

# Optimization of Tourism Destination Road Network Layout Based on MCR and Circuit Theory Model

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**Abstract:** The development of the tourism industry drives the growth of transportation demand in tourist destinations. The road network layout directly affects the tourist experience and local development. Therefore, optimizing road network layouts has become an important issue to enhance tourism competitiveness and sustainable development. In response to this situation, a road network layout model based on an optimized minimum cumulative resistance model combined with circuit theory is proposed to optimize the road network in tourist areas. The layout optimization model demonstrated the most outstanding performance. The key novelty lies in the first-time fusion of Max Coverage Region's (MCR's) spatial resistance analysis with circuit theory's complex network optimization capabilities. This establishes a multi-objective framework that simultaneously balances ecological protection, traffic efficiency, and visitor experience. The mean square error was 0.21, and the root mean square error and mean absolute error were as low as 0.001 and 0.0015, respectively. These values demonstrate its high efficiency and accuracy. The layout accuracy of the proposed model mostly remained above 94.62%, while the accuracy of the traditional layout method fluctuated between 91.82% and 94.65%, demonstrating a decrease in efficiency over time. This indicates that the proposed model maintains high accuracy over long periods of operation, while the traditional layout method exhibits significant volatility. The model optimizes the road network layout, and also considers ecological protection and environmental impact, which can better support the sustainable development of tourist areas. This is significant for protecting the natural environment and cultural heritage. These results offer actionable insights for tourism planners, transportation infrastructure developers, ecological conservation agencies, and tourists, supporting evidence-based decision-making for high-quality and sustainable tourism development.

**Keywords:** Minimum cumulative resistance model, circuit theory, road network layout optimization, scenic area planning, model building.

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## 1. Introduction

Since 2021, the country has successively issued documents such as the "National Comprehensive Three dimensional Transportation Network Planning Outline" and the "Guiding Opinions on Promoting High-Quality Development of Rural Passenger Transport", which clearly propose to promote the integrated development of transportation and tourism and strengthen the construction of tourism resources and industries (Ruan, 2025 and Wang et al., 2024). The 2024 "Five-Year Action Plan for Promoting High-Quality Development of Tourism Highways (2023-2027)" further refines these goals and plans to build a standard system for tourism highways through five major actions, including improving facility quality and upgrading services. Self-driving tours now account for over 70% of domestic travel in China, and tourist's demand for personalized and in-depth experiences is driving the transformation of transportation infrastructure towards "scenic routes". Moreover, global tourism and "micro vacation" models require the road network layout to balance accessibility and experience (Md Ayman et al., 2024). Optimizing the layout of tourism destination road networks can not only promote high-quality development gaps, but also help address ecological and sustainable development challenges. However, the road network density of many tourist destinations is currently low. In particular, the coverage of branch roads and scenic area connecting lines is insufficient. Therefore, how to effectively avoid over-development, reduce environmental damage through ecological corridor design, and explore cultural elements along highways has become an urgent problem for the tourism industry to solve (Retzlaff et al., 2024). The road network layout in tourist destinations requires the consideration

of various factors, such as traffic flow, tourist distribution, and accessibility between attractions. This involves the spatial relationship between tourists and attractions. Therefore, to obtain the most accurate road network layout method, the Minimum Cumulative Resistance (MCR) model is introduced to calculate the resistance factors of attractions. In addition, to ensure the comprehensiveness of road network excavation, the study also introduces circuit theory to support road network node control.

The MCR model has been largely applied in rural planning and layout, biological seasonal migration planning, natural tourism resource structure layout, and tourism corridor planning and design. Numerous scholars have conducted research on the applicability of the MCR model. Li and Zeng constructed the urban ecological network of Jingzhou City based on the MSPA-MCR model to enhance the urban ecological health and the quality of the human settlement environment. The research employed the GIS platform, used morphological spatial pattern analysis to identify ecological source areas, and combined landscape connectivity evaluation and multi-factor weighting method to construct a refined resistance surface. Then, an ecological corridor network was generated through the MCR model. Compared with traditional methods that only rely on land use types or single ecological indicators, this framework could more accurately identify core patches and key connection paths with high ecological value, and accordingly propose targeted spatial optimization strategies, providing an operational technical paradigm for ecological network planning in small and medium-sized cities (Li and Zeng, 2024). Bowen et al. combined MSPA, MCR, the gravitational model and hydrological analysis to construct and optimize the ecological corridor system in the main urban area of Putian City. The study identified 14 core ecological source areas through MSPA and landscape connectivity index, extracted 29 hierarchical ecological corridors using MCR and gravity model, and further introduced hydrological analysis to identify 205 radiation corridors and 53 ecological function nodes. Compared with the single methods that only rely on MCR or connectivity indicators, this multi-model fusion framework not only enhanced the ecological rationality of the spatial layout of corridors, but also strengthened the systematic linkage between nodes, corridors, and source areas through hydrological processes, providing a scientific basis for the refined identification and hierarchical control of urban ecological networks (Bowen et al., 2024). Xu et al. (2025) took Maotai Town in Guizhou Province as an example and constructed a commercial spatial accessibility evaluation system integrating Point of Interest (POI) analysis, spatial syntax, cost-weighted model, and MCR. The research first identified commercial hotspots and their service blind spots through POI visualization, then assessed spatial accessibility in both topological and geometric dimensions, and finally identified the actual resistance paths of tourists within the town area based on the MCR model. Compared with the traditional methods that rely only on Euclidean distance or road network density, this multi-dimensional framework could more truly reflect tourists' behavior and space utilization efficiency. Taking the Giant Panda National Park as an example, Qiu et al. integrated the Maximum Entropy Model (MaxEnt), MCR, hydrological analysis and ant colony algorithm to construct an ecological network for rare animal habitats. The research identified 24 ecological sources based on habitat suitability and precisely extracted 55 ecological corridors and 14 key restoration points by combining MCR and ant colony algorithms. Compared with the traditional methods that only rely on MCR, this framework significantly improved the ecological rationality and connectivity efficiency of corridor spatial positioning by introducing intelligent optimization algorithms and habitat probability distribution (Qiu et al., 2024).

Circuit theory models are important tools in electrical engineering to describe and analyze circuit behavior. In recent years, many experts and scholars have conducted applied research. For example, Kaliaperumal and Chidambaram built a thermal management system based on an equivalent circuit model to address the difficulty in accurately estimating the state of charge of lithium-ion battery packs in strongly nonlinear intervals. Compared with traditional constant current cooling systems, this method could reduce pumping power by 14% while maintaining battery temperature safety (Kaliaperumal et al., 2024). Kervellec et al. proposed a new spatial occupancy model that combined circuit theory to address the limitations of traditional spatial dynamic occupancy models in considering landscape connectivity. This model combined commuting time distance with cross-site accessibility. This method provides a more flexible framework for species dispersal ecology research (Kervellec et al., 2024). Mou et al. proposed a bionic synaptic neuron model based on discrete memory containers for simulating the memory and dynamic characteristics of biological synapses. The study first verified the memory-like behavior of the memory container. This neuron model could exhibit complex dynamic characteristics such as extreme multi-stability and multiple discharge modes, and these behaviors were highly dependent on the parameter settings of the memory container synapse. Finally, they successfully implemented the chaotic attractor generated by this model on the DSP hardware platform. Compared with traditional memristor synapses, this memristor synapse neuron had greater potential in terms of bionic accuracy and dynamic richness, providing a new idea for the development of brain-like computing hardware (Mou et al., 2024). Furrutter et al. first applied the Denoising Diffusion Model (DM) to quantum circuit synthesis, guiding the generation of gate-level quantum circuits that meet specific quantum operation requirements through text conditions. This method effectively avoided the exponential computational cost bottleneck faced by classical simulation of quantum dynamics during the training stage, which was significantly superior to previous schemes that relied on traditional machine learning. The validity of the model was verified in two tasks: entangled state generation and unitary operator compilation. It was also demonstrated that the model supported extended functions such as masking and editing, and could flexibly adapt to the hardware constraints of the target quantum device (Furrutter et al., 2024).

In summary, numerous researchers have conducted extensive research on the MCR model and circuit theory and have achieved significant results. However, few scholars have combined the two technologies to optimize the layout of tourist destination road networks. This study proposes a tourism destination road network layout optimization model based on an improved MCR and circuit theory. Relevant experiments were performed to verify the model's performance and practical application value. The research aims to accurately and efficiently optimize the road network in tourist areas. The innovation lies in combining the MCR model with circuit theory to form a new optimization method. This fusion not only fully utilizes the advantages of the MCR model in spatial resistance analysis but also leverages the efficient processing capability of circuit theory for complex networks, providing a new perspective and solution for optimizing tourism destination road

network layout.

## 2. Methods and Materials

### 2.1. MCR Model Layout and Scenic Area Pattern Control

The tourism road network is often divided into external tourism roads and regional internal tourism roads. External highways primarily connect tourist sources and destinations, while internal highways serve the transportation needs between attractions. The optimization of a tourist destination's road network layout must consider various factors, such as traffic flow, tourist distribution, and accessibility between attractions. Based on these requirements, this study introduces the MCR model, which describes and predicts the movement of objects or individuals through space. The MCR model can predict the spatial distribution and abundance of species by simulating their movement across a landscape (Song et al., 2024). The mathematical expression of MCR is shown in Eq. (1).

$$MCR = f_{min} \sum_{j=n, i=m} (D_{ij} \times R_i) \quad (1)$$

In Eq. (1),  $MCR$  can be understood as the distance that can be built at the minimum cost for tourists to travel from the source of the attraction to the location of each attraction.  $f$  signifies the positive correlation function between MCR and uncertain factors.  $i$  represents the initial point of the scenic area, such as the ticket office.  $j$  represents the location of a certain landscape in the scenic area.  $D_{ij}$  represents the straight-line distance that  $j$  disperses to a certain point in the scenic area and crosses  $i$ .  $R_i$  represents the dispersion resistance coefficient of  $i$  in the direction of the initial point. A scenic road is a multifunctional linear channel whose core function is to meet the needs of tourists. It carries the horizontal flow of tourists, including the transmission of personnel, information, and materials. Essentially, a scenic road represents the spatial resistance that tourists overcome on their journey from a departure point to their destination. This spatial resistance is composed of multiple factors. The greater the resistance, the more difficult it is for tourists to reach their destination; conversely, the smaller the resistance, the smoother the passage for tourists (Xu et al., 2025). To further evaluate the average distance between tourists dispersed across various attractions and popular attractions, the study introduces the Average Nearest Neighbor (ANN) ratio to optimize the MCR model. The ANN determines whether the spatial distribution of point features is clustered, random, or discrete by comparing the ANN distance of observed data with the expected ANN distance assuming a random distribution (Zhang et al., 2025). The range calculation principle of ANN is shown in Fig. 1.

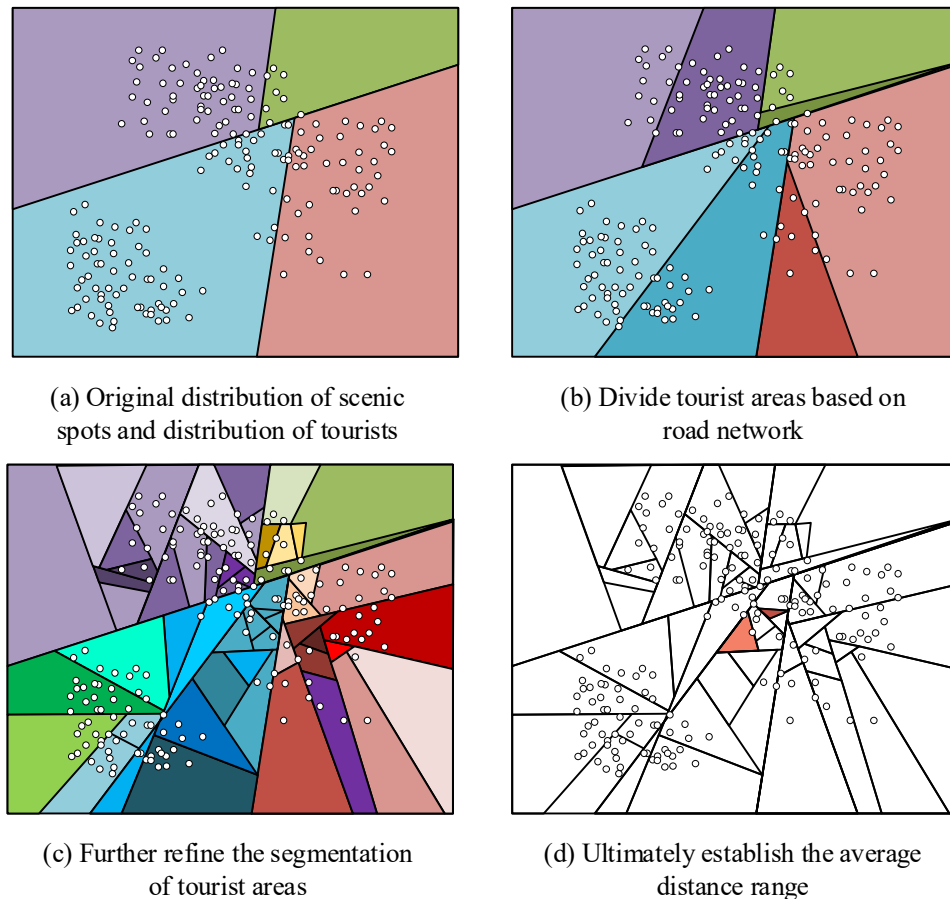


Fig. 1. Range calculation principle of ANN

According to fig. 1, ANN can determine whether the current road network layout is reasonable by calculating road network nodes (such as intersections, bus stops). If the ANN approaches 1, the node distribution is relatively random and may require further optimization. If ANN is less than 1, the node distribution is too clustered, which may lead to traffic congestion. If the ANN is greater than 1, the node distribution is relatively uniform, but further evaluation may be adopted to determine if it is excessively dispersed. If the nearest neighbor distance of the target sample is greater than the nearest neighbor distance under random distribution, this process is shown in Eq. (2).

$$ANN = \frac{D_0}{D_r} = \frac{D_0}{1/2\sqrt{N/A}} = 2D_0\sqrt{N/A} \quad (2)$$

In Eq. (2),  $D_0$  represents the average distance between tourist attractions and their adjacent points.  $D_r$  represents the expected average distance of tourist attractions in a hypothetical random pattern.  $N$  signifies the number of popular attractions in the tourist area.  $A$  signifies the area of the attraction. ANN can simultaneously reflect the two distribution states of passenger aggregation and dispersion. When the ANN value is less than 1, it indicates that the current state is aggregation. Otherwise, it represents dispersion. On a 3D map, people and road network status can be distinguished by the depth of colors, and this step is calculated, as presented in Eq. (3).

$$f_n(x) = \frac{1}{nd} \sum_{i=1}^n k \left( \frac{x - X_i}{d} \right) \quad (3)$$

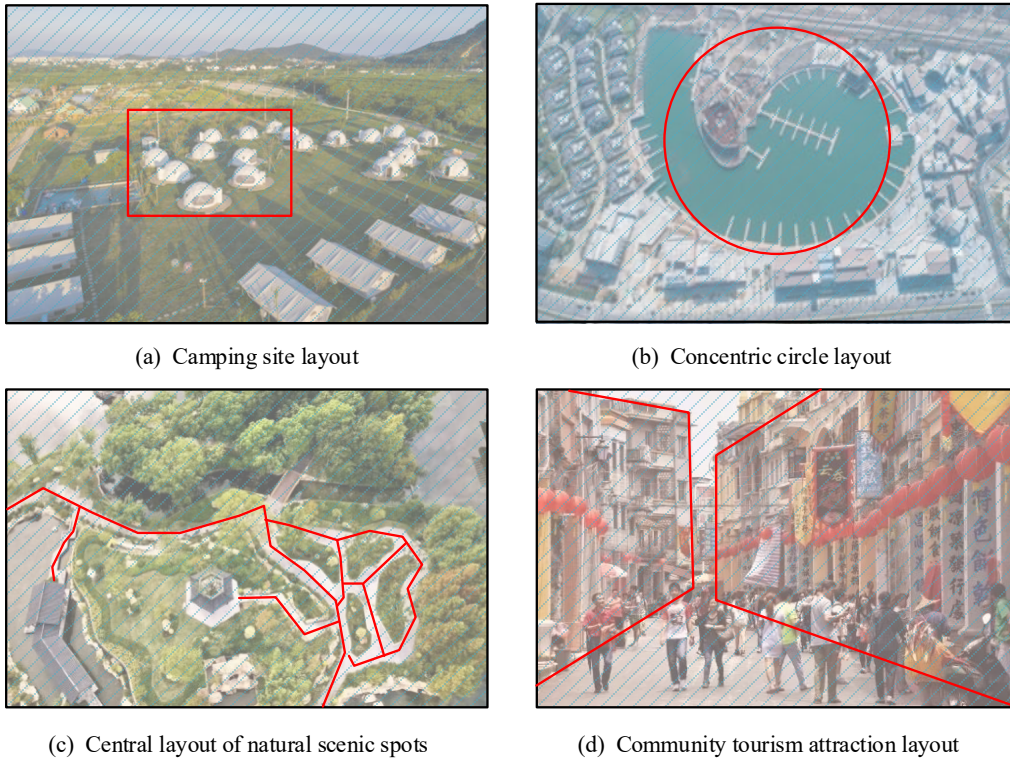
In Eq. (3),  $f_n(x)$  represents the population density at a certain location  $(x, y)$  in the scenic area.  $d$  represents the diffusion radius.  $n$  signifies the actual distance.  $k$  signifies the density function.  $x - X_i$  signifies the road network distance from the current location to the  $i$ -th actual attraction. The clustering of tourists in different attractions is inconsistent, which has important reference significance for road network layout. Therefore, the spatial distribution status of tourists is calculated. The calculation is shown in Eq. (4).

$$G(d) = \frac{\sum_{i=1}^n \sum_{j=1}^n w_{ij}(d) x_i x_j}{\sum_{i=1}^n \sum_{j=1}^n x_i x_j} \quad (4)$$

In Eq. (4),  $w_{ij}(d)$  represents distance weight.  $x_i x_j$  is the coefficient of movement for positions  $i$  and  $j$ . From a statistical perspective, this method is used to detect whether there are abnormally high or low values in the size of residential areas within a significant local area. Therefore, "hot" and "cold" areas are spatially identified. The mathematical expression for this step is shown in Eq. (5).

$$G_i^*(d) = \frac{\sum_{j=1}^n w_{ij}(d) x_j}{\sum_{j=1}^n x_j} \quad (5)$$

In Eq. (5), if the final result is a positive number, it represents that passengers are gathering in the "hot spot" area, where the road network needs to be heavily sparse. On the contrary, if the result is negative, it means that low values are scattered in the "cold spot" area, which can be considered as a secondary factor for optimizing the road network. In the research on optimizing the layout of tourist attractions, a landscape pattern index is often introduced to grasp the block area and the total area. of different types of attractions. Therefore, it combines the optimized MCR and landscape pattern index to grasp the block size and passenger density of attractions. The commonly used methods for the distribution of concentrated landscape patterns are shown in Fig. 2.



**Fig. 2.** Common layout methods for scenic area road networks

In Fig. 2, the total area of various types of attractions are shown in Eq. (6).

$$CA = \sum_{i=1}^B a_i \quad (6)$$

In Eq. (6),  $CA$  represents the total area of the tourist destination.  $B$  signifies the number of scattered attractions.  $a_i$  signifies the area of the  $i$ -th attraction. The degree of segmentation of the dispersed attraction road network is calculated, as shown in Eq. (7).

$$NP = B \quad (7)$$

In Eq. (7),  $NP$  represents the degree of fragmentation of the scenic area road network. The average land area of each scattered attraction is calculated, as shown in Eq. (8).

$$MPS = \frac{1}{n} \sum_{i=1}^n a_i \quad (8)$$

In Eq. (8),  $MPS$  represents the average land area of each scattered attraction.  $\frac{1}{n}$  represents dividing the total area of all attractions by the total number of attractions to obtain the average value. The layout of the road network is also related to the outer shape of the attraction, as calculated in Eq. (9).

$$MSI = \frac{\sum_{i=1}^n (0.25P_i / \sqrt{a_i})}{B} \quad (9)$$

In Eq. (9),  $MSI$  represents the peripheral shape index of the attraction.  $P_i$  represents the perimeter of the attraction. From this, it can be inferred that the road network density of each attraction is shown in Eq. (10).

$$PD = \frac{n}{\sum_{i=1}^n a_i} \quad (10)$$

In Eq. (10),  $PD$  represents the density of tourist attractions, and the larger the value, the higher dispersion. In summary, the study aims to segment tourist destinations by optimizing MCR and landscape pattern index, which facilitates subsequent road network optimization.

### 2.2. Circuit Theory and Optimization of Road Network Planning

Although the optimized MCR model is more convenient and comprehensive than traditional methods for optimizing ecological patterns, it has certain limitations. For example, ecological nodes are often defined as corridor intersections, an approach that can yield results significantly different from reality. Therefore, multiple factors, such as corridor importance and the magnitude of resistance values, should be comprehensively considered for node determination. This study proposes viewing tourist destinations as complex circuit systems, where roads are analogous to wires. The conventional circuit theory structure is shown in Fig. 3.

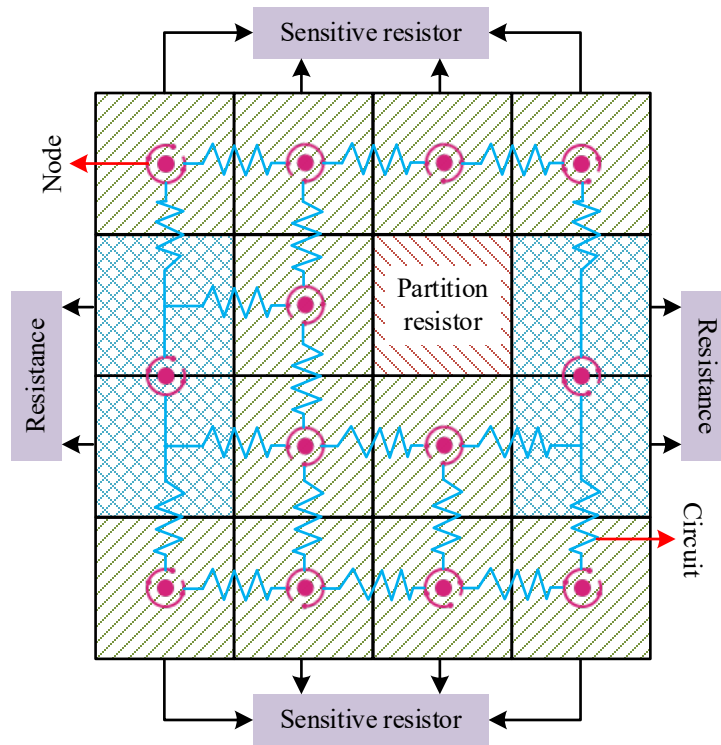


Fig. 3. The conventional structure of circuit theory

Fig. 3 shows three paths with different resistances, demonstrating that a greater number of paths between tourist attractions results in a smaller overall resistance value. The potential road network within the scenic area can be identified using circuit theory. This approach is based on the principle that, in physical circuits, current is directly proportional to voltage and inversely proportional to resistance (Zhang 2025). This step is calculated in Eq. (11).

$$I = \frac{V}{R_{eff}} \quad (11)$$

In Eq. (11),  $I$  represents the conductor current.  $V$  represents the voltage measured at both ends of the conductor.  $R_{eff}$  represents the effective circuit inside the conductor. The magnitude of current is inversely proportional to the effective resistance; that is, under constant voltage conditions, an increase in effective resistance will lead to a decrease in current. In tourist destinations, if the effective resistance of a certain path is high, tourists may tend to choose paths with lower resistance that allow for more convenient movement. When the number of available travel paths between two locations increases, the "resistance distance" between them decreases. The application of circuit theory utilizes the actual ecological network structure of a tourist destination to analyze its nodes and connection paths. In circuit theory, the ecological network closure index represents the complexity of the scenic road network, as calculated by Eq. (12).

$$\alpha = \frac{l - v + 1}{2v - 5} \quad (12)$$

In Eq. (12),  $\alpha$  represents network closure, and the closer the result is to 1, the more complex the road network structure within the scenic area.  $l$  represents the number of connections in an ecological network, which refers to the number of interactions or connections between different ecological components.  $v$  signifies the number of vertices in an ecological network, the number of different ecological components in the network. From this, it can be inferred that the integrity of the line points in each network structure is shown in Eq. (13).

$$\beta = \frac{l}{v} \quad (13)$$

In Eq. (13),  $\beta$  represents the line point rate. The degree of connection between each line is calculated, as shown in Eq. (14).

$$\gamma = \frac{l}{3(v - 2)} \quad (14)$$

In Eq. (14),  $\gamma$  represents the network connectivity, and the closer the result is to 1, the higher the network connectivity. The cost ratio of road network layout is shown in Eq. (15).

$$R_{cost} = 1 - \frac{l}{d} \quad (15)$$

In Eq. (15),  $R_{cost}$  signifies the cost of road network connection.  $d$  signifies the total length of the road network in the tourism destination's spatial network. Using the equations above, the study derives connectivity principles for tourist destination road networks from circuit theory. The principle of road network planning for tourist areas, based on circuit theory, is shown in Fig. 4.

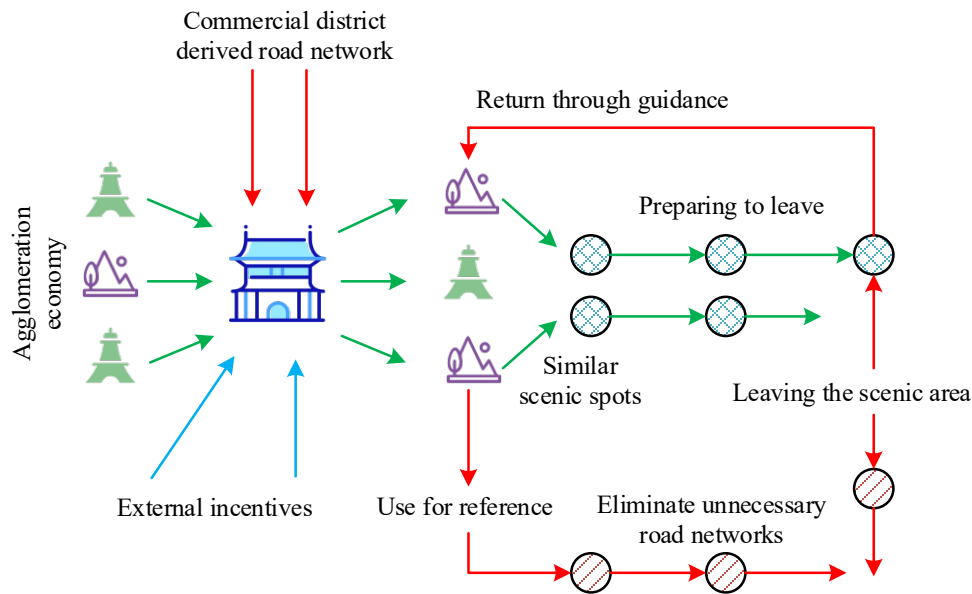


Fig. 4. Principles of road network planning in tourist areas under circuit theory

In Fig. 4, the types of different attractions have a significant impact on the road network layout. Circuit theory regards tourist attractions, service facilities, in tourist areas as components in the circuit. By applying analysis methods in circuit theory, such as node analysis and mesh analysis, it is possible to optimize road network design, improve traffic flow, reduce congestion, and ensure that tourists can smoothly access various attractions.

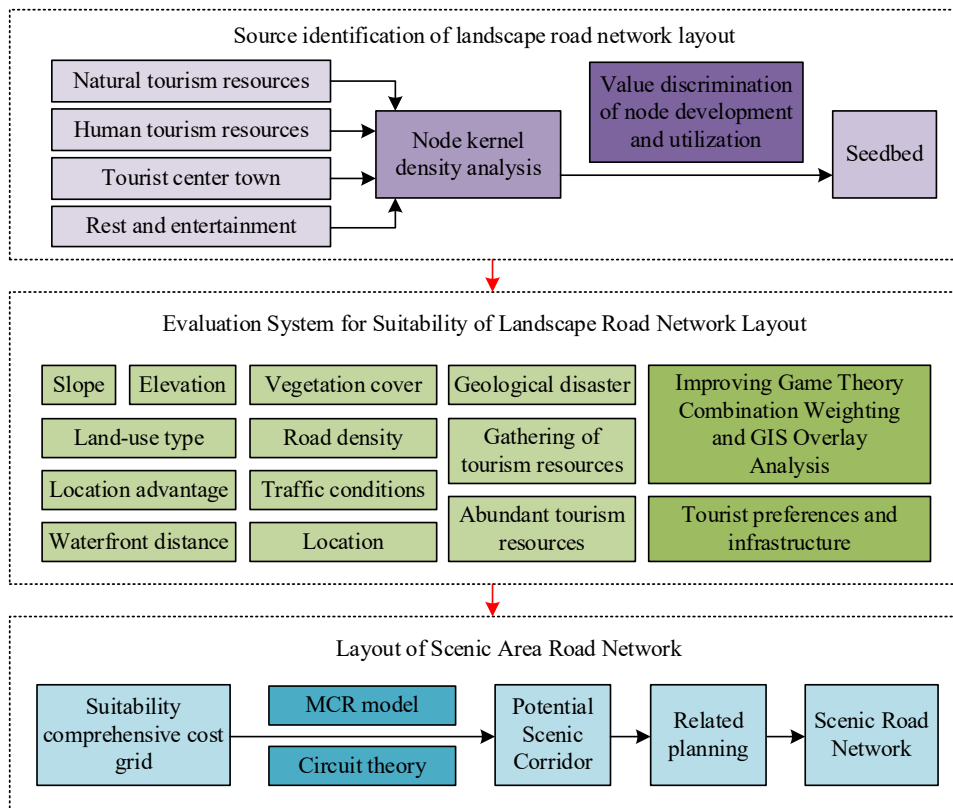
### 2.3. Optimization Model for Road Network Layout of Tourist Destinations

The study combines the optimized MCR model with circuit theory, aiming to effectively optimize the road network layout of attractions through this method. The study first conducts a comprehensive on-site investigation of a certain attraction, collects core data including the distribution of tourism resources, land use, and altitude, and imports these data into ArcGIS software to build a database. The data collection sources for the tourist area are presented in Table 1.

**Table 1.** Specific data information collection methods for tourist areas

Data Name	Data Category	Resolution	Data Sources
Scenic Area Data	Vector	/	Gaode API
Geological hazard data	Vector	/	Resource and Environmental Science and Data Center of Chinese Academy of Sciences
Administrative boundary	Vector	/	National Bureau of Surveying, Mapping and Geoinformation Standard Map Service Website
Road data	Vector	/	OpenStreetMap
DEM data	Grid	30m*30m	Geospatial Data Cloud
Slope gradient, slope direction	Grid	30m*30m	Resource and Environmental Science and Data Center of Chinese Academy of Sciences
Spatial distribution data of landform types	Grid	1km*1km	Institute of Geographic Sciences and Resources, Chinese Academy of Sciences
Land use data	Grid	30m*30m	Institute of Geographic Sciences and Resources, Chinese Academy of Sciences
Vegetation type	Grid	1km*1km	Resource and Environmental Science and Data Center of Chinese Academy of Sciences

Based on Table 1, the features of tourism resource nodes are thoroughly analyzed, and a group of representative and highly recognizable tourism resource nodes and key hubs are then selected. ArcGIS technology is used to visualize these source points. Finally, the study utilizes the MCR and circuit theory model to preliminarily identify potential scenic corridors between source areas. On this basis, combined with relevant local planning and policy guidance, a layout model of the scenic road network in the tourist area is constructed, as shown in Fig. 5.



**Fig. 5.** The layout model framework for the road network of tourist attractions in the tourist area

In Fig. 5, there are many factors that affect the road network layout for tourists, and the weights affected by indicators vary among different attractions. Therefore, to ensure the scientific and rational advantages of the constructed tourism scenic road network layout model, a road network layout optimization adaptability evaluation system is established, as shown in Fig. 6.

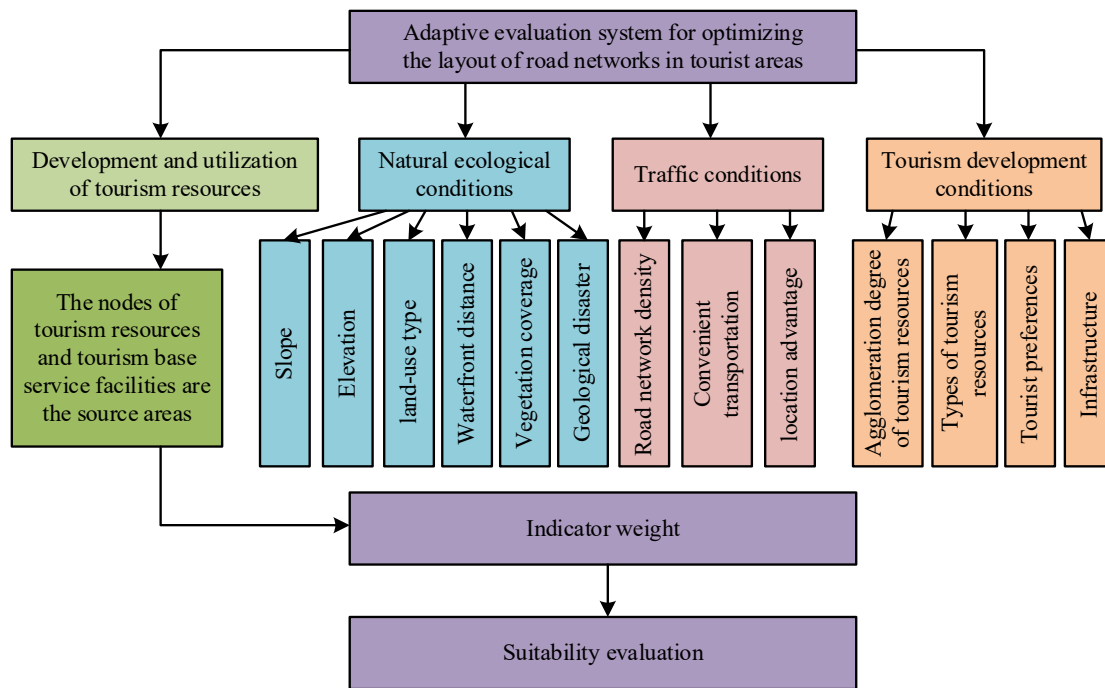


Fig. 6. Adaptive evaluation system for optimizing road network layout

Fig. 6 shows the evaluation system for optimizing the tourist area road network layout, which considers various influencing factors. Areas with high slope and elevation values are generally not suitable for road network construction due to high costs. In mountainous tourist attractions, road construction can also increase the potential for geological disasters. The cost and adaptability of road construction vary among different land types. Therefore, the primary consideration when optimizing the road network layout should be to utilize land with high constructability. Construction should be carefully avoided on sensitive lands such as residential areas, farmland, and freshwater lakes. Waterfront distance, defined as the distance between the tourist area and the water source, is another potential factor affecting the road network layout. Furthermore, the tourism system is a comprehensive structure, in which service facilities constitute the core elements, integral to every stage of the tourism process. These facilities play a crucial role in promoting and supporting tourism activities, and are decisive for enhancing the attractiveness of tourism resources and the destination’s public image.

### 3. Results

#### 3.1. Analysis of Joint Optimization Method based on MCR and Circuit Theory

This study selects Siguniang Mountain Scenic Area in Sichuan Province, China, as the empirical case. It is a UNESCO World Natural Heritage site and a national AAAAA-level tourist destination. The area is characterized by steep terrain, high ecological sensitivity, clustered tourism resources, and rapidly growing self-driving visitation. These features represent planning challenges commonly encountered in mountainous tourism regions. Therefore, this site ensures the representativeness and practical relevance of the proposed model. The methodology relies on widely available geospatial datasets, including Digital Elevation Models (DEMs), land use maps, and road network data. It incorporates a flexible resistance-weighting system that can be adapted to diverse geographical contexts. For instance, the influence of slope can be reduced in lowland lake districts, while the connectivity of cultural nodes can be enhanced in heritage zones. Computational tests were conducted on a standard workstation equipped with an Intel i7-12700H processor and 32 gigabytes of RAM, using ArcGIS version 10.8 and Circuitscape version 5.0. Under this configuration, the model processed a 10km<sup>2</sup> with approximately 200 nodes in about 8 minutes and a 50km<sup>2</sup> area with approximately 800 nodes in about 35 minutes. These results confirm the model's feasibility for medium-scale tourism planning applications. The experiment was repeated 10 times to verify the stability of the results. The original values of the evaluation indicators were set as displayed in Table 2.

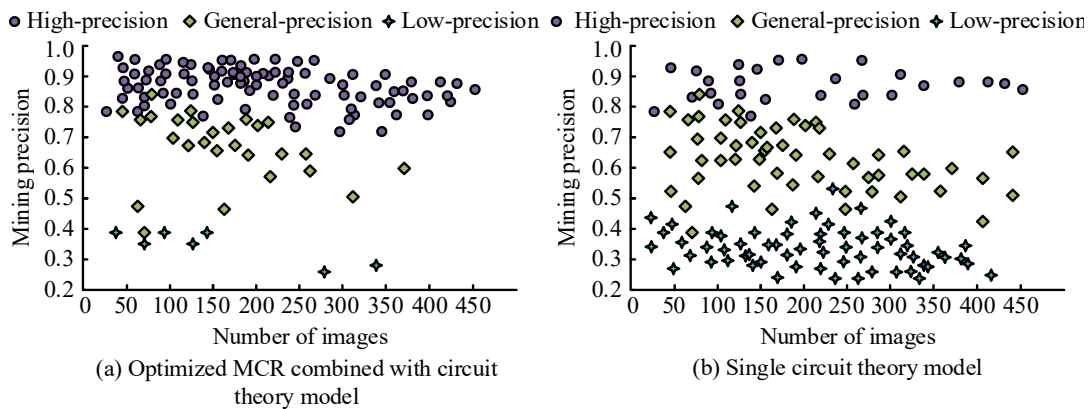
The experiment first verified the resistance surface generated by the optimized MCR model. Based on Table 2, the experiment randomly selected a tourist attraction from the public map data as the basis for verifying the weight of the resistance factor data. The weights of resistance factors for each indicator are shown in Table 3.

As shown in Table 3, tourism development conditions are the key factors affecting tourism resistance, particularly the spatial agglomeration of tourism resources and the coverage of tourism service facilities. The spatial agglomeration of tourism resources had a weight of 0.215895 and a resistance value of 100, indicating its significant impact on resistance and its high importance among tourism development conditions. The resistance value of tourist preference was 20, and the impact of tourist preference on resistance was relatively small. The resistance value of the coverage of tourism service facilities was 50, which had a moderate impact on resistance. This indicates that the concentrated distribution of tourism resources significantly reduces resistance, and improved service facilities enhance the tourist experience while also reducing resistance. The weight value of the indicators related to natural ecological conditions was 0.065508, indicating a

relatively weak overall impact on the maximum resistance calculation. However, slope and elevation had high resistance, which also indicates that the influence of natural ecology on road network optimization cannot be ignored. The weight value of the indicators related to transportation location conditions was 0.027895, among which traffic accessibility and locational advantage had a significant impact on resistance. Traffic conditions play a key role in tourist attraction accessibility. The results indicate that when planning tourism road network structure, attention should be paid to the rational layout of tourism resources and the improvement of tourism service facilities to enhance the attractiveness of tourist attractions and the tourism experience of tourists. In addition, natural ecological conditions and transportation location conditions cannot be ignored, and the impact of these factors on tourism resistance should be reduced through scientific planning and management. This also demonstrates that the optimized MCR model can accurately determine the optimal road network layout based on the characteristics of attractions, significantly improving layout efficiency. The road network identification capability of circuit theory was subsequently validated through experiments. The identification precision of the combined optimized MCR and circuit theory approach was compared to that of single circuit theory alone. The results are shown in Fig. 7.

**Table 2.** Initial value setting of evaluation indicators for the layout of tourist destination tunnel networks

First level Indicator	Secondary Indicators	Original Value	Attribute
Natural ecological conditions	Slope	0.00-81.57	Negative indicator
	Elevation	450-7,500	Negative indicator
	Land-use type	/	/
	Waterfront distance	/	Negative indicator
	vegetation coverage	/	Positive indicators
	Geological hazard impact degree	0.00-6.88	Negative indicator
Transportation location conditions	Road network density	0.07-0.99	Positive indicators
	Traffic accessibility	0.0000-0.6690	Positive indicators
	location advantage	3.20-12.00	Positive indicators
Tourism development conditions	Spatial clustering degree of tourism resources	0.000-0.300	Positive indicators
	Abundant types of tourism resources	7.00-25.00	Positive indicators
	Tourist preferences	0.0000-0.0100	Positive indicators
	Coverage of tourism service facilities	0.00-6.55	Positive indicators



**Fig. 7.** Comparison of road network mining capability of circuit theory

In Fig. 7(a), the optimized MCR method combined with circuit theory maintained high identification precision across different numbers of image datasets. The proposed method was less affected by variations between attractions. When the number of images was less than 250, the distribution points were denser, with a numerical range of 0.8-1.0 for high-precision identification. When the number of images exceeded 250, the high-precision distribution points became more sparse with a numerical range of 0.7-0.9. However, the distribution of low-precision processing points was relatively small,

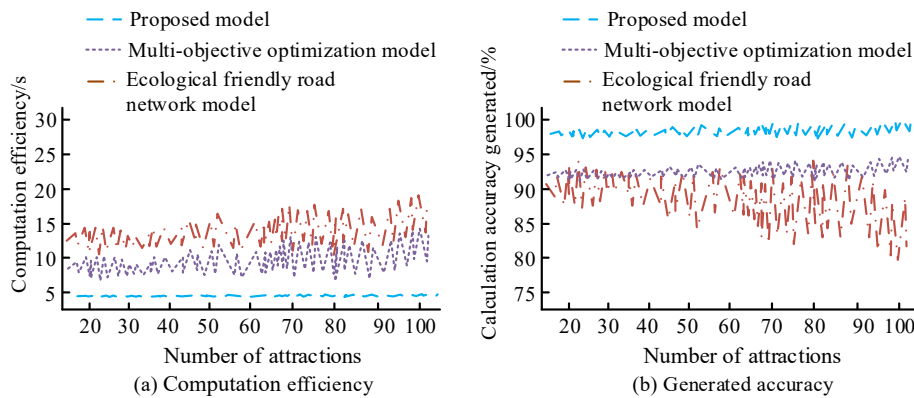
indicating that the method effectively controlled the identification precision for potential road networks. It could assist in building a refined road network structure for tourist destinations. In Fig. 7(b), the circuit theory method alone exhibited varying levels of identification success across different standard image datasets. When the number of images was less than 100, the high-precision distribution points were slightly more numerous, with a numerical range of 0.8-0.95. When the number of images exceeded 100, the high-precision distribution points gradually became sparse, with a numerical range of 0.8-0.9. The distribution of low-precision points was the highest, indicating that circuit theory alone was ineffective at identifying the potential road network in tourist destinations. In practice, it cannot help construction parties make accurate decisions, and the effect on road network layout is poor.

**Table 3.** Weight of resistance factors for each indicator

Resistance Factor	Resistance Level	Resistance Grading Standard	Resistance Value	Weight
Natural ecological conditions	Slope	0.00-81.57	100	0.065508
	Elevation	450-7,500	80	
	Land-use type	/	50	
	Waterfront distance	/	20	
	Vegetation coverage	/	1	
	Geological hazard impact degree	0.00-6.88	20	
Transportation location conditions	Road network density	0.07-0.99	50	0.027895
	Traffic accessibility	0.0000-0.6690	80	
	Location advantage	3.20-12.00	100	
Tourism development conditions	Spatial agglomeration degree of tourism resources	0.000-0.300	100	0.215895
	Abundant types of tourism resources	7.00-25.00	1	
	Tourist preferences			
		0.0000-0.0100	20	
	Coverage of tourism service facilities	0.00-6.55	50	

**3.2. Experimental Analysis of Optimization Model for Tourism Destination Road Network Layout**

To further verify the effectiveness of the tourism destination road network layout optimization model based on the optimized MCR and circuit theory, relevant experiments were conducted. To ensure the fairness of the experiment, two widely used road network layout models were introduced for comparison: a multi-objective optimization model and an ecologically conscious road network model. The comparative experiment was conducted with all models in their optimal state. The performance comparison results of the three road network layout models are shown in Fig. 8.



**Fig. 8.** Performance comparison results of three road network layout models

In Fig. 8(a), the computation speed curve of the proposed model remained stable. As the number of attractions increased, the computation time remained between 4.8 s and 5.0 s. The computation speed curves of the other two models showed significant fluctuations. When the number of attractions was equal to or greater than 100, the computation time for these models increased to 20 seconds. This indicates that the proposed method has a faster processing speed in practical applications, which facilitates the large-scale generation of road network layout schemes and improves optimization efficiency. In Fig. 8(b), the accuracy of the proposed model showed a steady upward trend. As the number of attractions increased, its accuracy remained between 95% and 99%. However, the accuracy curves of the other two models showed

significant fluctuations. When the number of attractions was equal to or greater than 50, the accuracy of the other models was reduced to 82%. The proposed method has a stronger optimization effect in practical applications, which improves the efficiency of road network optimization decision-making. In addition, an error analysis was conducted on the layout of different models and the actual demand of attractions, as shown in Fig. 9.

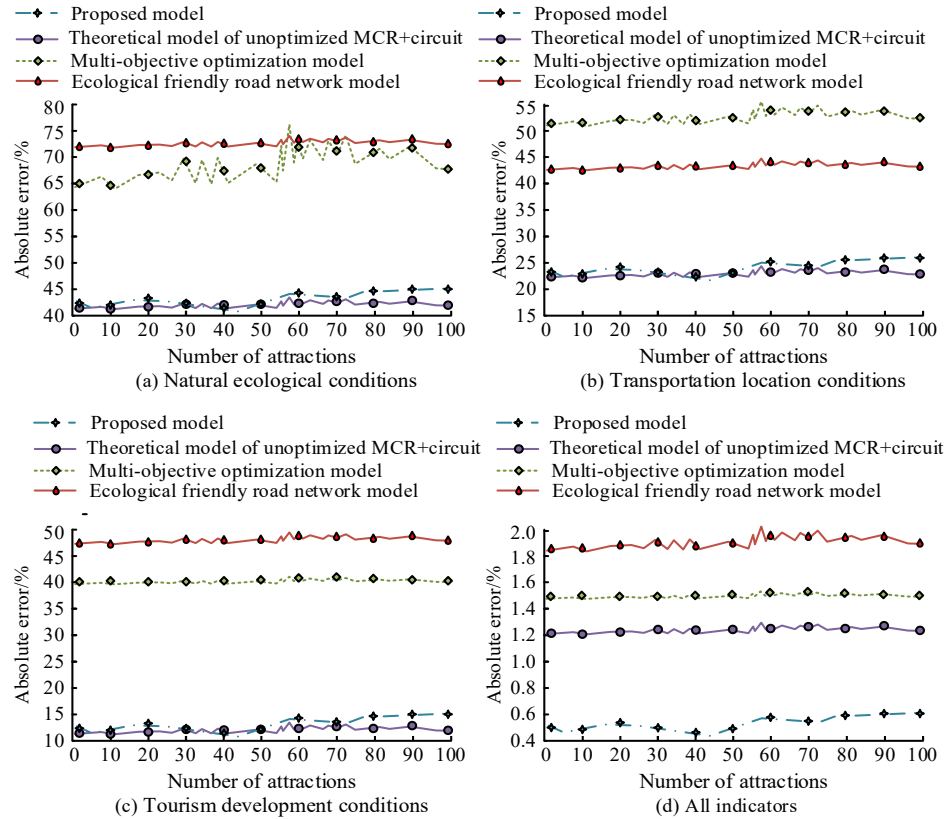


Fig. 9. Layout error results of different models

Figs. 9(a)-9(c) consider the influence of only some indicators. The proposed model had lower absolute errors than the introduced method. When fewer influencing factors were considered, the layout error of the model based on unoptimized MCR and circuit theory was relatively close to the proposed model. In Fig. 9(d), considering all indicator factors in the layout model, only the proposed model maintained a smaller error, with all values below 0.6, which is far lower than the other three models. This indicates that the proposed model can make more accurate judgments in road network layout, thereby minimizing construction costs. Finally, the comprehensive performance of the proposed model was compared with several related models through an ablation experiment, as presented in Table 4.

Table 4. Experimental results of ablation for all layout models

Model	MSE	RMSE	MAE
Theoretical model of unoptimized MCR+circuit	0.45	0.002	0.0022
Tourism destination road network layout optimization model based on optimized MCR and circuit theory	0.21	0.001	0.0015
Multi-objective optimization model	0.55	0.008	0.0045
Ecologically conscious road network model	0.67	0.013	0.0068

As shown in Table 4, among the models tested, the proposed tourism destination road network layout optimization model based on optimized MCR and circuit theory demonstrated the most outstanding performance. Its Mean Squared Error (MSE) was 0.21, and its Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE) were as low as 0.001 and 0.0015, respectively, proving its high efficiency and accuracy. However, when the MCR was not optimized, the model’s MSE, RMSE, and MAE values increased to 0.45, 0.002, and 0.0022, respectively, indicating a decrease in performance. Similarly, the multi-objective optimization model’s MSE, RMSE, and MAE values were also increased to 0.55, 0.008, and 0.0045, respectively, indicating poor performance. The MSE, RMSE, and MAE of the ecologically conscious road network model were 0.67, 0.013, and 0.0068, respectively. These comparative data validate the superiority of the proposed model for optimizing the tourism destination road network layout based on optimized MCR and circuit

theory, as it effectively improves decision-making efficiency and layout refinement.

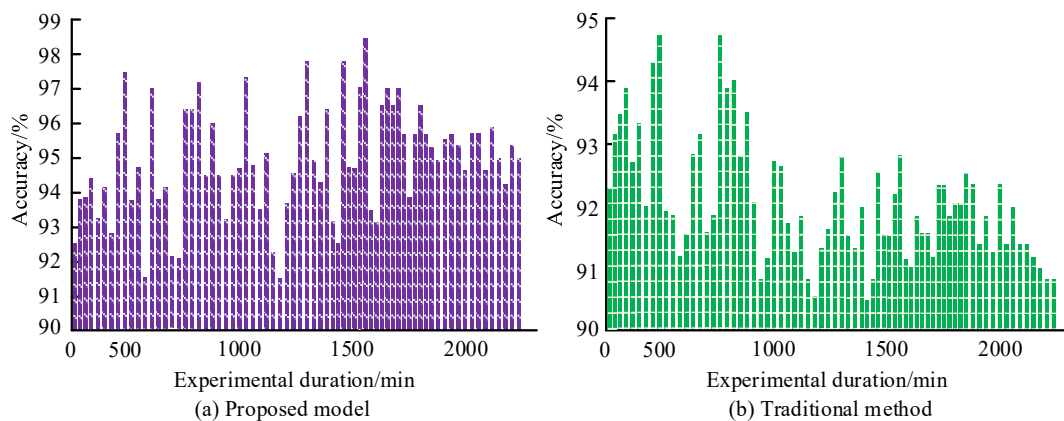
### 3.3. Practical Application Analysis of Road Network Layout Optimization in Tourist Destination

At the end of the experiment, to further verify the practical application of the tourism destination road network layout optimization model based on the optimized MCR and circuit theory, a practical application analysis was carried out. The experiment randomly selected the map of Mianyang City, China, as the experimental object. As a medium-sized city in Sichuan Province, the city has a certain representativeness. Geographical conditions, transportation status, and tourism development needs are common across many cities, thereby broadening the applicability of the experimental results. Mianyang City is located in the northwest of the Sichuan Basin, with complex and diverse terrain, including plains, hills, and mountainous areas. This complex terrain provides rich natural conditions for analyzing the tourism road network layout, which helps verify the model's applicability to different terrains. Although Mianyang City has abundant tourism resources, its tourism road network layout is not sufficient, and some tourist attractions have poor transportation accessibility. In summary, the study utilized the tourism destination road network layout optimization model based on optimized MCR and circuit theory to optimize the road network layout of Mianyang City, as displayed in Table 5.

**Table 5.** Optimization results of road network layout in Mianyang City, China

Road network situation in Mianyang City, China	Tourism destination road network layout optimization model based on optimized MCR and circuit theory	Multi-objective optimization model	Ecologically conscious road network model
Total construction cost (in 10,000)	2,155	3,578	2,780
Optimized road network (kilometers)	28.1	23.6	25.44
Technology strength (L*km/100) Ten thousand yuan	0.75	1.84	1.52
Jumping ability(L)	97.20	78.15	76.2
Attracting tourism resources (%)	99.5	89.7	92.66

In Table 5, the proposed model has a total construction cost of 21.55 million yuan for optimizing the road network in Mianyang City, which had significant cost advantages compared to the multi-objective optimization model (35.78 million yuan) and the ecologically conscious (eco- friendly, or ecologically sustainable) road network model (27.8 million yuan). The road network length was 28.1 kilometers for the proposed model, 23.6 kilometers for the multi-objective optimization model, and 25.44 kilometers for the ecologically conscious model. The technological strength of the proposed model was 0.75L\*km/1 million, indicating that the optimized MCR and circuit theory model was more efficient in technical applications. The jumping ability was 97.20 for the proposed method, 78.15 for the multi-objective model, and 76.2 for the ecologically conscious model. The jumping ability reflects the connectivity and flexibility of the road network, and the proposed method performs the best in this regard. The rate of attracting tourism was 99.5% for the proposed model, the multi-objective optimization model achieved 89.7%, and the ecologically conscious model achieved 92.66%. This indicates that the proposed model has significant advantages in promoting the development of the tourism industry. The experiment also compared the practical application performance of the proposed model based on optimized MCR and circuit theory and used the traditional layout optimization method as a comparison method, as displayed in Fig. 10.



**Fig. 10.** Performance comparison between the proposed model and the traditional layout method

As shown in Fig. 10, the performance difference between the proposed tourist destination road network layout model and the traditional method is clear. The accuracy of the proposed model exceeded that of the traditional layout optimization

method. The layout accuracy of the proposed model remained consistently above 94.62%, whereas the traditional method's fluctuated between 91.82% and 94.65%, and demonstrated a decreasing trend over time. This indicates that the proposed model can maintain high accuracy over long periods, while the traditional method exhibits significant volatility. The results indicate that the proposed model provides a reliable decision-making basis for the planning and management departments of tourist areas through scientific methods and data support. This helps to improve the scientific and rationality of planning and reduce decision-making errors.

#### **4. Conclusion**

In recent years, constructing ecological security patterns or recreational space networks based on MCR models has become an important direction in landscape planning and sustainable tourism research. However, the existing work still faces challenges such as functional fragmentation, ambiguous trade-offs and insufficient dynamics. For instance, in the research on rural tourism in Mashan by Liu et al., although the InVEST, ArcSWAT and MCR models were combined to respectively construct the ecological security pattern and the recreational space pattern, and the eight types of landscape functional areas were divided through the "trade-off matrix", the corridor identification still relied on the superposition of static resistance surfaces. The actual choices of tourists among multiple paths were not simulated, nor were the dynamic conflicts or synergistic effects between ecological and recreational corridors quantified in spatial interaction (Liu et al., 2024). Similarly, Li et al. constructed the ecological security pattern in Yanchi County, Ningxia, and identified ecological sources and corridors by integrating MSPA, MCR, and gravity models, emphasizing the spatial differentiation of landscape ecological quality. However, its network structure remains a one-way, deterministic path, lacking multi-path redundancy and network resilience. Other studies have attempted to apply MCR to urban environmental issues (Li et al., 2025). For instance, Zhao et al. utilized MCR to construct a thermal environment spatial network for mitigating the urban heat island effect in Fuzhou and proposed an optimization plan based on the current land use, demonstrating the potential of the model in regulating urban microclimate (Zhao et al., 2024). However, the optimization of its corridors still aims for static connectivity and has not introduced a flow distribution mechanism, making it difficult to reflect the actual impact of crowd activities on the thermal environment. In contrast, this study has broken through the above limitations by deeply integrating the MCR model with circuit theory. Circuit theory regards the landscape as a conductive surface and uses "current" to simulate the probability distribution of tourist or ecological flows across multiple paths. This not only retains the MCR's ability to characterize spatial heterogeneity but also introduces key features such as path redundancy, flow distribution, and network robustness. The empirical results show that this method effectively avoids the problems of "path islands" or "excessive concentration" that are prone to occur in traditional MCR models while maintaining high layout accuracy, and more realistically reflects the coupling mechanism between ecological processes and leisure behavior in tourist destinations. The experimental results show that the weight of spatial agglomeration of tourism resources is 0.215895, the weight of related indicators of natural ecological conditions is 0.065508, and the weight of indicators related to transportation location conditions is 0.027895. The model's computing speed curve shows a stable expansion state. As the number of attractions increases, the calculation time remains between 4.8 seconds and 5.0 seconds, and the accuracy of layout scheme generation remains between 95% and 99%. In addition, this method has a relatively high optimization effect in practical applications and is conducive to improving the decision-making efficiency of road network optimization. The layout model takes into account all index factors. Only the proposed model has a small error, all below 0.6, which is far lower than that of the comparison models. This model provides a reliable decision-making basis for tourism area planning and management departments through scientific methods and data support. This helps to enhance the scientific and rationality of planning to reduce decision-making errors.

Although this study has achieved positive results, there are still several limitations. First, as the road network scale expands, the computational complexity increases nonlinearly. When applied directly to large-scale regions, such as at a provincial level, it may encounter efficiency bottlenecks. Future work should explore parallel computing or cloud acceleration strategies. Second, the model relies on preset weights to balance ecological protection and tourism development. Although flexible, the weight setting remains subjective. Future studies could introduce public participation or multi-objective Pareto optimization to handle the trade-off between ecology and development more scientifically. Third, the current model output is a technical road network solution and has not yet been integrated into the legal policy systems, such as territorial space planning and ecological protection red lines. Future work should strengthen collaboration with planning management departments to promote the effective translation of technical results into policy. In addition, the model has positive implications for sustainable tourism in three dimensions: ecology, economy, and culture. At the ecological level, the model avoids ecologically sensitive areas by assigning high resistance values to steep slopes, geological disaster zones, and areas with high vegetation coverage, which helps reduce the infrastructure's interference with natural systems and supports biodiversity conservation. At the economic level, the optimized road network enhances the accessibility of scattered attractions and service facilities, promotes a balanced distribution of tourist flows, and alleviates congestion in hotspots, thereby increasing tourist satisfaction and stabilizing local tourism revenue. At the cultural level, the framework allows cultural heritage sites and community tourism nodes to be designated as high-priority sources, ensuring their effective integration into the scenic road system. In summary, this research innovatively combines the optimized MCR model with circuit theory to construct a road network optimization framework for tourist destinations that accounts for ecological constraints, traffic efficiency and tourist experience. This method is superior to the existing technologies in both accuracy and stability, providing a decision-support tool that is both scientific and practical for tourism planners, transportation engineers and ecological protection managers. Future work will focus on automatic weight calibration, model scale expansion, and deep integration with policy processes to further enhance its application value and influence in real planning scenarios.

#### **Author Contributions**

Yefan Zou contributes to methodology, analysis, investigation, and draft preparation. Ninger Ma contributes to software, validation, data collection, and manuscript editing. All authors have read and agreed with the manuscript before its submission and publication.

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### Declaration of Artificial Intelligence (AI) Tools

The authors confirm that no AI tools were used in the preparation of this manuscript.

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