geographic base, showing a coordinated differentiation of superiority in the center and inferiority in the east and west, density in river valleys and sparsity in mountainous areas.

Specifically, the Qinhe and Danhe River valleys in the central part of the city have the best overall accessibility, with travel times generally in the low range. This area corresponds exactly to the three high-density agglomeration groups of traditional villages ("one main core and two secondary cores") identified earlier and constitutes the core carrying area of traditional villages in Jincheng. The gentle valley terrain provides favorable conditions for road network layout, and the dense transportation network further strengthens regional accessibility advantages. This not only lays the foundation for the formation and large-scale agglomeration of traditional villages but also provides continuous factor support for their preservation and development, ultimately forming a two-way empowering pattern between accessibility and village agglomeration.

In the deep mountainous areas of the Taihang and Taiyue Mountains on the eastern and western sides of the city, as well as the southern marginal mountainous areas, road density decreases significantly because of complex terrain constraints, and accessibility decreases sharply, accompanied by a synchronous decline in the kernel density of traditional villages. Only a few villages are scattered sparsely in this region without large-scale agglomeration. The worse the accessibility is, the sparser the village distribution. Such synchronous spatial changes further highlight the strong transmission effect among topography, transportation and village distribution in mountainous environments. The six villages with travel times exceeding 90 min in the city are located in low-kernel-density blank areas without any agglomeration characteristics, further confirming the strong restrictive effect of accessibility on the scale of village agglomeration.

5. Discussion and Conclusions

This study constructed a raster cost accessibility model suitable for the Taihang mountainous environment and analyzed 186 national-level traditional villages in Jincheng City. The results reveal a strongly coupled relationship between the spatial distribution of traditional villages and their transportation accessibility, which can be explained by three interrelated mechanisms. Historically, the Qinhe and Danhe River valleys served as ancient commercial routes where convenient transportation fostered population concentration and the formation of contiguous fortress-style villages, thereby establishing the fundamental "valley-concentrated, mountain-sparse" pattern. Naturally, the steep slopes of the Taihang Mountains, especially those exceeding 20°, simultaneously restrict large-scale road construction and limit the availability of gentle land for clustered settlements, creating a transmission chain from terrain constraints to road network differentiation, then to accessibility differentiation, and finally to village distribution. In modern times, townships act as core nodes of the regional road network: high-accessibility areas enjoy dense township distribution and strong service coverage, forming a positive cycle of agglomeration and preservation, while low-accessibility areas suffer from poor transportation, becoming increasingly marginalized and unable to form large clusters. Based on these findings, targeted strategies are proposed for villages with different accessibility levels. For the 89.8% of villages in high-accessibility areas, the three high-density clusters should be integrated into a cultural-tourism corridor, with priority given to slow-traffic systems to protect traditional spatial patterns. For the 6.9% of villages in medium-accessibility areas, county and township roads should be upgraded to connect the "last mile", and niche tourism formats such as farming experiences and heritage study tours should be developed to avoid homogenization. For the 3.2% of villages in low-accessibility areas, high-grade road construction should be avoided; instead, basic access should be secured with minimal intervention, promoting small-scale eco-study or wellness tourism.

In summary, traditional villages in Jincheng City are highly clustered along the Qinhe and Danhe River valleys, forming a "one main core, two secondary cores" pattern. Their overall accessibility is favorable but spatially differentiated, being higher in the central river valleys and lower in the eastern, western and mountainous areas. Accessibility and village distribution are strongly coupled, with high-accessibility zones coinciding exactly with high-density clusters; topography and road networks are the core drivers of this coupling pattern. Future work should incorporate multiple nodes such as highway interchanges and A-level scenic spots to construct a multidimensional accessibility evaluation system.

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