

Article

A Network Evaluation Framework for Identifying Structural Bottlenecks and Analyzing Circulation Efficiency in County-Level Delivery Networks

Ruifen Sun ¹, Han Wang ¹, Yang Shao ^{1,*}, Pengfei Li ² and Alireza Khani ³

¹ School of Modern Posts (Logistics), Xi'an University of Posts and Telecommunications, Xi'an 710061, China; sunruifen@xupt.edu.cn (R.S.); wanghan@stu.xupt.edu.cn (H.W.)

² School of Economics and Management, Xi'an University of Posts and Telecommunications, Xi'an 710061, China; lpf@xupt.edu.cn

³ Industrial and Systems Engineering (ISyE), College of Science and Engineering, University of Minnesota, Minneapolis, MN 55455, USA; akhani@umn.edu

* Correspondence: shaoyang2020@xupt.edu.cn

Highlights

Please indicate how your work links to systems science via your contributions to systems practice, theory, and or methodology.

- This study develops a network evaluation framework for county–township–village delivery networks from the dual perspectives of road-network morphology and hierarchical node structure.
- The framework integrates spatial syntax, complex network analysis, hierarchical connection-cost measurement, and coupling–coordination analysis to assess road accessibility, hierarchical connectivity, connection impedance, and morphology–structure coordination.

What are the main findings and/or the implications of the main findings?

- Higher road-network integration is generally associated with lower hierarchical connection costs, while stronger morphology–structure coordination is significantly related to lower county–village connection impedance and shorter average path length.
- The findings suggest that rural express delivery optimization should move beyond isolated facility expansion or single-route adjustment and instead emphasize coordinated improvement of road accessibility, node layout, and hierarchical connectivity.

Abstract

Fragmentation in road networks and hierarchical imbalances among nodes increase circulation impedance in China's county-level delivery networks, hindering efficient county–township–village circulation. This study integrates spatial syntax, complex network analysis, hierarchical connection-cost analysis, and a coupling–coordination degree model to develop a network evaluation framework for identifying structural bottlenecks and analyzing circulation efficiency. Using eight counties in Shaanxi Province as empirical cases, we quantify road-network accessibility using a spatial syntax axial model and examine hierarchical node organization across county, township, and village tiers using complex network indicators. Network-level circulation efficiency is analyzed using road accessibility, hierarchical connection costs, county–village connection impedance, and average path length. Correlation and regression analyses are further used to examine the relationship between morphology–structure coordination and network impedance. The results show that higher road-network integration is generally associated with lower hierarchical connection



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costs, and higher morphology–structure coordination is significantly associated with lower county–village connection impedance and shorter average path length. The proposed network-level evaluation framework provides a structural basis for identifying accessibility deficiencies, hierarchical connectivity constraints, and morphology–structure mismatches, thereby informing efforts to reduce circulation impedance in county–township–village delivery networks.

Keywords: county-level delivery networks; spatial syntax; complex networks; hierarchical connection costs; coupling–coordination; structural bottlenecks

1. Introduction

In China, counties, townships, and villages form the three-tier grassroots governance and service units that bridge urban and rural areas, collectively constituting the fundamental vehicles for the circulation of resources and delivery of social services across both sectors. Counties implement provincial and municipal policies while extending their influence to townships. As the immediate subordinate units of counties, townships provide direct services to villages. Villages represent the smallest settlement units under township administration, serving as fundamental nodes connecting farming households to markets. This tripartite coordination between counties, townships, and villages collectively forms a hierarchical county–township–village delivery network. The county-level delivery network examined in this paper—specifically the three-tier “county–township–village” system—serves not only as a key infrastructure and vehicle for facilitating the flow of resources between urban and rural areas, promoting integrated urban–rural development, and realizing rural revitalization, but also as a vital safeguard for supporting the national rural revitalization strategy and expanding domestic demand [1]. Structurally, the system features a three-tiered node layout of “county–township–village.” County-level distribution centers serve as critical infrastructure, township service outlets are key nodes for township delivery services, and village-level comprehensive service stations are the vital foundation for bridging the “last mile” of express delivery to rural areas and the “first mile” of agricultural products from villages to cities. In recent years, the scale of rural e-commerce transactions has expanded continuously [2,3], with delivery demands for both the upward flow of agricultural products and the downward flow of industrial goods increasing rapidly [4,5]. Against this backdrop of rapid development, the core challenge facing the county–township–village delivery logistics system is the high cost of the “last mile” [6]. On the one hand, topological defects in the spatial morphology of the road network result in highly circuitous delivery routes, causing last-mile delivery costs in rural areas to be significantly higher than in urban areas, with some administrative villages still underserved by delivery services [7]. On the other hand, there is an imbalance in the layout and hierarchical functions of logistics nodes, with a significant disconnect and insufficient integration between “strong county-level hubs” and “weak village-level endpoints” [8–10]. These issues ultimately result in inefficient two-way circulation of “industrial goods to rural areas” and “agricultural products to urban centers” [11], not only exacerbating the imbalance in urban–rural resource allocation [12,13] but also posing challenges for the “parcel delivery to villages” initiative, such as low coverage rates for last-mile delivery and high transport costs [14,15].

Given the operational models and efficiency optimization needs of the county–township–village delivery logistics system, existing research has primarily focused on logistics network planning, efficiency and performance evaluation, and the optimization of

logistics models and layouts to address specific operational and structural issues within the system [16–19]. Although these studies address important operational and structural issues, they often rely on static planning models or aggregate statistical data and therefore provide limited explanations of the micro-spatial characteristics of road networks and the hierarchical connectivity of delivery-network nodes.

In terms of the application of spatial syntax, scholars have used it to reveal the spatial organization patterns of road networks [20], providing an important perspective for analyzing the spatial organizational structure of logistics networks. LI et al. [21] applied spatial syntax to a quantitative analysis of suburban villages to explore the relationship between spatial form and industrial structure. Koohsari et al. [22] established a link between urban spatial structure and pedestrian traffic through quantitative spatial syntax analysis, providing a reference for logistics route accessibility; Zhang et al. [23] quantified road network depth, integration, and choice to validate the role of spatial syntax indicators in analyzing the impact of road network structure on the efficiency of logistics resource flow. Regarding the application of complex network theory, existing research has largely focused on macro-level logistics networks or single-tier nodes [24]. Particularly in the field of rural logistics, such approaches are often used to describe the distribution of e-commerce outlets or the circulation pathways of agricultural products [25]. However, research on the integrated structural organization of three-tier county–township–village delivery networks, their spatial heterogeneity, last-mile road accessibility, and the structural roles of hierarchical nodes remains relatively scarce [26]. Nevertheless, the analytical capabilities demonstrated by this method in fields such as urban transportation [27], international trade [28], and rail transit [29] provide important references for analyzing the node structure of delivery systems.

Based on the above review, we observe that existing studies primarily focus on individual cities or rural areas, with a strong emphasis on spatial structure and planning [30] and the relationship between urban road networks and economic activities [31]. However, these studies have not fully explained how road network morphology and node structure jointly shape circulation efficiency within delivery networks [32]. Existing operational logistics efficiency evaluations often rely on aggregate or static indicators [33], while the structural effects of road network topology and hierarchical node organization remain insufficiently examined [34,35]. Most critically, existing research lacks a systematic evaluation of rural delivery networks and has not yet established a comprehensive evaluation framework that integrates both the spatial morphology of road networks and the topological hierarchy of nodes, making it difficult to quantify how the relationship between road accessibility and node organization affects network-level circulation impedance and hierarchical connection costs.

Therefore, this study develops a network evaluation framework for identifying structural bottlenecks and analyzing network-level circulation efficiency in county-level delivery networks, using eight counties in Shaanxi Province as empirical cases. Network-level circulation efficiency is examined through road accessibility, hierarchical connection costs, circulation impedance, and average path length. By integrating spatial syntax and complex network analysis, the study investigates the relationships among road-network morphology, hierarchical node structure, and circulation efficiency. Spatial syntax is used to quantify road network accessibility, treating the road network as the physical framework of county–township–village circulation. Complex network analysis is used to characterize hierarchical topological relationships among county, township, and village nodes. On this basis, hierarchical connection-cost indicators are introduced to measure country–town, town–village, county–village, and village–village circulation impedance. The study further uses a morphology–structure coupling–coordination model and correlation and regression verifi-

cation to examine whether coordinated road morphology and node structure are associated with lower network-level connection costs. The analysis provides evidence for identifying morphology–structure mismatches, reducing hierarchical circulation impedance, and improving the structural organization of county–township–village delivery networks. Figure 1 presents the research framework.

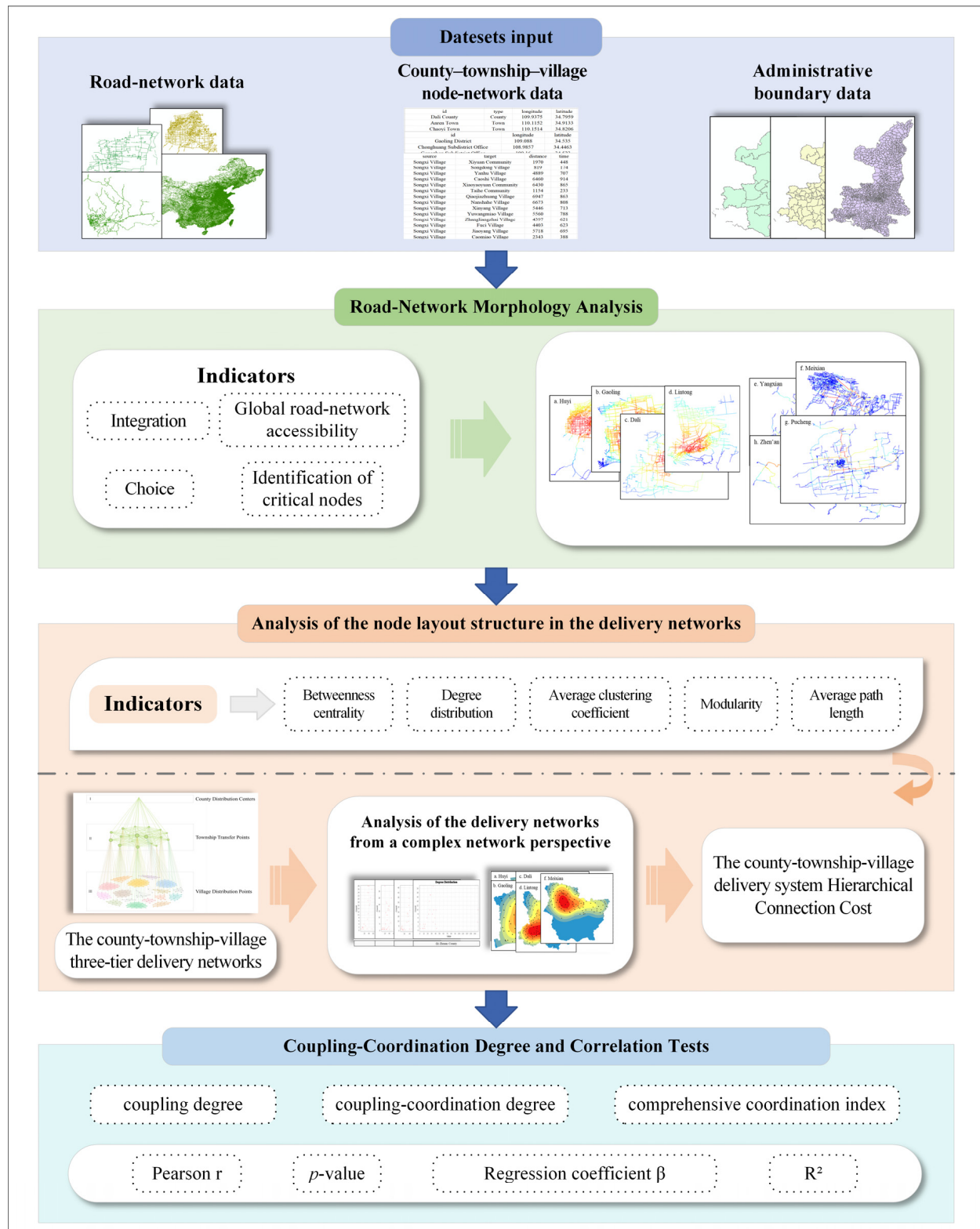


Figure 1. Graphical summary.

2. Data Sources and Research Methodology

2.1. Research Area

Shaanxi Province is located in China's inland hinterland, spanning the middle reaches of the Yellow River and the Han River basin, as shown in Figure 2. This paper selects eight county-level regions as representative county–township–village delivery networks: Huyi, Gaoling, and Lintong Districts in Xi'an City; Dali and Pucheng Counties in Weinan City; Meixian County in Baoji City; Yangxian County in Hanzhong City; and Zhen'an County in Shangluo City. These cases differ in road network density, settlement dispersion, terrain constraints, node hierarchy, and road–node coordination patterns. Huyi, Gaoling, and Lintong have relatively dense road networks and stronger urban–rural connectivity; Dali and Pucheng represent county networks with more dispersed township–village connections; Meixian exhibits a relatively balanced node organization; while Yangxian and Zhen'an are characterized by more severe terrain constraints, more dispersed settlements, and higher cross-tier connection impedance. Therefore, the eight counties are used as multi-case county-level delivery networks to examine how differences in road-network morphology, node-network structure, and road–node coordination are reflected in network-level circulation impedance.

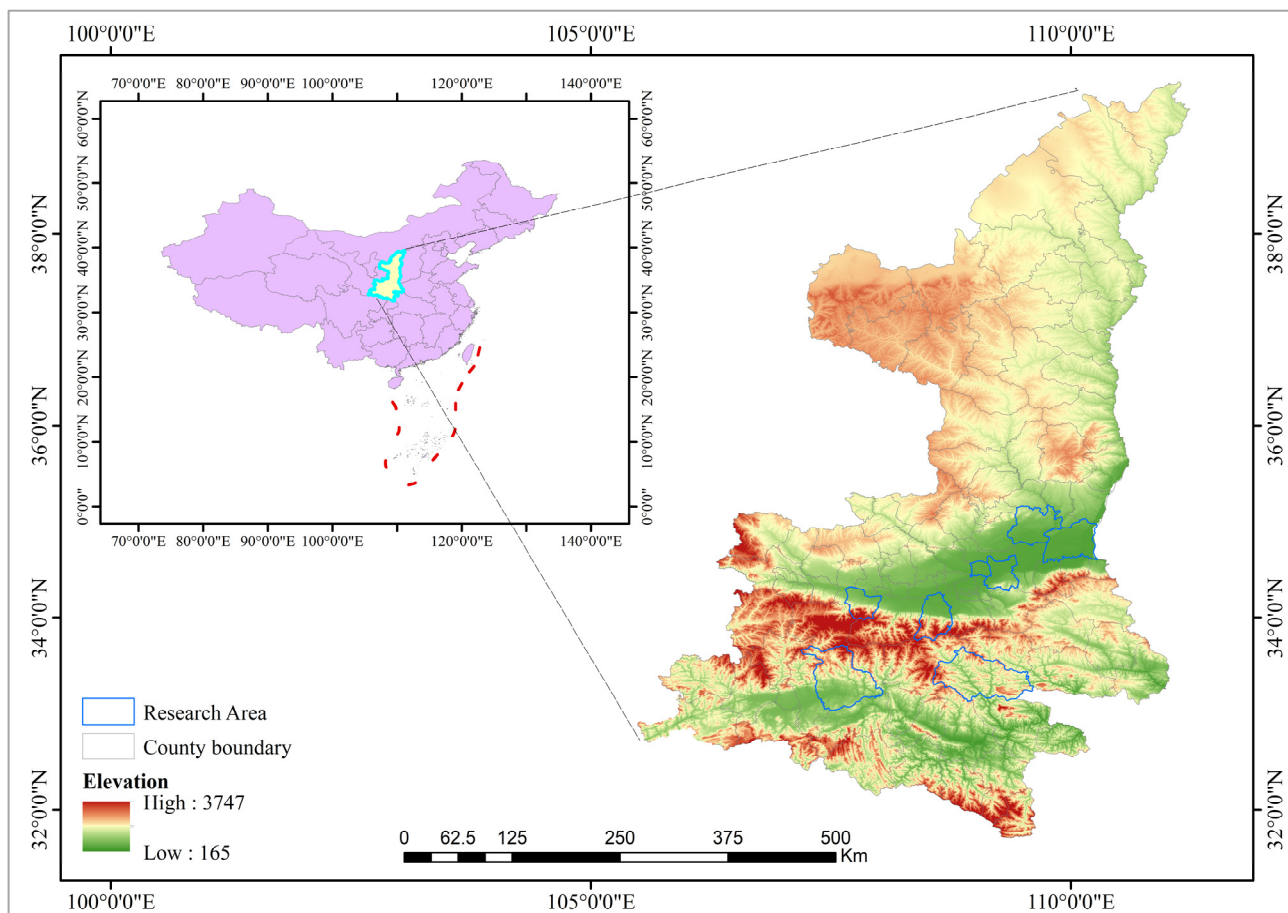


Figure 2. Location overview map of Shanxi Province.

2.2. Data Sources

The data used in this study include:

(1) Road-network data for the study areas were obtained from open platforms such as OpenStreetMap (OSM) and processed through vectorization. The dataset covers highways, national highways, county roads, and village roads.

(2) The hierarchical delivery-network data include county-, township-, and village-level node coordinates, node-link relationships, and inter-node distances. The latitude and longitude data of the county-township-village nodes were obtained through Amap and were used to construct the hierarchical node network. The inter-node distance data were used to calculate hierarchical connection costs, including county-town, town-village, county-village, and village-village connection distances. Because this study focuses on the county-township-village hierarchical delivery network, enterprise outlet locations were not incorporated into the main analysis to maintain consistency with the network-level research object.

(3) During the study period, the dataset underwent standardized processing. Before constructing the network, duplicate nodes, records with anomalous coordinates, and isolated records were removed. The consistency between the road network data and node locations was verified using the OSM road layer, Amap coordinates, and county-level administrative boundaries. All county-level indicators were aggregated and standardized at the county level before conducting cross-county comparisons.

2.3. Research Methods

2.3.1. Spatial Syntax Axial Analysis

Spatial syntax analysis is a quantitative approach to examining spatial form and has been widely applied in urban planning, transport network design, and urban morphology research [36,37]. This paper quantifies road network morphological characteristics using two commonly employed variables from the spatial syntax axial model: integration and choice. Integration denotes a node's centrality within the global road network, while choice reflects a node's mediating role in path selection [38,39].

First, based on vector road network data, the actual road network of the study area is simplified into straight lines using AutoCAD 2021 software to represent the connectivity of the road network. The data are then exported in DXF format and imported into Depthmap+ Beta 1.0 (2012) software to generate an axial analysis model capable of topological calculations. This enables integration and choice analysis of the spatial morphology within the study area, thereby completing the construction and analysis of the axis diagram model. The relevant formulas are as follows:

1. Global integration: A measure of the accessibility of road network nodes in the overall topology, calculated as:

$$I_i = \frac{n \cdot \log(n + 1)}{D_i}$$

where I_i is the integration value of node i , n is the total number of nodes, and D_i is the average topological depth of node i to other nodes.

2. Choice: Characterizes the mediating role of nodes in the shortest path and is calculated as:

$$C_i = \sum_{s \neq i \neq t} \frac{\sigma_{st}(i)}{\sigma_{st}}$$

where C_i is the choice value of node i , is the total number of shortest paths from node s to t , is the number of shortest paths $s \rightarrow t$ passing through node i , and the summation ranges over all pairs of nodes satisfying $s \neq i \neq t$.

2.3.2. Complex Network Analysis

In urban transport systems, complex network models have been employed to analyze the “small-world” properties and scale-free characteristics of road networks [40,41]. By identifying key transport hubs through node betweenness centrality and degree distribution, these models optimize the redundancy and fault tolerance of urban road networks.

This study applies complex network analysis to model the hierarchical relationships among county–township–village delivery nodes and constructs a three-tier network representing their spatial organization. County-level distribution centers, township-level transfer stations, and village-level delivery points serve as primary, secondary, and tertiary nodes, respectively. Using Gephi 0.10.1 software, network topology diagrams are generated to analyze node metrics, including betweenness centrality, degree distribution, average clustering coefficient, modularity, and average path length. The relevant formulas are shown in Table 1. This approach visualizes potential circulation paths within the hierarchical delivery network and identifies weak links in inter-tier connectivity [42,43].

Table 1. Formulas for complex-network indicators.

Name of Indicator	Formula	Connotation
Betweenness Centrality	$BC(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$	σ_{st} denotes the total number of shortest paths from node s to t ; $\sigma_{st}(v)$ denotes the number of shortest paths through node v ; v, s, t are nodes in the network.
Degree Distribution	$P(k) = \frac{N_k}{N}$	N_k denotes the number of nodes of degree k ; N denotes the total number of network nodes.
Average Clustering Coefficient	$C = \frac{1}{N} \sum_v \frac{2T(v)}{k_v(k_v - 1)}$	$T(v)$ denotes the number of edges that actually exist between neighbors of node v ; k_v denotes the degree of node v ; N denotes the total number of network nodes.
Modularity	$Q = \frac{1}{2m} \sum_{ij} \left[A_{ij} - \frac{k_i k_j}{2m} \right] \delta(c_i, c_j)$	A_{ij} denotes the element of adjacency matrix, where 1 denotes connection and 0 denotes no connection; k_i denotes the degree of node i ; m denotes the total number of edges in the network; $\delta(c_i, c_j)$ denotes 1 if nodes i, j are in the same community and 0 otherwise.
Average Path Length	$L = \frac{1}{N(N-1)} \sum_{i \neq j} d_{ij}$	d_{ij} denotes the shortest path length from node i to j ; N denotes the total number of nodes in the network.

2.3.3. Hierarchical Connection-Cost Analysis

To provide a network-level proxy for circulation impedance, this study constructs hierarchical connection-cost indicators based on graph-theoretic shortest-path distance and average path length [44]. The indicators measure the circulation impedance among county-, township-, and village-level nodes.

3. The average hierarchical connection cost is calculated as:

$$\overline{D}_{ab} = \frac{1}{|P_{ab}|} \sum_{(i,j) \in P_{ab}} d^*(i, j)$$

where a, b represent node types at different hierarchical levels, which can be country–town, town–village, county–village, or village–village, respectively; P_{ab} denotes the set of a – b hierarchical node pairs included in the calculation; $|P_{ab}|$ is the number of node pairs; and $d^*(i, j)$ denotes the network path distance between node i and node j .

2.3.4. Coupling–Coordination Degree Model

To further quantify the coordination relationship between road-network morphology and node-network structure, this study introduces the coupling–coordination degree model. The coupling–coordination model is widely used to measure the interaction and coordinated development level between two or more subsystems [45]. In this study, road-network morphology and node-network structure are regarded as two interacting subsystems.

The model is used to supplement the quadrant classification by providing a continuous quantitative measure of morphology–structure coordination.

The coupling degree is calculated as:

$$C_i = \frac{2\sqrt{MI_i} \times SI_i}{MI_i + SI_i}$$

where C_i denotes the coupling degree of county i , and MI_i and SI_i denote the comparable positive values of the morphology index and structure index, respectively.

The comprehensive coordination index is calculated as:

$$T_i = \alpha MI_i + \beta SI_i$$

where T_i is the comprehensive coordination index, and α and β are the contribution coefficients of road-network morphology and node-network structure. Because the two subsystems are assigned equal importance in this study, α and β are both set to 0.5.

The coupling–coordination degree is calculated as:

$$D_i = \sqrt{C_i \times T_i}$$

where D_i denotes the morphology–structure coupling–coordination degree. A higher D_i indicates a higher coordination level between road-network morphology and node-network structure.

3. Analysis of Delivery Network Morphology and Structural Layout from Dual Perspectives

3.1. Analysis of Road-Network Morphology from a Spatial Syntax Perspective

3.1.1. Global Road Network Accessibility Based on Integration

Global integration is used to measure the accessibility and centrality of a node in the entire spatial road network, usually by calculating the average topological depth of a node to its neighboring nodes. Higher integration values are represented by warmer colors, whereas lower values are represented by cooler colors.

Topological analysis of the road networks of eight study areas was conducted using the spatial syntax axial model on the road network data of these eight regions to calculate their global integration indices. As shown in Figure 3, the spatial distribution of global integration exhibits a “warm-center, cold-periphery” pattern overall, indicating differences in road accessibility within the county-level delivery network. It follows that these roads with higher integration scores are largely situated along axes in the central zones of the entire network, connecting major thoroughfares or pathways to form radial- or grid-like topological structures. The Huyi and Gaoling regions exhibit distinct grid-like patterns, while Yangxian and Zhen’an counties display pronounced radial configurations.

These areas show stronger global accessibility within the road network and provide important spatial support for cross-tier circulation between county, township, and village nodes. This indicates that highly integrated roads may function as key circulation corridors within the county-level delivery network. Conversely, peripheral roads, which are predominantly situated at the edges of the network, exhibit relatively low accessibility. Their road network morphology displays linear extensions or tree-like branching characteristics, largely connecting remote villages with complex topography or sparsely populated areas. Their topology exhibits stronger fragmentation and greater path detours, resulting in weaker overall reachability. Such road morphology may increase network depth and path detours, thereby raising potential circulation impedance for terminal village nodes.

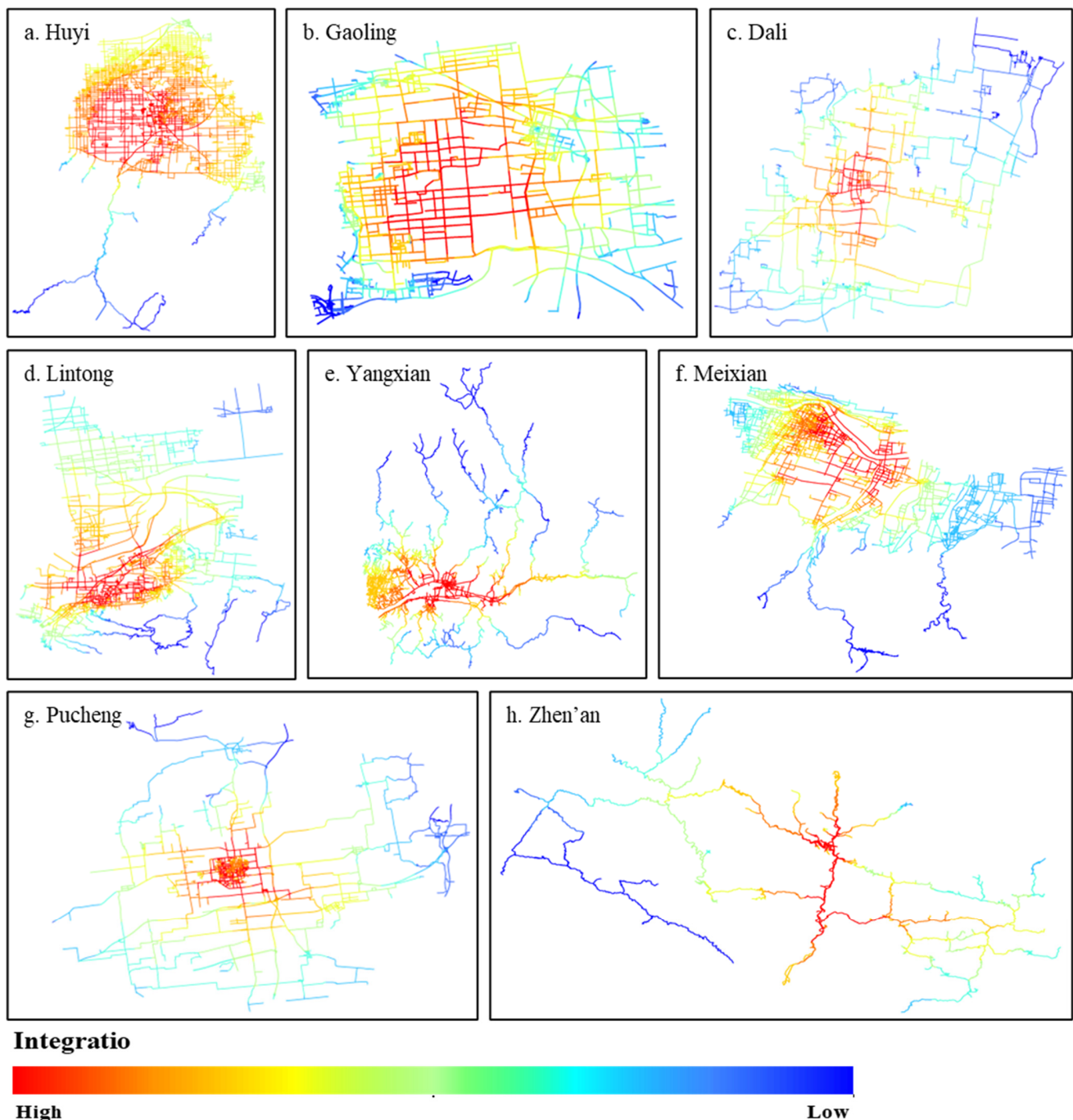


Figure 3. Road network integration analysis for each study area.

3.1.2. Key Road Network Corridors Based on Choice

Choice quantifies the importance of a network node as an “intermediary bridge” within the network. A higher choice value indicates that the node appears more frequently in connection paths between other nodes. Nodes or road segments with high choice are often located at the intersection of multiple shortest paths, indicating stronger path-mediating functions within the delivery network. In Figure 4, warmer colors represent higher choice degrees, while cooler colors indicate lower choice degrees.

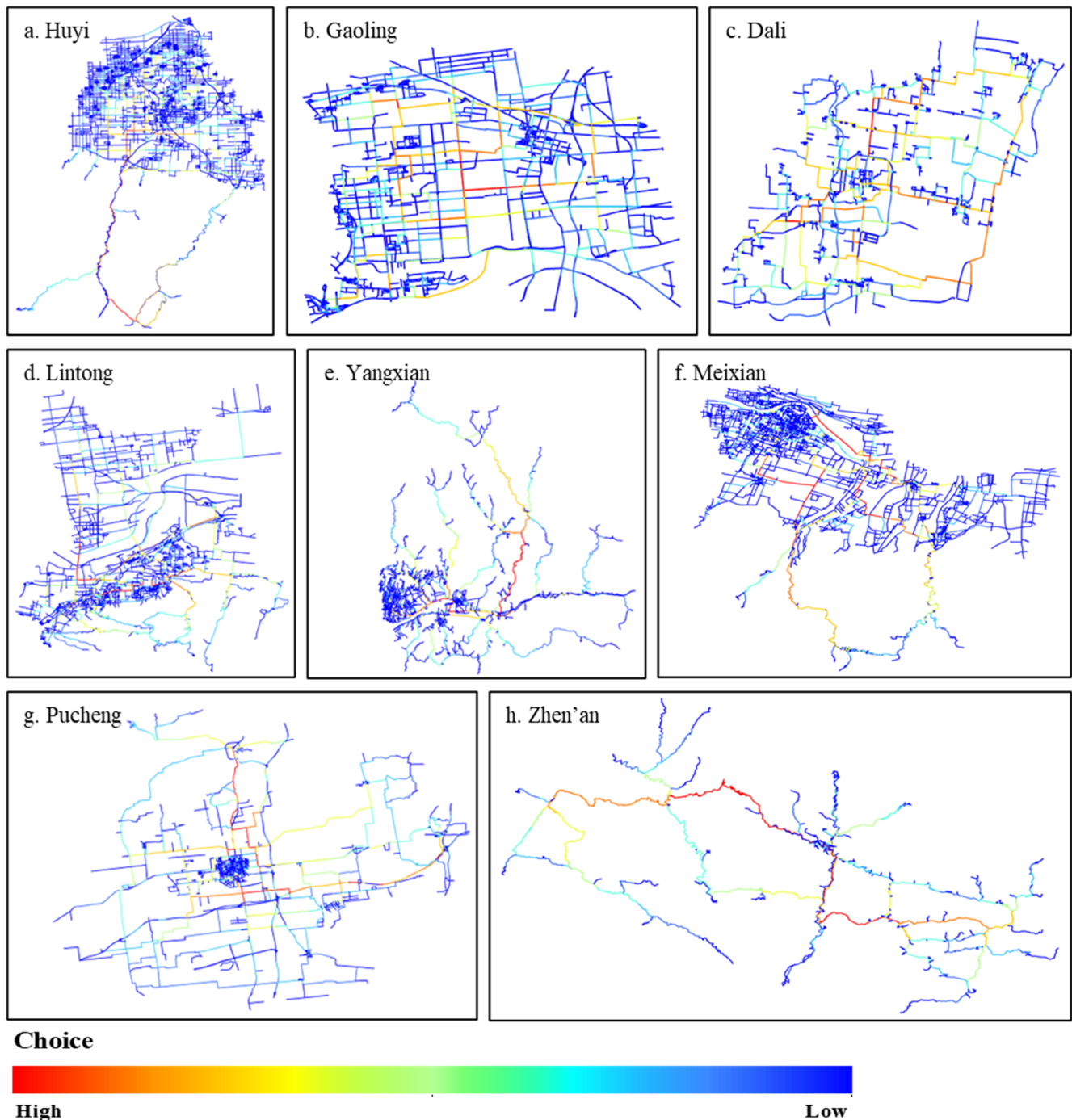


Figure 4. Road network choice degree analysis for each study area.

Overall, the intermediary nodes within the road networks of the eight study regions exhibit a hierarchical distribution pattern characterized by “hub-and-spoke” differentiation, as illustrated in Figure 4. Nodes with higher choice within the study areas are concentrated at the intersections of critical network paths, forming darker warm-toned lines within the road network. These high-choice routes indicate stronger path-mediating functions and may serve as key circulation corridors within the county-level delivery network. The spatial distribution of these routes suggests that they play an important role in linking different subareas and reducing detours across the road network. In contrast, terminal roads within each region generally exhibit lower choice, with nodes predominantly distributed along village-level secondary roads or in topographically isolated areas. These roads have

weaker intermediary functions, and circulation between nodes may depend more heavily on indirect or longer paths, resulting in higher potential path impedance.

3.2. Hierarchical Node Network Structure Analysis Based on Complex Networks

Nodes at various levels within Yangxian County, Shaanxi Province, are used as an example to illustrate the hierarchical characteristics of the county–township–village delivery node system, as shown in Figure 5.

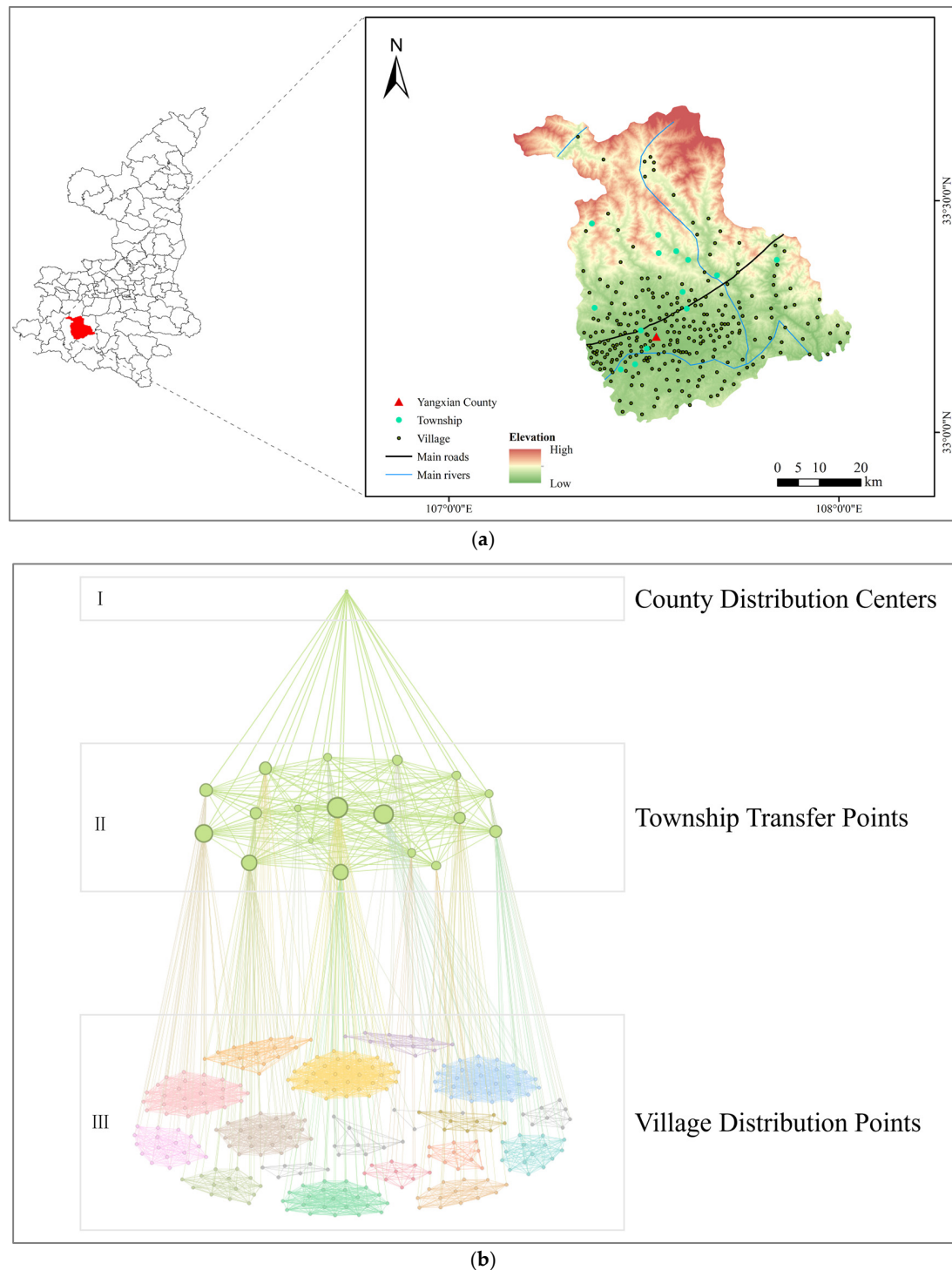


Figure 5. (a) Distribution of nodes at county, township, and village levels in Yangxian County. (b) Hierarchical structure of the county–township–village delivery network. In panel (b), different colors represent administrative-village nodes affiliated with different townships.

3.2.1. Identification of Hub Nodes Based on Betweenness Centrality

Betweenness centrality serves as a core metric for evaluating a node's intermediary function in complex network analysis. This study calculates the betweenness centrality values for nodes across counties, towns, and villages within the research area based on their geographic distribution. These values are visualized using heatmaps, as shown in Figure 6. This metric indicates the frequency with which a node appears in the shortest path between any two other nodes. Higher values signify stronger path-mediating functions and greater influence on hierarchical network connectivity. This allows for the identification of key transshipment nodes and potential weak points in hierarchical connections within the network.

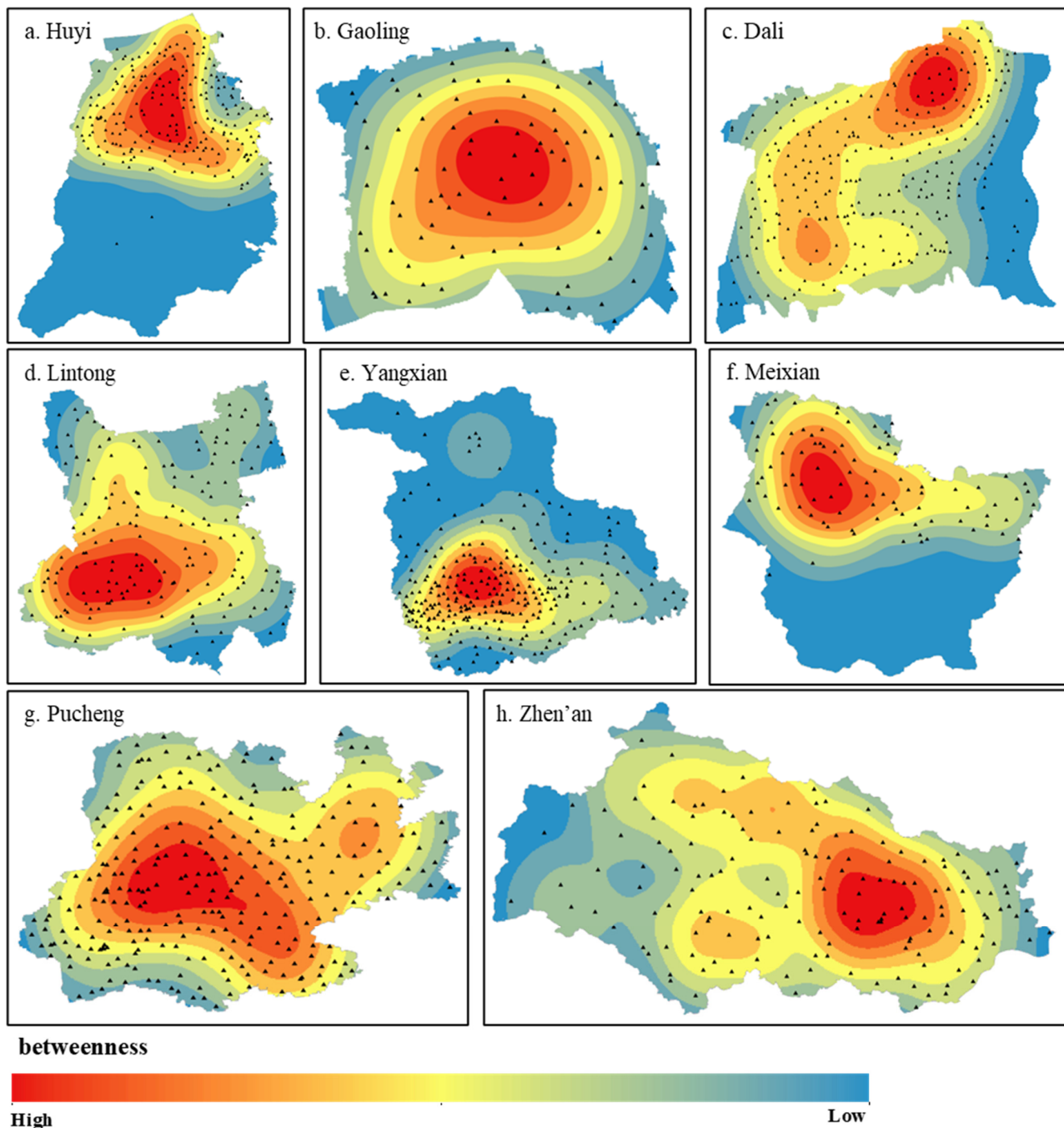


Figure 6. Betweenness centrality analysis for each study area. Black triangles represent county-, township-, and village-level nodes.

In areas with high centrality values for county-level distribution centers, such as Yangxian and Zhen'an Counties, county-level nodes play a stronger intermediary role in connecting township and village nodes. Conversely, township-level transshipment stations and village-level delivery points exhibit generally low centrality values, indicating that their network functions are more localized. In regions like Gaoling and Meixian Counties, county-level distribution centers and township-level nodes form a more coordinated connection pattern, suggesting smoother hierarchical organization and lower dependence on a single central node.

3.2.2. Node Connectivity Analysis Based on Degree Distribution

Degree distribution describes the probability distribution of connection counts between nodes in a network, reflecting the overall connection patterns among nodes. As shown in Figure 7, county-level distribution centers and town-level transfer stations in each region serve as hub nodes. Due to their high connection counts, their degree centrality values are significantly elevated. In contrast, village-level delivery points exhibit relatively uniform connection counts, without prominent hub nodes.

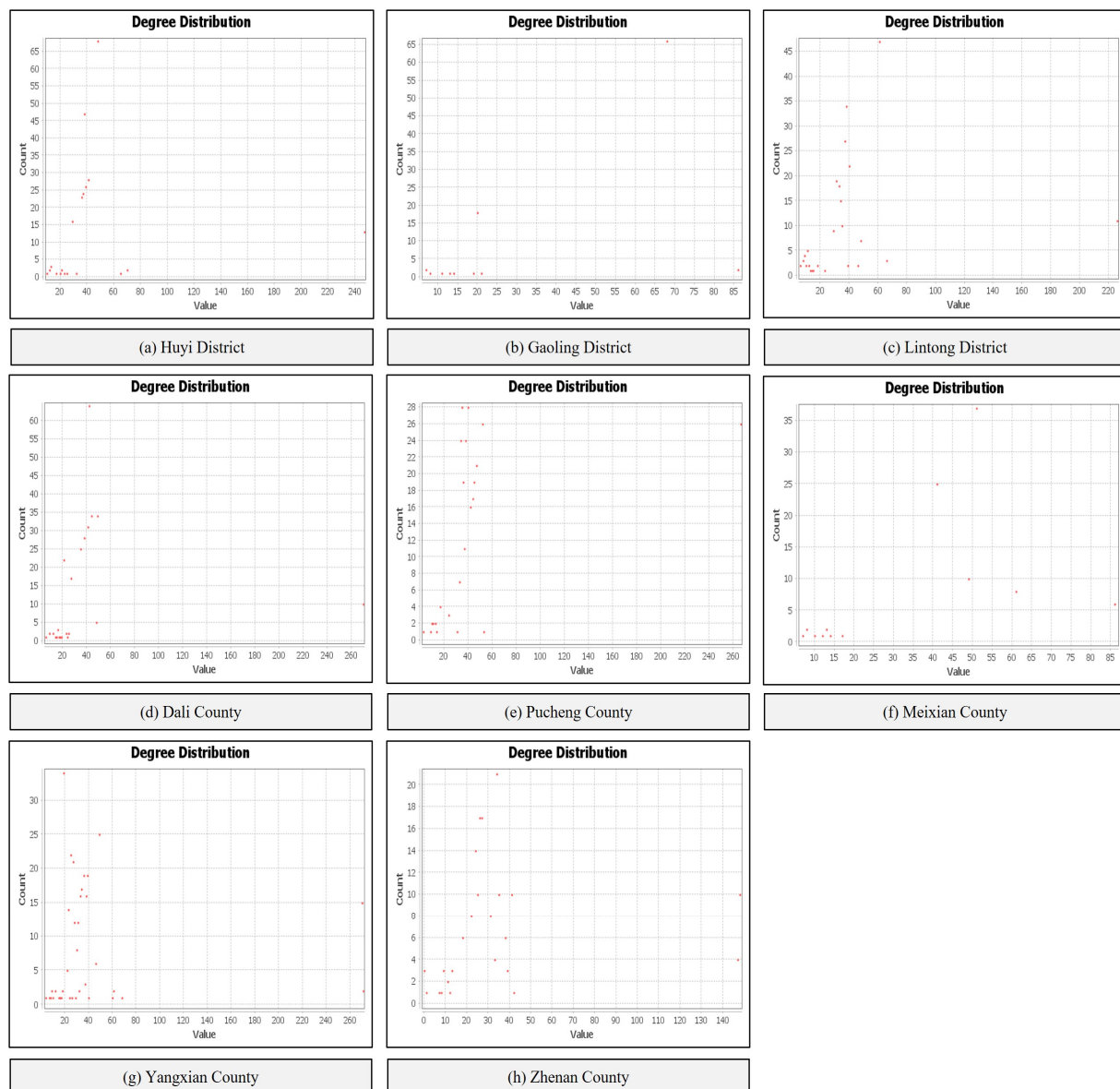


Figure 7. Analysis of degree distribution by study area.

In areas such as Gaoling and Huyi, the number of connections for county-level hubs and town-level nodes exhibits a distribution pattern where “a small number of hub nodes concentrate a large volume of connections, while the majority of terminal nodes have sparse connections.” This indicates that network connections are highly concentrated at county- and town-level hubs. Among village-level nodes, however, degree centrality values are generally low, with connections distributed evenly, reflecting the relatively flat structure of the terminal node network. In Zhen’an County and Yangxian County, the degree distribution shows higher degree centrality values for county-level hubs, while town-level and village-level nodes exhibit significantly lower degree centrality compared to county seats, with a stark disparity in connection numbers across hierarchical levels.

3.2.3. Analysis of the Tightness of Network Nodes Based on Average Clustering Coefficient

The average clustering coefficient measures the closeness of connections between nodes, reflecting the redundancy within local networks. Higher values indicate greater local path redundancy and stronger local connection stability. Table 2 reveals that Gaoling District and Dali County exhibit clustering coefficients of 0.931 and 0.910, respectively, significantly surpassing other regions. This suggests relatively dense local connections between town-level transfer stations and village-level nodes. In contrast, Zhen’an County and Pucheng County exhibit lower clustering coefficients of 0.856 and 0.865, respectively, reflecting a looser terminal network structure. Zhen’an County’s village-level branch routes extend in a tree-like pattern, with limited lateral connections between nodes and stronger dependence on town-level nodes for secondary circulation.

Table 2. Complex network related metrics.

Name of County (District)	Average Clustering Coefficient	Modularity	Average Path Length
Huyi District	0.899	0.571	1.808
Gaoling District	0.931	0.136	1.427
Lintong District	0.869	0.572	1.868
Dali County	0.910	0.642	1.876
Pucheng County	0.865	0.319	1.789
Meixian County	0.878	0.379	1.501
Yangxian County	0.876	0.398	1.865
Zhenan County	0.856	0.382	1.793

3.2.4. Identification of Community Structures Based on Modularity

Modularity serves as a measure of the cohesiveness of a network’s division into community structures, with values ranging from 0 to 1. Higher values indicate tighter internal connections within communities and fewer cross-community links. Highly modular areas with values > 0.4, such as Huyi District, Dali County, and Lintong District, show stronger community segmentation, indicating that circulation may be more concentrated within local subgroups. Low-modularity areas with values (<0.3), notably Gaoling District (0.136), exhibit low modularity, indicating a highly integrated network. County-level nodes are more directly connected with town and village nodes through radial pathways, suggesting a more integrated hierarchical connection pattern. Dali County and Lintong District exhibit the highest modularity values at 0.642 and 0.572, respectively, where networks are segmented into distinct sub-communities along township administrative boundaries. Notably, Yangxian County and Zhen’an County exhibit modularity values of 0.398 and 0.382, respectively, revealing transitional characteristics in node-network segmentation. Some village communities distributed along valley corridors show relatively strong internal connections,

while cross-community connections remain limited, indicating that the hierarchical node network has not yet formed a fully balanced structure.

3.2.5. Overall Network Impedance Based on Average Path Length

The average path length represents the mean of the shortest paths between all nodes within a network, reflecting the overall path impedance of node circulation. A lower value indicates that nodes can be connected through fewer intermediate steps, suggesting a more compact network structure and lower network-level circulation impedance. Gaoling District and Meixian County exhibit the shortest average paths, indicating relatively compact node-network structures and lower overall path impedance. Conversely, Dali County and Lintong District feature longer average path lengths, where stronger community segmentation may require more intermediate connections for cross-community circulation. Although Zhen'an County exhibits marginally shorter path lengths than Dali County, its lower clustering coefficient indicates weaker local connection redundancy, suggesting that terminal circulation may still face structural constraints. These differences suggest that settlement dispersion, road-network configuration, and community segmentation jointly influence path impedance within county-level delivery networks. Therefore, average path length is used as a structural indicator of network impedance in the subsequent verification of morphology–structure coordination.

3.3. Verification of Hierarchical Connection Costs

To further examine whether the structural differences identified by complex network indicators are reflected in measurable inter-tier circulation impedance, hierarchical connection costs were calculated for the eight counties, as shown in Table 3. The indicators include country–town, town–village, county–village, and village–village connection distances. These indicators are used to characterize network-level circulation efficiency by measuring hierarchical connection impedance.

Table 3. Hierarchical connection costs of the eight counties.

County	County–Town km	Town–Village km	County–Village km	Village–Village km	County–Village Median km	Village–Village Median km
Gaoling	7.561	10.235	7.71	10.862	7.219	9.994
Huyi	12.146	8.193	11.651	9.674	11.607	7.463
Lintong	11.077	12.107	15.97	11.083	15.236	8.35
Dali	15.044	9.015	25.49	15.136	25.899	11.89
Pucheng	13.377	12.964	19.269	22.144	19.669	18.151
Meixian	16.863	8.492	14.976	12.958	14.297	11.901
Yangxian	24.772	6.39	26.544	29.162	21.008	22.747
Zhen'an	27.345	21.782	44.928	40.847	44.406	30.733

The results show clear differences in hierarchical circulation impedance among the eight counties. Gaoling has the lowest country–town average connection distance (7.561 km) and county–village average connection distance (7.710 km), indicating a compact vertical circulation structure. Huyi also shows relatively low county–village and village–village connection distances, suggesting lower terminal circulation costs. In contrast, Zhen'an has the highest country–town average connection distance (27.345 km), county–village average connection distance (44.928 km), and village–village average connection distance (40.847 km), indicating high vertical and terminal-level circulation impedance. Yangxian also shows relatively high county–village and village–village connection costs, reflecting the constraints of dispersed settlements and longer network detours.

These results indicate that the differences identified by complex network indicators are not only reflected in abstract topology, but also in measurable hierarchical connection costs. Therefore, hierarchical connection costs provide a direct network-level basis for the subsequent verification of whether morphology–structure coordination is associated with lower circulation impedance.

4. Morphology–Structure Coupling Coordination and Network Impedance Verification

After identifying road-network accessibility, hierarchical node organization, and hierarchical connection costs, the analysis further examines whether the coordination between morphology and structure is associated with lower network-level circulation impedance. In this context, morphology represents the accessibility condition of the road network, while structure represents the organization of county, township, and village nodes. MI and SI are first constructed to describe the two subsystems, and the coupling–coordination degree is calculated to measure their matching relationship. The morphology–structure relationship of the eight counties is then classified and compared, followed by correlation and regression analyses to verify whether higher coordination corresponds to lower county–village connection cost and lower average path length.

4.1. Regional Classification and Coordination Identification Based on Morphology–Structure Characteristics

Based on the dual-perspective analysis of road-network morphology and node-network structure, this study constructs a morphology index (MI) and a structure index (SI). MI is derived from standardized road-network integration because integration directly reflects the global accessibility and topological depth of the road network, which is consistent with the study's focus on inter-tier circulation impedance. Choice is used to identify key corridors and path-mediating routes, but it is not included in MI because it mainly reflects local route control rather than overall county-level accessibility. SI integrates betweenness centrality and modularity to capture the two core structural features of the node network: hub control and community fragmentation. Betweenness centrality reflects the transshipment capacity of key nodes, while modularity reflects the degree of structural segmentation. The quadrant classification method based on MI and SI is used to identify representative morphological-structural types, and the coupling–coordination model further quantifies the continuous coordination level between road-network morphology and node-network structure.

Table 4 presents the standardized data for each indicator. The relevant formula is as follows:

1. Data Standardization (Normalization): Min–Max Normalization Method.

$$X_{\text{norm}} = \frac{X - X_{\min}}{X_{\max} - X_{\min}}$$

where X denotes the raw value of the indicator requiring standardization, $X_{\min}$ denotes the minimum raw value of that indicator across all samples in the county, and $X_{\max}$ denotes the maximum raw value of that indicator across all samples in the county.

2. MI: Uses the standardized integration measure to quantify spatial accessibility.

$$MI = \text{Norm_Integration}$$

3. SI: Constructed based on standardized betweenness centrality and modularity to reflect hub control and structural fragmentation.

$$SI = \frac{-\text{Norm_Modularity} + \text{Norm_Betweenness}}{2}$$

Table 4. Standardized indicators for morphology–structure analysis.

Id	I	B	M	I_norm	B_norm	Q_norm
Huyi	0.063512	0.000075	0.571000	0.230323	0.014744	0.859684
Gaoling	0.235300	0.000877	0.136000	1.000000	0.710321	0.000000
Lintong	0.115000	0.000541	0.572000	0.461010	0.418474	0.861660
Dali	0.135300	0.000207	0.642000	0.551961	0.128794	1.000000
Pucheng	0.126900	0.000058	0.319000	0.514326	0.000000	0.361660
Meixian	0.095400	0.001211	0.379000	0.373194	1.000000	0.480237
Yangxian	0.027700	0.000063	0.398000	0.069872	0.004337	0.517787
Zhen'an	0.012105	0.000223	0.382000	0.000000	0.143105	0.486166

Note: I denotes road-network integration, B denotes betweenness centrality, M denotes modularity, and norm indicates a standardized value.

Based on these standardized indicators, MI, SI, coupling degree, comprehensive coordination index, and coupling–coordination degree were further calculated. The results are shown in Table 5.

Table 5. Morphological–structural classification and results on coupling coordination.

County	MI	SI	Type	C	T	D
Huyi	0.230	−0.422	Network-fragmented	0.452	0.122	0.235
Gaoling	1.000	0.355	Highly collaborative	0.993	0.895	0.943
Lintong	0.461	−0.222	Form-dominant	0.931	0.338	0.560
Dali	0.552	−0.436	Form-dominant	0.003	0.276	0.027
Pucheng	0.514	−0.181	Highly collaborative	0.941	0.385	0.602
Meixian	0.373	0.260	Hub-dependent	0.953	0.534	0.714
Yangxian	0.070	−0.257	Network-fragmented	0.899	0.124	0.334
Zhen'an	0.000	−0.172	Hub-dependent	0.004	0.132	0.023

Note: C denotes coupling degree, T denotes comprehensive coordination index, and D denotes coupling–coordination degree.

As shown in Table 5, MI reflects the global accessibility of the road network, while SI reflects the organizational condition of the hierarchical node network. The results show clear morphology–structure differences among the eight counties. Gaoling has the highest MI and a positive SI, indicating strong road-network accessibility and relatively coordinated node organization. In contrast, Yangxian and Zhen'an have lower MI values, while Huyi and Dali show lower SI values, suggesting that accessibility weakness and structural fragmentation appear in different counties.

To visualize these differences, the eight counties were mapped into a morphology–structure quadrant framework based on MI and SI, with the quadrants defined by the median values of MI and SI as the dividing thresholds (Figure 8). The quadrant classification identifies representative morphology–structure types, while the coupling–coordination degree in Table 5 further provides a continuous measure of the matching level between road-network morphology and node-network structure. Gaoling shows the highest coordination level ($D = 0.943$), indicating that strong road accessibility and relatively organized node structure reinforce each other. Meixian, Pucheng, and Lintong also show moderate-to-high coordination levels, suggesting that their road morphology and node organization are relatively compatible. In contrast, Dali ($D = 0.027$) and Zhen'an ($D = 0.023$) have the lowest coordination levels, but for different reasons: Dali has relatively favorable road morphology but weak node-network organization, while Zhen'an is mainly constrained by weak road-network accessibility. This contrast shows that low coordination may result from either structural fragmentation or accessibility deficiency.

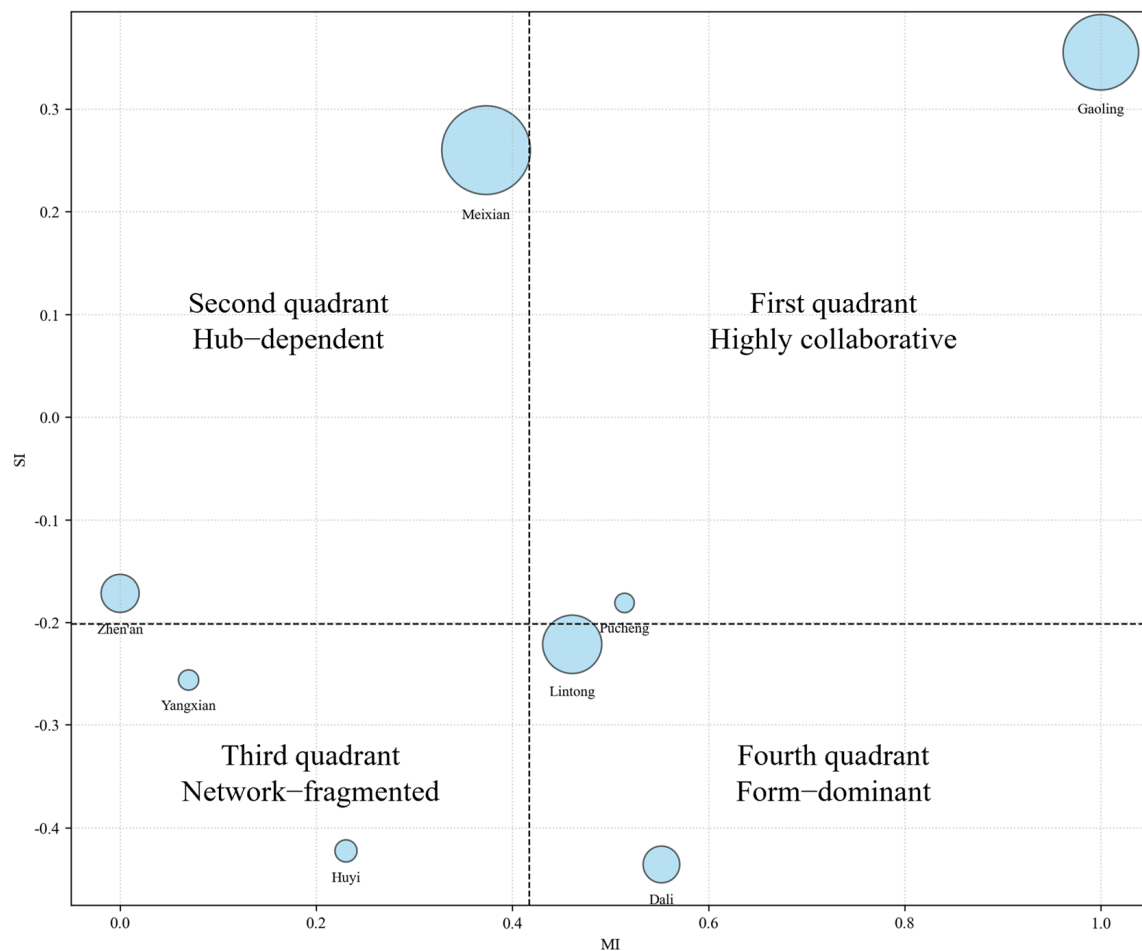


Figure 8. Quadrant distribution of morphology–structure characteristics.

Overall, the differences among counties are not determined by a single subsystem, but by the matching relationship between road accessibility and node organization. The coupling–coordination degree helps identify whether road-network morphology and node-network structure support each other or remain mismatched.

4.2. Verification of the Relationship Between Morphology–Structure Coordination and Network Impedance

To further verify whether morphology–structure coordination is associated with network-level circulation efficiency, this section selects county–village connection cost and average path length as the core verification indicators. County–village connection cost reflects cross-tier accessibility from the county center to village nodes, while average path length reflects the overall network impedance of the node network. Since the coupling–coordination degree is a continuous county-level indicator, it is directly used in the correlation and regression analysis. Before the statistical tests, skewness adjustment was applied to the cost variables to reduce the influence of scale differences and extreme values.

As shown in Table 6, the coupling–coordination degree is significantly and negatively associated with county–village mean connection distance ($r = -0.760, p = 0.028$), county–village median shortest-path distance ($r = -0.780, p = 0.020$), and average path length ($r = -0.754, p = 0.026$). The regression coefficients are all negative, indicating that higher morphology–structure coordination corresponds to lower cross-tier connection impedance from county centers to village nodes and lower overall network impedance. The R^2 values show that the coupling–coordination degree explains 57.7%, 60.8%, and 56.9% of the variation in these three indicators, respectively.

Table 6. Correlation and regression results for morphology–structure coordination and network impedance.

Verification Indicator	Pearson r	p -Value	Regression Coefficient β	R^2
County–village mean connection distance	−0.76	0.028	−1.248	0.577
County–village median shortest-path distance	−0.78	0.02	−1.285	0.608
Average path length	−0.754	0.026	−0.243	0.569

Note: Pearson r denotes the correlation coefficient; p -value denotes the significance level of the two-tailed test; β denotes the regression coefficient; R^2 denotes the coefficient of determination of the regression model.

The negative regression coefficients indicate that counties with higher morphology–structure coordination tend to have lower county–village connection impedance and lower overall network impedance. This finding is consistent with the theoretical mechanism proposed in this study: road-network morphology shapes accessibility conditions, hierarchical node structure affects the organization of cross-tier circulation, and the coordination between the two is associated with network-level circulation efficiency in county–township–village delivery networks.

Therefore, the coupling–coordination degree not only serves as a descriptive metric of morphology–structure matching, but also provides an explanatory link between network configuration and cross-tier accessibility. These findings suggest that improving the coordination between road accessibility and node organization may contribute to lower circulation impedance in rural express delivery systems. This shifts the focus of rural express delivery optimization from isolated facility expansion or single-route adjustment to the coordinated improvement of road accessibility and node layout, providing a network-scale perspective for mitigating circulation resistance.

5. Discussion

This study was designed to explain how road-network morphology and hierarchical node structure jointly shape network-level circulation efficiency in county–township–village delivery networks. Unlike studies that evaluate logistics performance mainly from operational indicators or facility allocation, this study focuses on the structural conditions that generate circulation impedance within the delivery network. By combining spatial syntax, complex network indicators, hierarchical connection-cost measurement, and a coupling–coordination model, the analysis shows that road accessibility and node organization do not function independently. Road-network integration provides the accessibility foundation for cross-tier circulation, while node-network structure affects transfer dependence, community segmentation, and path impedance. The negative association between morphology–structure coordination and county–village connection cost further indicates that better matching between road accessibility and node organization is related to lower network-level circulation impedance.

These results indicate that road-network accessibility and hierarchical node organization jointly influence network-level circulation efficiency in county–township–village delivery networks. This is consistent with studies on spatial syntax, road accessibility, and complex transport networks, which show that road and transport network configuration is closely associated with accessibility, movement potential, network connectivity, and circulation efficiency [27,33,38]. They also echo studies of rural logistics and last-mile delivery that emphasize network planning, node layout, route organization, and delivery model optimization [16,18]. However, the present study differs from many existing last-mile studies in its analytical perspective. Previous studies often focus on route opti-

mization, service coverage, facility location, or operational decision-making. This study extends this perspective by examining the structural conditions that precede these operational choices. In county–township–village delivery networks, road accessibility defines the physical circulation base, while hierarchical node organization shapes the connection relationships among county, township, and village nodes. Therefore, the coordination between these two dimensions provides a network-level explanation for differences in circulation efficiency.

This study deepens the understanding of network-level circulation efficiency in county–township–village delivery networks by combining spatial syntax, complex network analysis, hierarchical connection costs, and coupling coordination. In this study, network-level circulation efficiency is interpreted as a structural property associated with road accessibility, node hierarchy, and cross-tier connectivity, rather than as a direct measure of operational logistics efficiency. This provides an explanatory path from road-network morphology and hierarchical node organization to network-level circulation efficiency, with hierarchical connection costs serving as a measurable link between structural configuration and circulation impedance. The analysis further clarifies that road accessibility and node organization need to be considered together. Higher road accessibility may not correspond to lower circulation impedance when the node network remains fragmented, and a hierarchical node system may not effectively support circulation if road accessibility is insufficient. Therefore, morphology–structure coordination offers a useful perspective for explaining network-level efficiency differences through the matching relationship between the physical circulation base and the hierarchical organization of delivery nodes.

This study provides a structural interpretation of network-level circulation efficiency in county–township–village delivery networks by linking road accessibility, node organization, and hierarchical connection costs. The circulation-efficiency analysis reflects structural circulation conditions and potential network impedance rather than directly observed operational logistics efficiency. The current results are based on static road-network and node-network data, while actual delivery performance may also be affected by parcel flows, vehicle trajectories, delivery times, transportation costs, seasonal demand, and temporal fluctuations in logistics operations. Future research can introduce these operational and time-series data to examine how network-level impedance indicators are translated into actual logistics performance, and can further test the framework in additional county-level delivery networks and at township or village scales. On this basis, the framework may also be connected with joint delivery optimization using complex networks and machine learning, where node importance and network partitioning support delivery organization [46], and with multicriteria decision-making methods for parcel machine location selection, such as the IMF SWARA WASPAS approach, to support facility siting, shared delivery planning, and adaptive rural last-mile logistics optimization [47].

6. Conclusions

This study develops a network evaluation framework for identifying structural bottlenecks and analyzing network-level circulation efficiency in county–township–village delivery networks across eight counties in Shaanxi Province. The framework integrates spatial syntax and complex network analysis to examine road-network morphology and hierarchical node structure. Road-network integration and choice characterize accessibility and route-mediating functions, while complex network indicators describe hub control, clustering, modularity, and path impedance. Hierarchical connection costs and the coupling–coordination degree further reveal accessibility deficiencies, hierarchical connectivity constraints, and morphology–structure mismatches. Together, these analyses provide

a structural explanation for differences in network-level circulation efficiency among the study areas. The main conclusions are as follows:

(1) Road-network morphology is closely associated with hierarchical connection impedance in the county–township–village delivery network. Counties with higher road-network integration generally show better accessibility and lower cross-tier connection costs. For example, Gaoling has the highest integration value and relatively low country–town and county–village connection distances, whereas Zhen’an has the lowest integration value and much higher country–town and county–village connection distances. This indicates that road-network accessibility provides the physical basis for reducing inter-tier circulation impedance.

(2) The hierarchical organization of nodes affects connectivity and path impedance within the delivery network. Betweenness centrality, modularity, clustering, and average path length reveal differences in hub control, community fragmentation, and path impedance among counties. Counties with fragmented node organization or weak cross-tier connections tend to show higher county–village or village–village connection costs, suggesting that node-network structure is an important condition influencing network-level circulation efficiency.

(3) Hierarchical connection-cost analysis provides a quantitative diagnosis of circulation impedance across different network layers. Country–town, town–village, and village–village connection costs identify the internal sources of impedance, while county–village connection cost reflects the integrated cross-tier accessibility from county centers to village nodes. This distinction helps clarify that the network bottleneck is not only a local road-distance problem but also a hierarchical accessibility problem across county, township, and village nodes.

(4) The coordination between road-network morphology and node-network structure helps explain differences in network-level circulation impedance. The coupling–coordination degree shows clear variation among the eight counties, with Gaoling having the highest coordination level and Dali and Zhen’an showing the lowest levels due to different forms of morphology–structure mismatch. Further statistical verification shows that the coupling–coordination degree is significantly and negatively associated with county–village mean connection distance, county–village median shortest-path distance, and average path length. This provides quantitative evidence that better morphology–structure coordination is associated with lower cross-tier connection impedance and lower overall network impedance.

(5) The results suggest that the structural improvement of rural delivery networks should consider road accessibility and hierarchical node organization in a coordinated manner. Road-network improvement alone may reduce local travel impedance, but its effect can be limited if node organization remains fragmented or poorly connected. Similarly, strengthening node layout without improving cross-tier accessibility may not effectively reduce circulation impedance from county centers to village nodes. Therefore, rural express delivery optimization should move beyond isolated facility expansion or single-route adjustment and instead focus on the coordinated improvement of road accessibility, node layout, and cross-tier network connectivity.

Overall, this study constructs an integrated analytical framework linking road-network morphology, hierarchical node structure, and network-level circulation efficiency in county–township–village delivery networks. The findings show that the coordination between road accessibility and node organization is closely associated with cross-tier accessibility and overall network impedance. This provides a basis for diagnosing structural bottlenecks and supporting the coordinated optimization of rural express delivery networks.

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