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Sustainable Rural Road Network Planning Under Hierarchical Constraints in Complex Mountainous Terrain: A Case Study of Zhangjiachuan Hui Autonomous County, China

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Abstract

Sustainable rural road planning in mountainous areas must coordinate existing-road use, hierarchical connectivity, and construction requirements. This study proposes a network generation method integrating existing-road topology with roadless space through a hexagonal occupancy grid. Existing-road neighborhood and cross-neighborhood edges represent different access characteristics. Sequential rules generate a county-level backbone, township-level links, and village-level access while identifying reuse, upgrading, and new construction. Six scenarios are compared in Zhangjiachuan Hui Autonomous County, Gansu, China. The proposed scenario generates an 880.001 km network, with existing roads accounting for 94.53%. New construction totals 48.128 km, 85.63% less than in E1, which represents all existing roads as cross-neighborhood edges and reuses them directly. On the full post-planning evaluation network, mean shortest travel times for village-to-township government, township government-to-county seat, and village-to-county seat connections decrease by 29.69%, 45.24%, and 37.06%, respectively, relative to the existing-road network. All three hierarchical compliance rates reach 100%. Using entropy weights of 11.90%, 44.82%, and 43.28% for network composition, service accessibility, and construction requirements, respectively, the proposed scenario achieves the highest composite score among the six scenarios. The method supports resource-efficient rural transport planning by coordinating existing-road use, hierarchical service connections, and new-construction requirements in preliminary layouts for mountainous counties with comparable terrain and road data.

Keywords: sustainable rural transport; rural road networks; mountainous terrain; hexagonal occupancy grid; hierarchical road-network constraints; existing road infrastructure utilization

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1. Introduction

Mountainous rural road planning is constrained by terrain relief, dispersed settlements, limited construction corridors, and heterogeneous existing-road conditions. Steep gradients and circuitous alignments raise construction requirements, while no-build areas and access rules restrict feasible connections. Planning must use existing roads while satisfying county-level continuity, township-level linkage, and village access within the assigned township; merely connecting all nodes does not guarantee these functions. Rural road networks also connect urban and rural trunk transport systems, support local industries, and provide essential access to everyday services. In China, rural revitalization and the initiative to build, manage, maintain, and operate rural roads effectively have reinforced their role in local transport networks [1].

In road network planning and route alignment, spatial representations used for path search include graph models [2], occupancy grids [3], continuous-space models [4], and navigation meshes [5]. Graph models represent a road network as $G = (V, E)$, where V denotes transport nodes and E denotes road segments; edge weights express travel costs [2]. Occupancy grids divide a planning area into regular rectangular, triangular, or hexagonal cells, assign costs from cell attributes, and search through neighboring cells [6,7]. Continuous-space models represent routes as curves rather than discrete graph connections. Routes are optimized through functional optimization or numerical procedures, including genetic algorithms [8,9], particle swarm optimization [10], and hybrid methods [11]. Navigation meshes divide traversable space into irregular convex polygons based on terrain boundaries and obstacles, simplifying collision checks and supporting A* search and its variants [12,13].

For county-level road planning, grid-only representations can have difficulty preserving both existing road geometry and topology. Converting roads into cost cells incorporates road conditions and terrain costs in a common grid [14], but discretization is sensitive to resolution and may introduce positional shifts, discontinuities, or distorted intersections [15,16]. Hybrid road-network and grid graphs retain vector roads and connect them to roadless grid space, enabling searches across both representations [15,17]. Hierarchical county-level planning additionally requires a consistent representation of the connectivity of different road administrative categories, their connections with the grid, and their cost differences. A high-resolution grid can represent the planning area, while topological edges retain existing roads and support differentiated connection costs associated with road administrative categories.

Cost models underpin path search and route optimization. Depending on their inputs, costs can be classified as spatial-state-dependent, local-transition-dependent, or cumulative-state-dependent. Spatial-state-dependent costs reflect location-specific properties such as land use, ecological sensitivity, geological hazards, and land cover [18]. Local-transition-dependent costs represent movement between neighboring locations, including distance, gradient, travel direction, curvature, and engineering quantities [19,20]. Cumulative-state-dependent costs depend on the path already formed and its history, including changes in direction, resource consumption, and road utilization states. Vehicle-oriented traversability models can also incorporate energy consumption and acceleration [21]. Road planning commonly combines these components in a composite cost model.

County-, township-, and village-level nodes differ in service coverage and passenger and freight requirements. Rural road planning therefore extends beyond generating individual low-cost segments to organizing a hierarchical network. County roads provide county-wide connections, township roads support local distribution, and village roads provide access to settlements. Planning must connect functional nodes, avoid no-build areas, use existing infrastructure, and coordinate connections between road levels.

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Relevant approaches include hierarchical network design, terrain-constrained hierarchical road generation, and simulations of hierarchical network evolution. Hierarchical network design uses abstract nodes and candidate connections, organizing backbones and branches through node classification, minimum spanning trees, and multilevel optimization [22,23]. Terrain-constrained generation assigns road levels and connection tasks according to settlement size, road type, or specified endpoints, then searches for alignments using terrain costs [16,24]. Evolutionary models simulate traffic assignment and investment updates based on demand, benefits, construction costs, and changing road performance to explain emerging road and hub hierarchies [25]. These approaches organize networks using node levels, candidate links, settlement size, or endpoint type. County boundaries, township affiliation, service functions, and permitted interlevel connections require more explicit treatment to ensure that county, township, and village roads serve their intended areas and functions. Administrative affiliation, node levels, search extents, permitted access targets, and no-build areas must therefore be translated into explicit network generation constraints.

Existing-road use can be represented through static low-cost guidance, condition-specific costing, and sequential network reuse. Static guidance assigns zero costs, low costs, or off-road distance costs to existing roads and nearby areas to encourage their use [14,16]. Condition-specific costing distinguishes direct reuse, maintenance, upgrading, reconstruction, and new construction according to road class, pavement condition, and required engineering works [19,26]. Sequential reuse incorporates existing and previously generated roads into the current network and reduces subsequent access or travel costs, encouraging later routes to share infrastructure [14,27,28]. Hybrid road-topology and traversable-space representations further treat existing roads as a backbone with low incremental construction costs, connected to regular grid cells or irregular traversable units through neighborhood relations [15,27]. These approaches support route search through mixed spatial representations and preferential use of existing infrastructure, but mountainous county-level planning still requires one generation process to coordinate legal access by road level, node hierarchy and township affiliation, and the identification of reuse, upgrading, and new construction.

This study develops a hierarchical-constraint network generation method for preliminary mountainous county layouts. Here, hierarchical constraints specify permitted connections among county-, township-, and village-level planning nodes and their administrative affiliations. It integrates existing road topology and roadless space by representing roads as neighborhood or cross-neighborhood edges according to administrative category and access characteristics. It then translates county-level continuity, township-level linkage, and village access within the assigned township into sequential connection rules. Finally, it updates construction costs during generation and records each selected segment as reuse, upgrading, or new construction. Six scenarios are used to compare the effects of access and associated road-use rules, network organization, and cost settings.

2. Materials and Methods

2.1. Study Area and Data

Zhangjiachuan Hui Autonomous County is located in southeastern Gansu Province, China, at the transition between the Liupan Mountains and the Longxi Loess Plateau (Figure 1). The county covers approximately 1311.8 km^2, with a mean elevation of 2011.4 m and an elevation range of 1173.4 m. Terrain relief is generally greater in the northeast and lower in the central and western parts. This varied topography strongly constrains rural road layouts and construction costs. The study uses a digital elevation model (DEM),

administrative boundaries, existing roads, county-, township-, and village-level planning nodes, and no-build areas (Table 1).

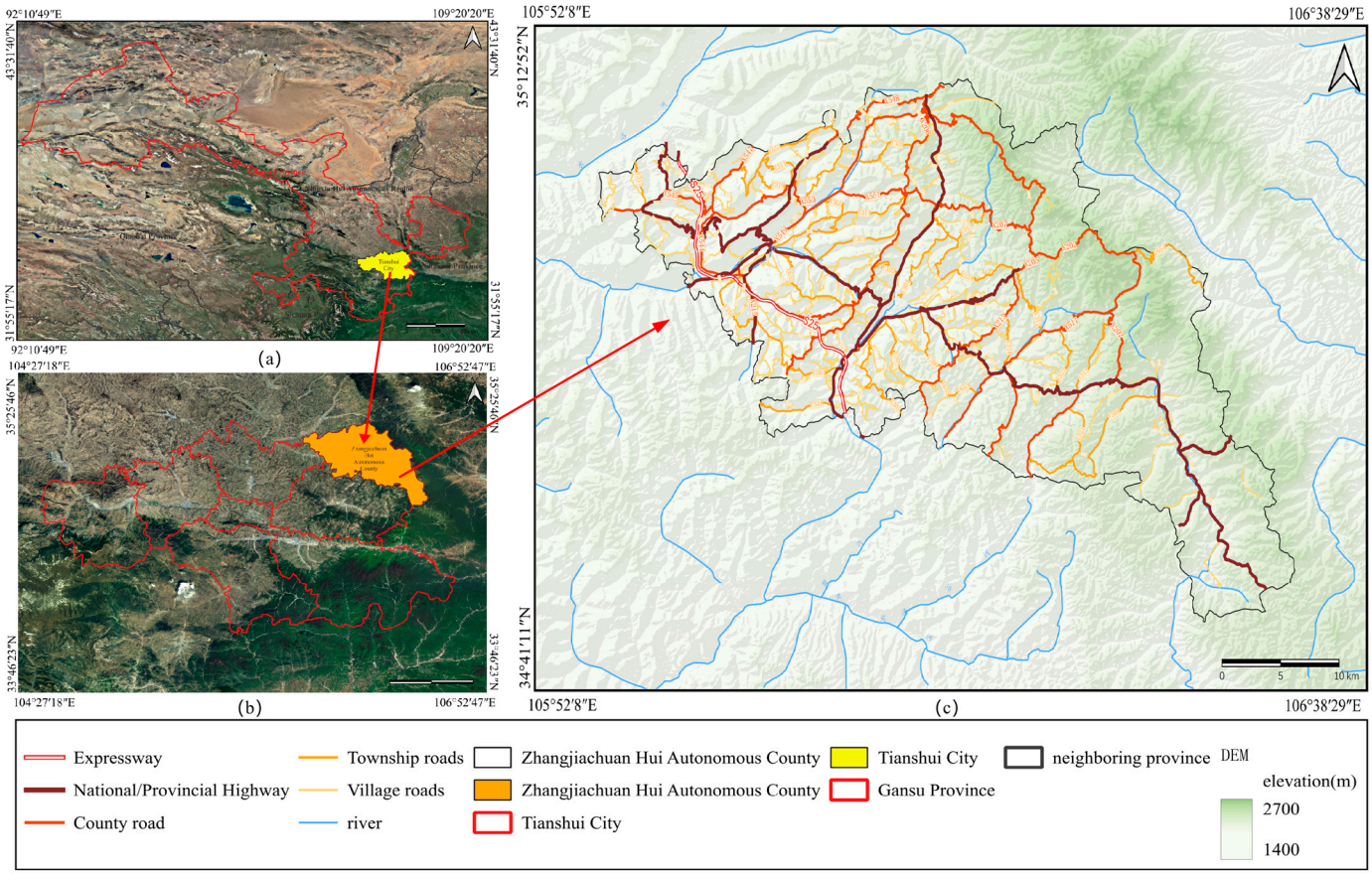


Figure 1. Location and existing road network of Zhangjiachuan Hui Autonomous County. (**a**) location of Tianshui City in Gansu Province; (**b**) location of Zhangjiachuan Hui Autonomous County in Tianshui City; (**c**) existing road network and terrain of the county. Digital elevation model (DEM).

Table 1. Input data and their main uses.

Data	Main Use
Digital elevation model (DEM)	Elevation differences, three-dimensional distances, directional slopes, and terrain conditions
Administrative boundaries	Define the study area, node administrative affiliation, service groups, and township-specific village-road searches
Existing roads	Construct differentiated topological connections and identify roads available for reuse
Planning nodes	Administrative, transport (bus and railway stations and expressway entrances/exits), and economic nodes (industrial parks and tourist sites). Nodes are assigned to county, township, or village levels according to function, service coverage, and importance, supporting sequential backbone, linkage, and access generation.
No-build areas	Impassable areas, including water bodies, protected areas, and permanent basic farmland

The workflow comprises six steps: data alignment, integrated representation of the hexagonal occupancy grid and existing roads, composite edge-cost calculation, sequential county–township–village network generation, identification of road construction types, and evaluation of the planning results (Figure 2).

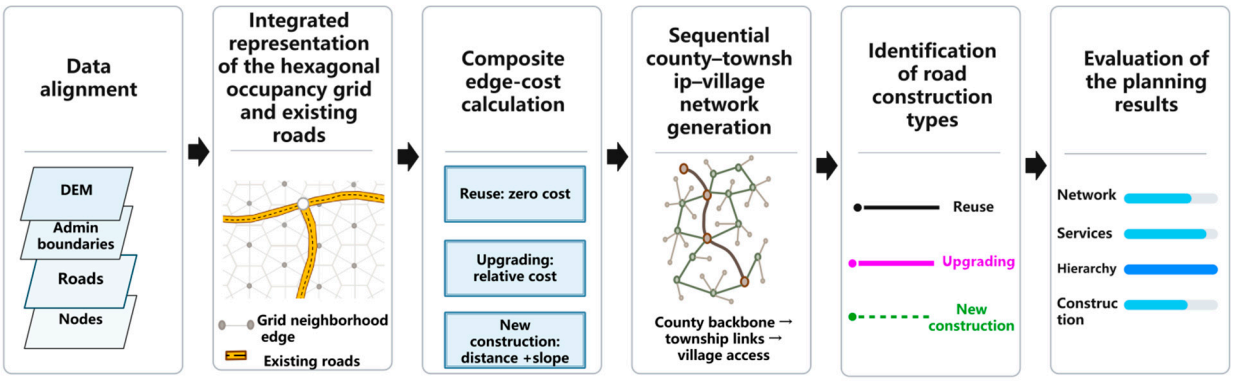


Figure 2. Methodological workflow.

2.2. Construction of the Hexagonal Occupancy Grid

A regular hexagonal tessellation with a fixed coordinate origin is generated within the county boundary [29]. Cells in no-build areas are removed to obtain the basic spatial units (Figure 3). Each regular hexagon has six equidistant neighboring centers, providing six expansion directions with a common adjacency distance rather than the two-axis restriction of a four-neighbor square grid. Low-category roads predominate in the study area (Figure 4), and 89% of road widths lie between 3.5 and 5.5 m. A hexagon side length of 5 m is used for the case-study planning representation.

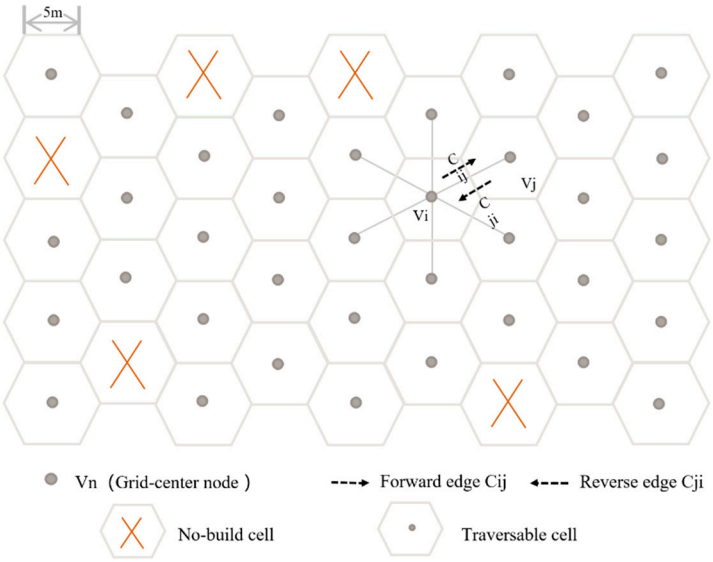
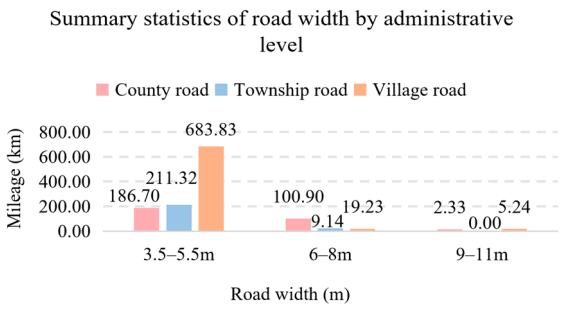


Figure 3. Hexagonal occupancy grid.



(**a**)

Road width (m) / Mileage (km)	3.5–5.5m	6–8m	9–11m
County road mileage (km)	186.70	100.90	2.33
Township road mileage (km)	211.32	9.14	0.00
Village road mileage (km)	683.83	19.23	5.24

(**b**)

Figure 4. Road-width distribution: (**a**) road lengths by width class and category; (**b**) tabulated values.

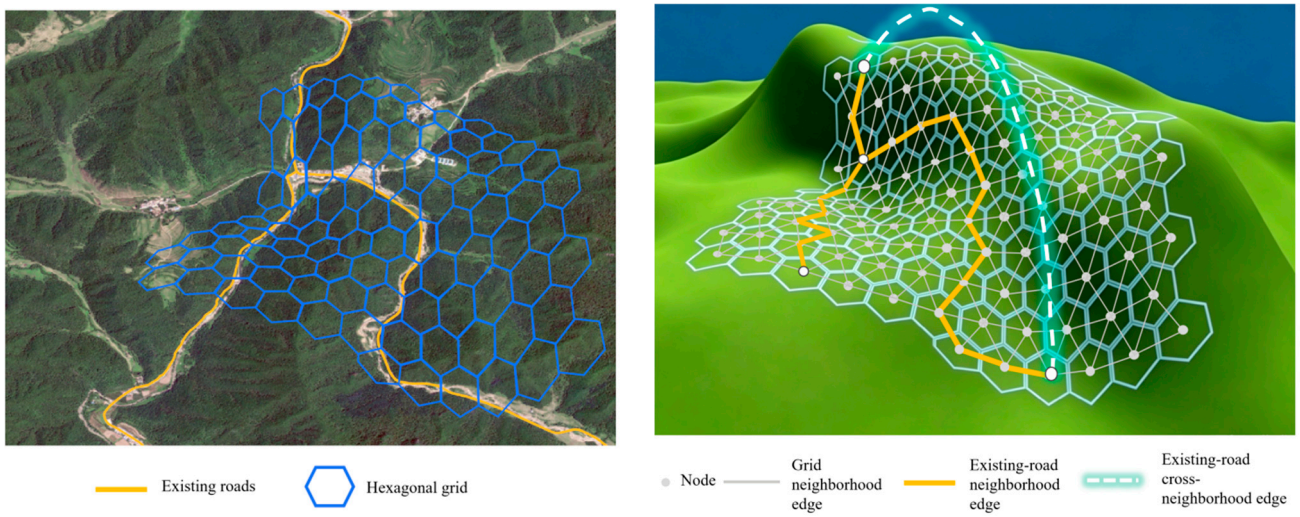
Grid attributes describe geometric indexing, terrain, administrative affiliation, area status, and adjacency. Table 2 summarizes the principal attributes and assignment methods.

Table 2. Hexagonal grid attributes and assignment methods.

Category	Attribute	Assignment Method	Main Use
Geometric indexing	Cell ID, row, column, and center coordinates	Calculated from grid centers	Unique identification, spatial alignment, and six-neighbor lookup
Terrain	Center elevation	DEM sampling at each grid center	Elevation differences, three-dimensional distances, and slopes of neighboring edges and road segments
Administrative affiliation	County and township	Point-in-polygon matching of grid centers and administrative boundaries	Restrict search extents and organize planning nodes and village-road groups
Adjacency	Six neighboring nodes and edges	Generate six directions using row/column indices and odd/even column offsets	Construct the basic traversable graph

2.3. Integrated Representation of Existing-Road Topology and Roadless Space

Hexagon centers serve as nodes, and grid neighborhood edges form the basic search graph. Existing roads are represented by existing-road neighborhood edges or existing-road cross-neighborhood edges according to road administrative category and access rules (Figure 5). Cross-neighborhood edges connect nonadjacent nodes and may traverse multiple hexagons, whereas neighborhood edges represent road segments between consecutive access locations along a road. Expressway cross-neighborhood edges connect grid nodes containing road endpoints or entrances and exits. National and provincial roads are divided into continuous segments between nodes containing endpoints, connected intersections, or attribute-change locations. County, township, and village roads are matched to the grid nodes along their alignments to form neighborhood edges.



(**a**) (**b**)

Figure 5. Integrated road-network representation: (**a**) existing roads overlaid on the hexagonal grid; (**b**) the grid and existing-road edges over three-dimensional terrain.

Figure 5a shows the spatial relationship between existing roads and the hexagonal grid. Figure 5b illustrates the integrated graph formed by grid nodes, grid neighborhood edges, existing-road neighborhood edges, and cross-neighborhood edges over three-dimensional terrain.

The grid-center nodes and three edge types form the integrated road-network graph:

$$G = (V_H, E_H \cup E_A \cup E_R) \quad (1)$$

The symbols in Equation (1) are defined in Table 3, and edge attributes are listed in Table 4.

Table 3. Components and connection rules of the integrated graph.

Symbol	Spatial Entity	Generation or Connection Rule
V_H	Nodes	Centers of valid hexagonal cells
E_H	Grid neighborhood edges	Connect adjacent grid-center nodes
E_A	Existing-road neighborhood edges	Road segments between consecutive access locations
E_R	Existing-road cross-neighborhood edges	Connect permitted access points along actual road alignments

Table 4. Edge attributes of the integrated graph.

Category	Field	Applicable Edges	Meaning and Assignment
Identifier	Edge ID	All	Primary key identifying each edge
Topology	Source ID	All	ID of the starting node
Topology	Target ID	All	ID of the ending node
Edge type	Type code	All	Grid neighborhood, existing-road neighborhood, or existing-road cross-neighborhood
Geometry	Edge geometry	All	Geometry of the grid or existing-road connection
Terrain	Source elevation	All	Extracted from the DEM
Terrain	Target elevation	All	Extracted from the DEM
Terrain	Slope angle	All	Check slope conditions and calculate costs
Road attributes	Road ID	Both existing-road types	Links to the source road feature; null for grid neighborhood edges
Road attributes	Road administrative category	Both existing-road types	Expressway, national, provincial, county, township, or village road
Road attributes	Technical class	Both existing-road types	Recorded for later design; not used in the upgrading or cost rules here.
Road attributes	Pavement type	Both existing-road types	Recorded for later design; not used in the upgrading or cost rules here.
Search cost	Cost	All	Grid neighborhood edges use new-construction costs; existing-road neighborhood edges use reuse or upgrading costs under K_1 and a uniform length-based cost under K_0; existing-road cross-neighborhood edges use direct-reuse costs. Detailed assignment and stage-specific updates are provided in Sections 2.4 and 2.5.

2.4. Edge-Cost Calculation

Relative incremental construction costs represent differences in the investment required during network generation. They depend on distance, gradient, and construction type and do not directly represent monetary engineering costs. Direct reuse means that an existing road can serve the current connection task without modification; its incremental construction cost is therefore zero. Upgrading requires engineering works, and its cost is expressed as a proportion of the cost of new construction under equivalent target conditions.

Actual upgrading decisions depend on geometric conditions, pavement condition, and the target road function [19,26]. For this county-level preliminary layout, the existing road administrative category relative to the generation level serves as a proxy for upgrading. Technical class and pavement type are retained as descriptive attributes, while road-width statistics inform the grid-scale selection in Section 2.2. Upgrading therefore denotes a potential improvement requirement, and specific measures and costs require engineering investigation, design, and economic evaluation [30].

The cost of a grid neighborhood edge is based on the slope-class least-cost model proposed by Yu et al. [31]. For adjacent nodes with three-dimensional coordinates (x_i, y_i, z_i) and (x_j, y_j, z_j), the directional slope angle is

$$\theta_{ij} = \frac{180}{\pi}\arctan\left(\frac{z_j - z_i}{L_{ij}}\right) \tag{2}$$

where the horizontal distance L_{ij} is

$$L_{ij} = \sqrt{\Delta x^2 + \Delta y^2} \tag{3}$$

Slope magnitudes are assigned to five finite-cost classes, with an additional excluded range [31]:

$$\omega(|\theta_{ij}|) = \begin{cases} 0 & 0° \le |\theta_{ij}| < 3° \\ 4 & 3° \le |\theta_{ij}| < 6° \\ 8 & 6° \le |\theta_{ij}| < 9° \\ 20 & 9° \le |\theta_{ij}| < 12° \\ 80 & 12° \le |\theta_{ij}| < 16° \\ +\infty & |\theta_{ij}| \ge 16° \end{cases} \tag{4}$$

Spatial distance D_{ij}, the mean basic cost of adjacent cells $\overline{C_{ij}}$, and the slope weight $\omega(|\theta_{ij}|)$ are combined to obtain the local cost of grid neighborhood edge ij:

$$c_E^{new} = D_{ij}\left[\overline{C_{ij}} + \frac{\pi}{180}|\theta_{ij}|\omega(|\theta_{ij}|)\right] \tag{5}$$

where the three-dimensional distance D_{ij} is

$$D_{ij} = \sqrt{{L_{ij}}^2 + \Delta z^2} \tag{6}$$

Here, $\overline{C_{ij}}$ is the mean basic cell cost at the two endpoints of the grid neighborhood edge [31].

Existing-road neighborhood edges have two construction states: reuse and upgrading. Reuse incurs no incremental construction cost, giving $c_E = 0$. Upgrading improves the road's technical condition before use, and its cost is calculated as

$$c_E = \rho_u \cdot c_E^{new} \tag{7}$$

where c_E^{new} is the new-construction reference cost calculated using Equation (5) for the corresponding grid neighborhood edge, and ρ_u is the upgrading cost coefficient.

Existing-road cross-neighborhood edges are directly reused, with $c_E = 0$.

Path search first minimizes cumulative incremental construction cost. If candidate paths have equal cumulative costs, their actual lengths provide a secondary criterion, and the shorter path is selected.

2.5. Road Network Generation Under Hierarchical Constraints

The network is generated sequentially as a county-level backbone, township-level links, and village-level access roads (Figure 6).

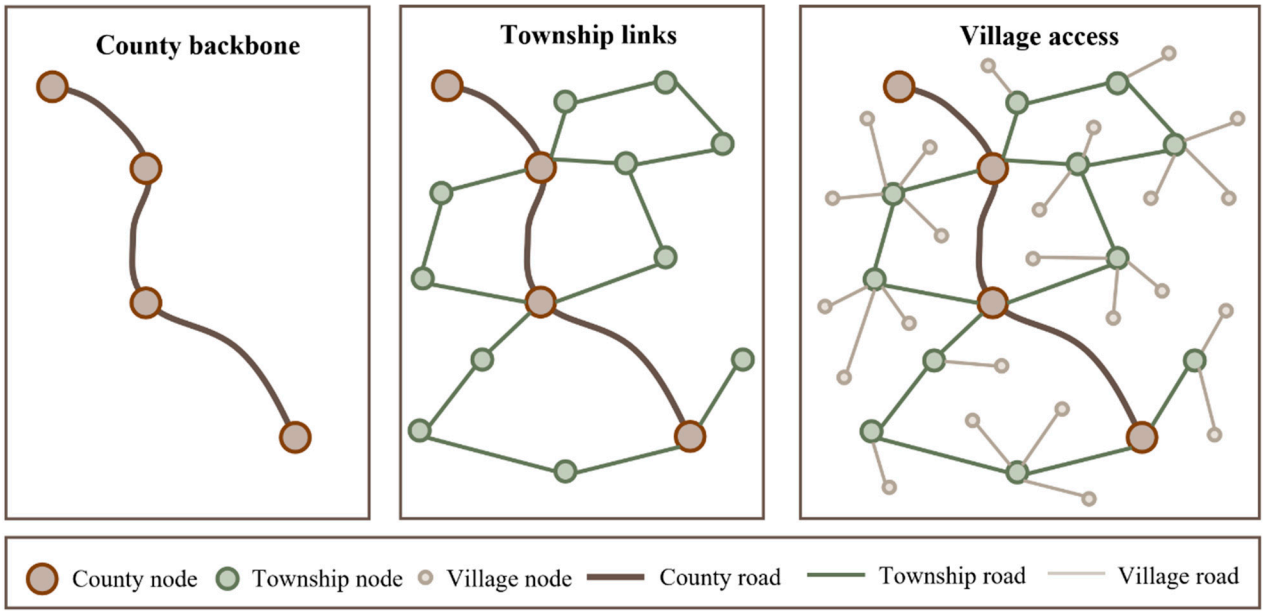


Figure 6. Sequential road network generation under hierarchical constraints.

Step 1. County-level backbone. Existing-road neighborhood edges below the county-road administrative category receive upgrading costs according to Equation (7); the remaining existing-road neighborhood edges receive reuse costs. These edges, existing-road cross-neighborhood edges, and grid neighborhood edges form the candidate graph G in Equation (1). For county- and township-level open traveling salesman problems (OTSPs) [32,33], calculate directed path costs and symmetric visiting costs using Equation (8).

$$d(u,v) = \min_{p \in P(u,v)} \sum_{E \in p} c_E \, , C_{uv} = \max\{d(u,v), d(v,u)\} \tag{8}$$

where $P(u,v)$ is the set of feasible directed paths from node u to node v in G; p is one such path and E an edge on p. The edge cost c_E follows Section 2.4 and the current stage's updates; $d(u,v)$ is the minimum cumulative cost and C_{uv} the symmetric visiting cost. Let $H = (h_0, \ldots, h_n)$ be a closed sequence of n planning nodes, where h_k is the node at position k and $h_n = h_0$. Equation (9) defines its cost $F(H)$ and the cut-edge index k^*.

$$F(H) = \sum_{k=0}^{n-1} C_{h_k h_{k+1}} \, , k^* \in \arg\max_{0 \le k < n} C_{h_k h_{k+1}} \tag{9}$$

(a) Initialize. Build a minimum spanning tree (MST) with Prim's algorithm using costs C_{uv} and traverse it in preorder to obtain H, following fixed node and adjacency orders.

(b) Improve once. For $i = 1, \ldots, n-1$ in ascending order and $j = n, \ldots, i+1$ in descending order, reverse the half-open segment $[i, j)$ to obtain H'. Replace H by H' only if $F(H') < F(H)$; perform this scan once.

(c) Open. Evaluate k^* on the improved closed tour and remove that edge, including the closing edge if it is largest. Equal-cost breakpoints follow the fixed scan order.

(d) Recover. Restore the directed shortest paths between consecutive nodes in the open order to obtain the selected road segments.

Step 2. Township-level links. Selected county-level segments receive reuse costs. Among the remaining existing-road neighborhood edges, those below the township-road category receive upgrading costs; the others receive reuse costs. Existing-road cross-neighborhood edges retain reuse costs. Recompute pairwise costs on the updated graph

and apply the procedure in Step 1 to the 19 township-level nodes. Select the minimum-cost township-to-county connection using Equation (10).

$$(u^*, v^*) \in \arg\min_{u \in V_2, v \in V_1} d(u, v) \tag{10}$$

where V_1 and V_2 are the county- and township-level node sets. All seven county-level nodes are eligible anchors, and the selected connection joins the township chain to the county-level backbone.

Step 3. Village-level access. The county–township backbone and all existing-road neighborhood edges are assigned reuse costs. Village-level planning nodes are grouped by township. Village–village and village–anchor candidates use the symmetric costs in Equation (8); connections unreachable in either direction are excluded. For each village v in township t, Equation (11) defines the lowest-cost eligible anchor, the virtual-root link weight, and the rooted MST.

$$\begin{gathered} a(v) \in \arg\min_{a \in A_t} C_{va}, w(v, r) = C_{v,a(v)} \\ T_t = \mathrm{MST}(G_t) \end{gathered} \tag{11}$$

where A_t contains the township-level nodes assigned to t, $a(v)$ is the selected anchor, and r is a virtual super-root. Build the undirected graph G_t from that township's villages, eligible village-to-village links weighted by C_{uv}, and one root link (v, r) per village with weight $w(v, r)$; retain the actual anchor identity on each root link. The virtual root represents no physical facility; root links retain the actual connection costs. Apply Kruskal's algorithm [34,35] to obtain T_t. Replace selected root links with their actual anchor connections and restore all selected links to their underlying shortest paths.

Step 4. Construction-type records. Existing-road neighborhood edges requiring no modification are classified as reuse, those requiring improvement to the target level as upgrading, and selected grid neighborhood edges in roadless space as new construction. Selected existing-road cross-neighborhood edges are classified as reuse. Later stages update search costs without changing construction types; recovered paths are merged and duplicate physical segments removed.

County-level tasks connect county nodes; township-level tasks connect township nodes or provide county-backbone access. Village-level tasks connect villages only to villages or township-level nodes within the same township; village-to-county and cross-township village tasks are excluded.

Hierarchical compliance is assessed for all 280 planning nodes: 7 county-level, 19 township-level, and 254 village-level nodes. Cross-level and cross-township errors are counted separately at the connection-task level. Accessibility is evaluated using 523 service origin–destination (OD) pairs.

2.6. Evaluation Indicators

The evaluation system covers network composition, service accessibility, and construction requirements (Table 5). Hierarchical compliance is reported separately as a reference and is not included in the composite score. Scored indicators are normalized according to their direction of preference and aggregated using the specified weights. Existing-road share and construction requirements both contain information about new construction, but the latter additionally includes upgrading; both are retained and examined through down-weighting and removal tests.

Entropy weighting is used to determine the weights of the three scored dimensions [36]. The directionally standardized dimension scores Z_{ij} (0–100, higher is better) for the six baseline scenarios form the 6×3 matrix used below. Scenario index i runs from 1 to 6, and dimension index j from 1 to 3. Column proportions, information entropy,

differentiation coefficients, weights, and composite scores are calculated using Equations (12)–(14):

$$p_{ij} = \frac{z_{ij}}{\sum_{i=1}^{6} z_{ij}} \tag{12}$$

$$h_j = -\frac{1}{ln\,6}\sum_{i=1}^{6} p_{ij}\, ln\, p_{ij}\,, d_j = 1 - h_j \tag{13}$$

$$w_j = \frac{d_j}{\sum_{j=1}^{3} d_j}, S_i = \sum_{j=1}^{3} w_j Z_{ij} \tag{14}$$

In Equations (12)–(14), Z_{ij} is the standardized score of scenario i on dimension j; p_{ij} is its proportion of the column total; h_j is the information entropy; d_j is the differentiation coefficient; w_j is the dimension weight; and S_i is the composite score of scenario i.

When $p_{ij} = 0$, $p_{ij}\ln(p_{ij})$ is defined as 0. A constant dimension has a differentiation coefficient of 0; equal weights would be used if all dimensions were constant. No dimension is constant in the present 6×3 matrix.

The resulting entropy weights are 11.90%, 44.82%, and 43.28% for network composition, service accessibility, and construction requirements, respectively. The upgrading coefficient used in construction evaluation is denoted by ρ_e and is 0.6 at baseline, distinguishing it from the path-search coefficient ρ_u.

Table 5. Evaluation indicators, scoring rules, and entropy weights.

Indicator	Definition and Scoring	Calculation and Parameters	Weight (%)
Network composition	Shorter total network length and a larger existing-road share receive higher scores. The two normalized scores are averaged with equal weights.	Network composition score: $Z_{\text{line}} = \frac{z_L + z_U}{2}$ z_L: normalized length score (lower is better). z_U: normalized existing-road share (higher is better). $z_L = 100\frac{L_{\max} - L_{\text{physical}}}{L_{\max} - L_{\min}}$ $z_U = 100\frac{U_{\text{road}} - U_{\min}}{U_{\max} - U_{\min}}$ L_{physical}: final network length; U_{road}: existing-road share. $L_{\text{physical}} = L_{\text{road}} + L_{\text{new}}$ $U_{\text{road}} = \frac{L_{\text{road}}}{L_{\text{physical}}} \times 100\%$ L_{road}: length of existing roads used. L_{new}: new-construction length represented by grid neighborhood edges.	11.90
Service accessibility	Time improvements are calculated for fixed village–township government, township government–county seat, and village–county seat OD pairs on the full evaluation network. Their normalized scores are averaged equally; higher improvements are better.	Service accessibility score: $Z_{\text{service}} = \frac{1}{3}\sum_{s=1}^{3} z_{\eta_s}$ z_{η_s}: normalized improvement score. $z_{\eta_s} = 100\frac{\eta_s - \eta_{s,\min}}{\eta_{s,\max} - \eta_{s,\min}}$	44.82

		η_s: relative travel-time improvement. $\eta_s = \frac{\overline{T}_{s,0} - \overline{T}_{s,1}}{\overline{T}_{s,0}} \times 100\%$ $\overline{T}_{s,0}$: pre-planning mean shortest time for service type s. $\overline{T}_{s,1}$: post-planning mean shortest time for service type s.	
Hierarchical compliance	County-level continuity, township access to the county backbone, village access to its assigned township backbone, and connection errors. Reported separately without a scoring weight.	County, township, and village compliance rates C_1, C_2, C_3: $\begin{cases} C_1 = \frac{N_1^{\max}}{N_1} \times 100\% \\ C_2 = \frac{N_2'}{N_2} \times 100\% \\ C_3 = \frac{N_3'}{N_3} \times 100\% \end{cases}$ $N_1, N_1^{\max}$: total county-level nodes and county-level nodes in the largest county-level connected component. N_2, N_2': total township-level nodes and those connected to the county-level backbone. N_3, N_3': total village-level nodes and those correctly connected to their assigned township backbone.	
Construction requirements	Coefficients of 0, ρ_e and 1.0 are used for reuse, upgrading, and new construction. Lower construction requirements receive higher scores from 0 to 100.	Construction requirements score: $Z_{\text{build}} = 100 \frac{I_{\max} - I_{\text{build}}}{I_{\max} - I_{\min}}$ I_{build}: construction requirements index. $I_{\text{build}} = \frac{\rho_e L_{\text{upgrade}} + L_{\text{new}}}{L_{\text{physical}}}$ $L_{\text{upgrade}}, L_{\text{new}}$: upgrading and new-construction lengths.	43.28
Composite score	Entropy-weighted sum of network composition, service accessibility, and construction requirements.	$S = 0.1190Z_{\text{line}} + 0.4482Z_{\text{service}} + 0.4328Z_{\text{build}}$	100

3. Experiments and Results

3.1. Experimental Design

A baseline scenario is defined for the complex terrain and multiple road administrative categories in Zhangjiachuan Hui Autonomous County, with $\overline{C_{ij}} = 1$, $\rho_u = 0.6$. Six scenarios combine existing-road representation strategies (Table 6), network organization strategies (Table 7), and edge-cost settings (Table 8), as summarized in Table 9. The scenarios examine the effects of these three components. Global MST and the global open traveling salesman problem (OTSP) serve as network organization comparisons without hierarchical differentiation; the hierarchical MST strategy provides a comparison under the same hierarchical constraints; and the uniform-cost strategy examines the effect of distinguishing construction states in edge costing. The construction-evaluation coefficient is denoted by ρ_e and is also set to 0.6 at baseline; it is distinct from the path-search coefficient ρ_u.

Table 6. Existing-road representation strategies.

Code	Strategy	Treatment of Existing Roads
R_1	Uniform cross-neighborhood representation	All existing roads are represented by cross-neighborhood edges between endpoints, connected intersections, and attribute-change locations.
R_2	Category-specific combined representation	Expressways use cross-neighborhood edges between endpoints and entrances/exits. National and provincial roads use continuous segments between endpoints, intersections, and attribute-change nodes. County, township, and village roads are matched to nodes along their alignments to form neighborhood edges.

Table 7. Network organization strategies.

Code	Organization	Node Connection Task
H_0	Global minimum spanning tree (MST)	One MST over all planning nodes, without county–township–village differentiation
H_1	Global open traveling salesman problem (OTSP)	One OTSP visiting order for all planning nodes, without hierarchical differentiation
H_2	Sequential hierarchical generation	County and township OTSPs; township-specific rooted MSTs for village nodes
H_3	Hierarchical MSTs	County MST, township-rooted MSTs, and village-rooted MSTs under the same hierarchical constraints as H_2

Table 8. Edge-cost settings.

Code	Grid Neighborhood Edges	Existing-Road Edges
K_0	New-construction cost from Equation (5)	Neighborhood edges: $c_E^{K0} = 0.04L_E$, without distinguishing reuse and upgrading. Cross-neighborhood edges: $c_E = 0$.
K_1	New-construction cost from Equation (5)	Neighborhood edges: zero for reuse and ρ_u times the corresponding new-construction cost for upgrading. Cross-neighborhood edges: $c_E = 0$.

In Table 8, L_E is the length of the corresponding existing-road edge, measured in the same units as in the new-construction cost model. The coefficient 0.04 specifies the relative cost per unit length of an existing-road neighborhood edge. It defines a uniform low-cost comparison to examine the effects of not distinguishing reuse from upgrading on network length, service accessibility, and new construction. This dimensionless coefficient does not represent a local monetary construction rate.

Table 9. Combinations of the six experimental scenarios.

Scenario	Representation R	Organization H	Cost K	Comparison
E1	R_1	H_2	K_1	Uniform cross-neighborhood representation
E2	R_2	H_2	K_1	Proposed complete scenario
E3	R_2	H_0	K_1	Global tree organization
E4	R_2	H_1	K_1	Global visiting-path organization
E5	R_2	H_2	K_0	Uniform existing-road cost, without reuse/upgrading differentiation
E6	R_2	H_3	K_1	Hierarchical tree organization under the same constraints

The E1–E2 comparison combines two rules: how existing roads are represented, and how their costs are treated. Upgrading costs are defined only for existing-road neighborhood edges. Under R_1, all existing roads are represented as cross-neighborhood edges and directly reused, so E1 necessarily has zero upgrading length. R_2 represents

county, township, and village roads as neighborhood edges; upgrading applies only below the target administrative category. Expressways, national roads, and provincial roads remain directly reused as cross-neighborhood edges. Their effects are therefore measured together rather than separately.

3.2. Network Composition

E2 produces a final road network of 880.001 km, comprising 831.873 km of existing roads and 48.128 km of new construction; existing roads account for 94.53% (Table 10). Relative to E1, E2 reduces total length by 113.150 km and new construction by 286.732 km. E5 has the shortest total network, at 525.078 km, but requires 262.601 km of new construction, with existing roads accounting for only 49.99%. E3 has the least new construction, at 41.130 km.

Table 10. Network composition by scenario.

Scenario	Total Network Length (km)	Existing-Road Length Used (km)	New-Construction Length (km)	Existing-Road Share (%)
E1	993.151	658.291	334.860	66.28
E2	880.001	831.873	48.128	94.53
E3	806.368	765.238	41.130	94.90
E4	918.985	868.543	50.443	94.51
E5	525.078	262.477	262.601	49.99
E6	864.524	818.178	46.346	94.64

3.3. Improvements in Service Accessibility

Service accessibility is evaluated using the same 523 fixed origin–destination (OD) pairs: 254 village-to-township government pairs, 15 township government-to-county seat pairs, and 254 village-to-county seat pairs. The 19 township-level planning nodes serve network generation (Table 1); the 15 township-government origins define the administrative-service OD set. The pre-planning evaluation network contains all existing roads. Each post-planning evaluation retains this complete existing-road network, including roads not selected by the scenario, adds newly constructed roads, and updates the status of upgraded segments. The selected planning network is therefore distinct from the full network used for travel-time evaluation. Following Chen et al. [37], expressways, national roads, provincial roads, county roads, and township/village roads are assigned speeds of 100, 80, 60, 40, and 30 km/h, respectively; other local roads are assigned 30 km/h. Directly reused roads retain the speed of their current administrative category, whereas new and upgraded roads receive the target-category speed, representing assumed post-construction service conditions rather than measured operating speeds. Mean shortest travel times are calculated for the same OD pairs before and after planning; all three OD types have 100% reachability in every evaluation network.

The updated full-network evaluation shows that E5 has the shortest village-to-township government mean time, at 8.048 min, whereas E1 has the shortest township government-to-county seat and village-to-county seat mean times, at 21.355 and 24.186 min, respectively (Table 11). The corresponding E2 times are 9.699, 21.554, and 25.643 min, representing reductions of 29.69%, 45.24%, and 37.06% in mean travel time relative to the existing road network. Under the same hierarchical constraints, E2 reduces the three mean travel times by 0.203, 2.041, and 2.006 min, respectively, compared with E6.

Table 11. Mean shortest travel times and changes relative to the existing road network.

Scenario	Village–Township Government		Township Government–County Seat		Village–County Seat	
	Time (min)	Improvement (%)	Time (min)	Improvement (%)	Time (min)	Improvement (%)
Pre-planning	13.794	—	39.359	—	40.742	—
E1	8.362	39.38	21.355	45.74	24.186	40.64
E2	9.699	29.69	21.554	45.24	25.643	37.06
E3	11.355	17.68	23.673	39.85	27.058	33.59
E4	9.882	28.36	21.799	44.61	25.801	36.67
E5	8.048	41.66	22.259	43.45	24.770	39.20
E6	9.902	28.22	23.595	40.05	27.649	32.14

Note: — indicates not applicable because the pre-planning network is the reference for calculating improvement.

E3 has the longest mean times for village-to-township and township-to-county trips. For village-to-county trips, E6 has the longest mean time (27.649 min), followed by E3 (27.058 min). The estimated reductions reflect both the added road connections and the target-category speeds assigned to new and upgraded segments.

3.4. Hierarchical Compliance

County-level compliance counts county-level nodes in the largest connected component of county-function edges (Table 12). Township-level compliance counts township-level nodes that can reach a county-level backbone node through permitted county- and township-level edges. Village-level compliance counts village nodes that can reach their assigned township backbone through permitted connections within that township. A cross-level error is an upper-level connection task that links a county-level and a village-level node directly, skipping the township level; a cross-township error is a village-level access task whose endpoints belong to different townships. E3 and E4 both connect all 254 village nodes to their assigned township backbones, but they contain 58 and 76 cross-township upper-level tasks, respectively, and their county-level counts are only 2/7. Thus, neither scenario satisfies all hierarchical constraints even though village access compliance is 254/254. An isolated node is a planning node with no permitted connection to the rest of the scenario network; no scenario contains isolated nodes.

Table 12. Hierarchical compliance counts and connection errors.

Scenario	County-Level Compliant Nodes/Total	Township-Level Access Nodes/Total	Village Assigned-Township Access Nodes/Total	Isolated Nodes	Cross-Level Tasks	Cross-Township Tasks
E1	7/7	19/19	254/254	0	0	0
E2	7/7	19/19	254/254	0	0	0
E3	2/7	1/19	254/254	0	5	58
E4	2/7	7/19	254/254	0	8	76
E5	7/7	19/19	254/254	0	0	0
E6	7/7	19/19	254/254	0	0	0

E1, E2, E5, and E6 satisfy the same permitted connection rules and therefore have identical compliance counts. Table 12 tests whether the required hierarchical connections are present; route length, construction requirements, and travel times are compared separately in Tables 10, 11 and 13. Differences in road representation, cost rules, and network organization can produce different layouts while satisfying the same structural constraints.

Table 13. Road lengths by construction type for E1–E6.

Scenario	Reuse (km)	Upgrading (km)	New Construction (km)	Total Network Length (km)	Construction Requirements Index
E1	658.291	0.000	334.860	993.151	0.3372
E2	825.141	6.732	48.128	880.001	0.0593
E3	764.417	0.821	41.130	806.368	0.0516
E4	865.873	2.670	50.443	918.985	0.0566
E5	231.716	30.761	262.601	525.078	0.5353
E6	810.560	7.618	46.346	864.524	0.0589

3.5. Construction Types

Table 13 reports reuse, upgrading, and new-construction lengths. E2 includes 825.141 km of reuse, 6.732 km of upgrading, and 48.128 km of new construction, yielding a construction requirements index of 0.0593. E3 has the lowest index (0.0516), whereas E5 has the highest (0.5353). E2 requires 214.473 km less new construction than E5, a reduction of 81.67%, but has longer service travel times, illustrating the trade-off between new construction and accessibility.

3.6. Composite Evaluation

Composite scores summarize network composition, service accessibility, and construction requirements; hierarchical compliance is reported independently and excluded from the score.

E2 achieves the highest entropy-weighted composite score of 79.73, followed by E4 at 76.38 and E1 at 63.29 (Table 14). Its scores for network composition, service accessibility, and construction requirements are 61.68, 66.47, and 98.42, respectively. E1 has the highest service-accessibility score but lower network-composition and construction-requirements scores. E3 and E4 participate in the composite comparison but do not satisfy all hierarchical constraints.

Table 14. Entropy-weighted composite evaluation results.

Scenario	Network Composition	Service Accessibility	Construction Requirements	Hierarchical Compliance	Composite Score	Rank
E2	61.68	66.47	98.42	Satisfied	79.73	1
E4	57.49	59.58	98.96	Not satisfied	76.38	2
E1	18.14	96.83	40.96	Satisfied	63.29	3
E6	63.45	15.77	98.50	Satisfied	57.25	4
E3	69.95	5.69	100.00	Not satisfied	54.15	5
E5	50.00	81.38	0.00	Satisfied	42.42	6

Hierarchical compliance is an independent feasibility requirement. E4 ranks second on the three scored dimensions but fails this requirement, so it is unsuitable as the final hierarchical plan. E5 satisfies the connection rules but ranks sixth because of its greater construction requirements. E2 combines the highest composite score with full hierarchical compliance. Figure 7 compares local network layouts.

The local layouts reveal differences in existing-road use and node organization (Figure 7). Green segments indicate new construction, while purple segments indicate upgrading of existing roads. E1 and E5 contain more extensive new links across roadless areas. In contrast, E2 relies mainly on existing roads, with localized upgrading and limited new construction to complete the required connections. Upgrading retains existing alignments while improving their technical conditions, whereas new construction

provides connections where existing roads are insufficient. Combined with the network-wide results, E2 satisfies the hierarchical requirements that E3 and E4 do not fully meet and achieves shorter average travel times than E6 for all three service categories.

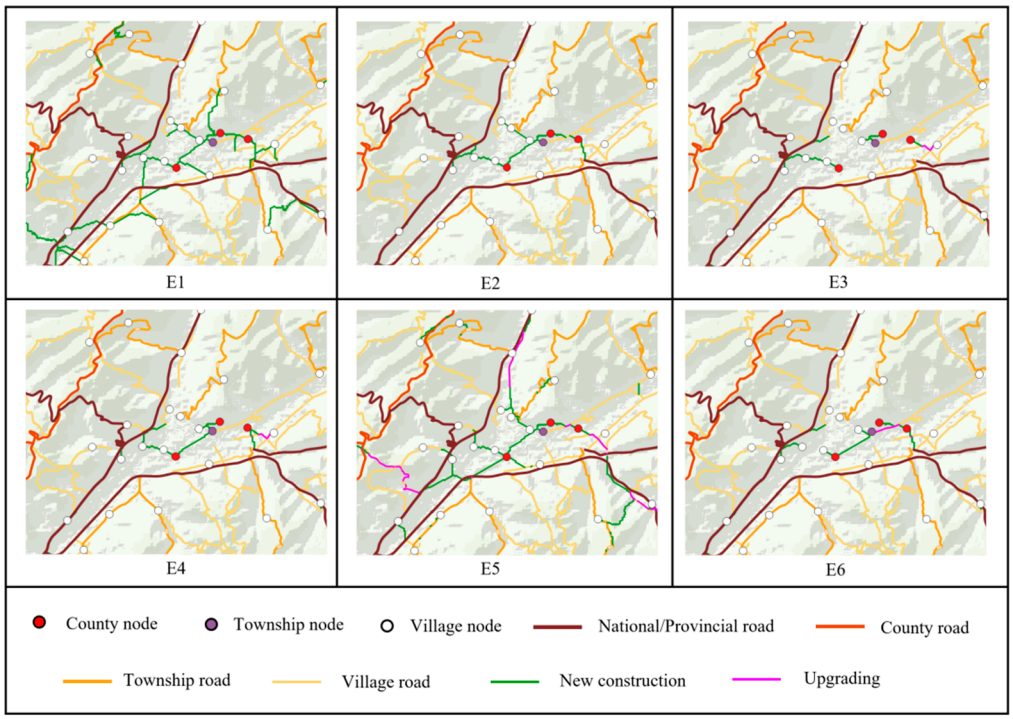


Figure 7. Local network layouts generated by E1–E6.

4. Discussion

4.1. Applicability and Trade-Offs

The highest composite score of E2 reflects the combined effects of three components. First, R_2 represents higher-category roads with cross-neighborhood edges and lower-category roads with neighborhood edges, incorporating existing infrastructure into the candidate graph. E2 uses 831.873 km of existing roads through reuse and upgrading, substantially more than E1 and E5. The E1–E2 comparison reflects the joint effects of representation and cost treatment. Second, sequential county–township–village organization in H_2 avoids the hierarchical deficiencies observed in the global strategies E3 and E4. Third, K_1 distinguishes reuse from upgrading costs, enabling a trade-off between existing-road use and new construction. E5 has the shortest village-to-township travel time but the highest construction requirements index and the lowest use of existing road resources, illustrating the greater new-construction requirement associated with its accessibility gains.

Network organization affects both service accessibility and functional structure. E2 and E6 use the same access and cost rules. With only 1.79% more network length, E2 reduces the three service travel times by 2.05%, 8.65%, and 7.26%, respectively. E3 and E4 have no isolated nodes, yet both attain only 28.57% county-level continuity. These results support treating hierarchical functional requirements as explicit planning priorities rather than relying on overall connectivity or minimum total length.

Global connectivity alone does not ensure a continuous county-level backbone or appropriate township links. In this case, the scenario with the shortest village-to-township travel time also requires substantial new construction. By incorporating road functions, administrative affiliation, and existing-road use into generation, the proposed method supports comparison across functional organization, service accessibility, and

construction requirements rather than a single length or cost measure. It translates rural road planning requirements into executable network generation rules for constructing and comparing candidate networks in mountainous counties.

4.2. Sensitivity to Weights and Cost Coefficients

Each baseline entropy weight is multiplied by 0.8, 1.0, or 1.2 and then renormalized, producing 25 unique weight combinations. E2 ranks first in all 25 combinations.

To examine indicator overlap, the internal weight of existing-road share within network composition is reduced from 50% to 25% and 0%, with the remainder assigned to total network length. The baseline entropy weights are retained rather than re-estimated. E2 remains first, with composite scores of 79.73, 77.50, and 75.27, respectively.

Sensitivity to the upgrading cost coefficient ρ_u is examined using values of 0.4, 0.6, and 0.8 while holding each scenario's terrain costs, existing-road representation, and node-connection rules fixed. Both tests compare all six scenarios at each coefficient value (Table 15). Test A changes only ρ_u while holding the construction-evaluation coefficient ρ_e at 0.6; Test B changes ρ_u and ρ_e together. Each test therefore contains 18 records. Normalization bounds are fixed using the pooled extrema within each test, and the three dimension weights remain at their baseline entropy values. Table 14 instead uses bounds from the six baseline scenarios. E1 and E5 do not use ρ_u in path search, so their networks and travel times remain at baseline; in Test B, E5's construction-evaluation score changes with ρ_e.

Table 15. Complete six-scenario cost-sensitivity results.

ρ_u	Scenario	A Score	A Rank	B Score	B Rank
0.4	E1	62.95	2	63.51	2
0.4	E2	81.14	1	81.14	1
0.4	E3	59.34	4	59.27	4
0.4	E4	53.37	5	53.39	5
0.4	E5	44.38	6	46.39	6
0.4	E6	61.30	3	61.41	3
0.6	E1	62.95	3	63.51	3
0.6	E2	80.31	1	80.23	1
0.6	E3	59.36	5	59.26	5
0.6	E4	77.49	2	77.41	2
0.6	E5	44.38	6	45.39	6
0.6	E6	62.75	4	62.68	4
0.8	E1	62.95	4	63.51	4
0.8	E2	78.61	1	78.47	1
0.8	E3	64.74	3	64.64	3
0.8	E4	59.89	5	59.78	5
0.8	E5	44.38	6	44.38	6
0.8	E6	69.36	2	69.17	2

At upgrading cost coefficients of 0.4, 0.6, and 0.8, the existing-road shares of E2 are 96.02%, 94.53%, and 92.59%, respectively. E2 ranks first in each tested setting, indicating that its recommendation is unchanged within this range. The decreasing existing-road share as the coefficient rises reflects the response of path selection to the assumed upgrading cost. Appendix A reports the inputs, normalization bounds, component scores, and all weight-perturbation results.

4.3. Implications for Sustainable Rural Transport Planning

Integrating existing-road use into network generation helps identify opportunities to improve county-wide connections through existing infrastructure. In this case, existing roads account for 94.53% of the proposed network, and new construction is reduced by 286.732 km relative to the uniform cross-neighborhood scenario. This demonstrates the planning value of infrastructure reuse in controlling new road requirements. New-construction length directly indicates the scale of additional road provision; land take, material consumption, and carbon emissions require further quantification using road widths, engineering structures, and construction conditions.

County-level continuity, township-level links, and village access within the assigned township provide a basis for functional connections between service nodes at different levels. The three travel-time indicators describe support for access to administrative services. They provide a foundation for further public-service accessibility analysis incorporating population, vulnerable groups, and facility capacity to examine differences in benefits among residents.

Accessibility is measured by mean shortest travel times across equally weighted administrative-service OD pairs, using speeds assigned by road category. Future applications can build demand matrices from population, employment, facility distribution, and travel surveys, and can use transport assignment models to assess capacity and operating conditions [38]. The generated connections, segment lengths, and construction types can serve as network-supply inputs for scenario refinement and construction scheduling.

The search identifies candidate corridors using distance, DEM-derived gradient, and no-build areas. Detailed geometric design, including horizontal and vertical alignment, curve radii, sight distance, and bridge and tunnel design, is left to subsequent engineering studies. Russo et al. [39] compare high-speed railway, conventional-line, and straight-line lengths to examine the relationship between route length and travel-time benefits. Rural-road candidate corridors similarly require terrain and geological investigation and geometric design against the target technical standards before route length, engineering requirements, and operating speeds are finalized.

5. Conclusions and Outlook

This study develops a rural road network generation method for mountainous areas under hierarchical constraints. An integrated representation of existing-road topology and roadless space brings infrastructure reuse and new-corridor search into one computational process. County-level continuity, township-level links, and village access within the assigned township are translated into sequential generation rules. Reuse, upgrading, and new construction are identified during generation, allowing the planning output to describe spatial layout, hierarchical functions, and construction requirements together.

Six comparative scenarios in Zhangjiachuan Hui Autonomous County show that E2 satisfies the hierarchical requirements and achieves the highest entropy-weighted composite score of 79.73. E2 ranks first across the tested weight combinations and upgrading-cost coefficients. Further validation across counties and links to demand modeling and detailed engineering design would support practical application. In this county case study, E2 combines full hierarchical compliance with 94.53% existing-road use and 48.128 km of new construction. These results support sustainable rural transport planning by identifying improvements that build on existing infrastructure while maintaining hierarchical service connections. In this case, reduced new-construction requirements and improved administrative-service accessibility provide a basis for comparing the resource and service implications of candidate rural road networks.

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Appendix A. Evaluation Inputs and Verification Results

The tables below use three-decimal input values and unrounded entropy weights; intermediate calculations are not rounded.

Table A1. Road-length inputs (km).

ρ_u	Scenario	Total Length	Reuse	Upgrading	New Construction
0.4	E1	993.151	658.291	0.000	334.860
0.4	E2	851.298	811.850	5.567	33.881
0.4	E3	806.403	764.370	1.018	41.015
0.4	E4	888.402	836.476	5.456	46.470
0.4	E5	525.078	231.716	30.761	262.601
0.4	E6	864.146	809.422	9.501	45.222
0.6	E1	993.151	658.291	0.000	334.860
0.6	E2	880.001	825.141	6.732	48.128
0.6	E3	806.368	764.417	0.821	41.130
0.6	E4	918.985	865.873	2.670	50.443
0.6	E5	525.078	231.716	30.761	262.601
0.6	E6	864.524	810.560	7.618	46.346
0.8	E1	993.151	658.291	0.000	334.860
0.8	E2	873.107	803.107	5.274	64.726
0.8	E3	818.820	776.981	0.272	41.567
0.8	E4	923.081	872.930	1.217	48.935
0.8	E5	525.078	231.716	30.761	262.601
0.8	E6	878.789	825.122	5.753	47.914

Table A2. Service-time inputs (min).

ρ_u	Scenario	Village-Township	Township-County	Village-County
0.4	E1	8.362	21.355	24.186
0.4	E2	9.946	22.018	25.022
0.4	E3	11.358	23.673	27.058
0.4	E4	10.460	24.500	28.356
0.4	E5	8.048	22.259	24.770
0.4	E6	9.909	23.781	27.805
0.6	E1	8.362	21.355	24.186
0.6	E2	9.699	21.554	25.643

0.6	E3	11.355	23.673	27.058
0.6	E4	9.882	21.799	25.801
0.6	E5	8.048	22.259	24.770
0.6	E6	9.902	23.595	27.649
0.8	E1	8.362	21.355	24.186
0.8	E2	9.697	21.546	25.632
0.8	E3	10.694	23.264	26.903
0.8	E4	10.196	23.781	27.751
0.8	E5	8.048	22.259	24.770
0.8	E6	10.047	22.953	26.431

Table A3. Normalization bounds for baseline and sensitivity evaluations. $z_j = 100\frac{x - a_j}{b_j - a_j}$ or $z_j = 100\frac{b_j - x}{b_j - a_j}$. The first expression is used for a benefit indicator and the second for a cost indicator. U is the existing road share, I is the construction requirements index, and a and b are the minimum and maximum within the relevant comparison set.

Set	Indicator	Lower Bound	Upper Bound
Baseline	Total length (km)	525.078000000	993.151000000
Baseline	U	0.499881922	0.948993512
Baseline	Village-township (min)	8.048000000	11.355000000
Baseline	Township-county (min)	21.355000000	23.673000000
Baseline	Village-county (min)	24.186000000	27.649000000
Baseline	I	0.051617376	0.535268284
A	Total length (km)	525.078000000	993.151000000
A	U	0.499881922	0.960200776
A	Village-township (min)	8.048000000	11.358000000
A	Township-county (min)	21.355000000	24.500000000
A	Village-county (min)	24.186000000	28.356000000
A	I	0.043722880	0.535268284
B	Total length (km)	525.078000000	993.151000000
B	U	0.499881922	0.960200776
B	Village-township (min)	8.048000000	11.358000000
B	Township-county (min)	21.355000000	24.500000000
B	Village-county (min)	24.186000000	28.356000000
B	I	0.042414995	0.546985019

Table A4. Entropy-weighted component scores when only ρ_u varies (Test A).

ρ_u	Scenario	Network	Service	Construction	Composite	Rank
0.4	E1	17.6996	96.8379	40.3013	62.9531	2
0.4	E2	65.1529	67.1765	100.0000	81.1423	1
0.4	E3	68.7470	19.1409	98.3936	59.3442	4
0.4	E4	59.8307	9.0433	97.5039	53.3724	5
0.4	E5	50.0000	85.7504	0.0000	44.3832	6
0.4	E6	62.4191	26.6172	96.9066	61.2988	3
0.6	E1	17.6996	96.8379	40.3013	62.9531	3
0.6	E2	60.4693	69.6178	96.8349	80.3094	1
0.6	E3	68.7350	19.1711	98.3939	59.3565	5
0.6	E4	56.2834	63.9152	97.3735	77.4885	2
0.6	E5	50.0000	85.7504	0.0000	44.3832	6
0.6	E6	62.2401	29.9061	96.9132	62.7545	4
0.8	E1	17.6996	96.8379	40.3013	62.9531	4
0.8	E2	59.0939	69.8106	93.0760	78.6053	1

0.8	E3	67.4311	31.4017	98.5269	64.7408	3
0.8	E4	56.0498	24.1586	97.9492	59.8903	5
0.8	E5	50.0000	85.7504	0.0000	44.3832	6
0.8	E6	60.6170	44.9865	97.0038	69.3599	2

Table A5. Entropy-weighted component scores when ρ_u and ρ_e vary together (Test B).

$\rho_u = \rho_e$	Scenario	Network	Service	Construction	Composite	Rank
0.4	E1	17.6996	96.8379	41.5831	63.5079	2
0.4	E2	65.1529	67.1765	100.0000	81.1423	1
0.4	E3	68.7470	19.1409	98.2259	59.2716	4
0.4	E4	59.8307	9.0433	97.5526	53.3935	5
0.4	E5	50.0000	85.7504	4.6442	46.3933	6
0.4	E6	62.4191	26.6172	97.1631	61.4098	3
0.6	E1	17.6996	96.8379	41.5831	63.5079	3
0.6	E2	60.4693	69.6178	96.6574	80.2325	1
0.6	E3	68.7350	19.1711	98.1762	59.2622	5
0.6	E4	56.2834	63.9152	97.1821	77.4057	2
0.6	E5	50.0000	85.7504	2.3221	45.3882	6
0.6	E6	62.2401	29.9061	96.7337	62.6768	4
0.8	E1	17.6996	96.8379	41.5831	63.5079	4
0.8	E2	59.0939	69.8106	92.7561	78.4668	1
0.8	E3	67.4311	31.4017	98.2926	64.6394	3
0.8	E4	56.0498	24.1586	97.6906	59.7784	5
0.8	E5	50.0000	85.7504	0.0000	44.3832	6
0.8	E6	60.6170	44.9865	96.5624	69.1689	2

Table A6. Entropy-weight perturbation results. Each baseline entropy weight is multiplied by 0.8, 1.0, or 1.2 and then renormalized, yielding 25 unique combinations. Displayed weights are rounded to six decimals; rankings use full precision.

Network Weight	Service Weight	Construction Weight	First	Highest Score	E2 Rank
0.082587	0.466726	0.450688	E2	80.4727	1
0.089553	0.421745	0.488703	E2	81.6536	1
0.089294	0.504631	0.406075	E2	79.0155	1
0.097802	0.368476	0.533721	E2	83.0521	1
0.097494	0.459142	0.443364	E2	80.1673	1
0.097187	0.549237	0.353576	E2	77.3006	1
0.101145	0.457284	0.441571	E2	80.0925	1
0.107352	0.404454	0.488194	E2	81.5520	1
0.106980	0.503817	0.389203	E2	78.3917	1
0.109490	0.412509	0.478001	E2	81.2162	1
0.109180	0.493612	0.397208	E2	78.6369	1
0.119335	0.359682	0.520983	E2	82.5419	1
0.118967	0.448217	0.432815	E2	79.7273	1
0.118602	0.536209	0.345189	E2	76.9300	1
0.128572	0.403670	0.467758	E2	80.7974	1
0.128216	0.483064	0.388720	E2	78.2744	1
0.130682	0.393883	0.475435	E2	81.0325	1
0.130241	0.490693	0.379065	E2	77.9563	1
0.139864	0.351298	0.508839	E2	82.0555	1
0.139443	0.437801	0.422756	E2	79.3078	1
0.139025	0.523785	0.337190	E2	76.5766	1
0.144414	0.435272	0.420314	E2	79.2060	1

0.152824	0.383851	0.463325	E2	80.5395	1
0.152322	0.478236	0.369442	E2	77.5430	1
0.168432	0.423053	0.408515	E2	78.7139	1

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