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Identification of Critical Links in Urban Road Network Based on GIS

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Abstract: A GIS-based method is proposed to identify critical links in urban road networks. This study utilizes a geographic information system (GIS) to evaluate the distribution of road infrastructure, road density, and network accessibility at the micro, meso, and macro levels. At the micro level, GIS is used to assess the distribution of public facilities along the roads. At the meso level, a city's road density distribution is evaluated. At the macro level, a spatial barrier model and a transportation network model are constructed to assess the network accessibility. An inverse distance weighting method is employed to interpolate the accessibility. Furthermore, a network topology is established, and the entropy method is utilized to evaluate the sections comprehensively. The sections are ranked based on the evaluation results to identify the critical links in the urban road network. The road-network data and points of interest (POI) data from the Anning District in Lanzhou are selected for a case study, and the results indicate that the top five critical links have scores of 0.641, 0.571, 0.570, 0.519, and 0.508, respectively. Considering the three indicators enhances the accuracy of critical section identification, demonstrating the effectiveness of the proposed method. Visualizing each indicator using GIS 10.7 provides a new approach to identifying critical links in urban road networks and offers essential theoretical support for urban planning.

Keywords: urban traffic; identification method; geographical information system; critical links; accessibility

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1. Introduction

Urban road networks play a crucial role in cities' economic and social functioning. The stability of these networks is determined by critical geographic locations such as transportation hubs, commercial centers, residential areas, and essential functional areas for transportation. Critical links, often important nodes within the road network, connect multiple major traffic routes in a geographical region. These sections typically experience a high traffic flow and complex traffic organization and are prone to congestion and accidents. Accurately identifying critical links is of great significance for urban planning and travel choices due to their decisive impact on the operational efficiency of the road network.

Transportation GIS refers to the concept of applying GIS technology in transportation research within a geographic information system [1]. An overview of GIS-based transportation applications has been provided, along with an analysis of the outcomes of spatial data operations [2]. GIS tools are commonly used to visualize classification outcomes by applying clearly defined rules and criteria for a functional and hierarchical classification of the road network [3]. The resilience of transportation infrastructure plays a vital role in ensuring the continuous operation of transportation services and impacts the location and capacity of critical transportation components. Points of interest (POI) are closely associated with urban development, and using GIS tools allows for the improved analysis of point-of-interest data from a spatial perspective [4].

Currently, numerous studies have been conducted using GIS in transportation. These studies include analyses of park accessibility, transportation network accessibility, and urban road analysis using POI data. These research endeavors have provided valuable analytical tools and reference points for our assessments and decision making [5]. Shabir employed GIS 10.7 to perform buffer analyses and analyze the accessibility of urban parks, ultimately determining their spatial distribution [6]. Christian utilized publicly available map data and digital elevation models to analyze existing transportation supply and identify areas with poor accessibility or blind spots within the transportation network [7]. Ahmadzai et al., on the other hand, employed geographic information systems to analyze the accessibility of road networks by evaluating the interactions between land use and transportation networks [8]. By establishing transportation network models within GIS and assigning cost values to features, the results of accessibility assessments can be visualized, enhancing the comprehensibility of the analysis. POIs refers to locations regularly visited, seasonally visited, or based on specific events, which can serve as significant reference points for our assessments, planning, and decision making.

Due to the large scale, broad scope, and diverse nature of road networks, numerous indicators have been proposed to identify the key components that significantly impact urban networks' efficiency and identify the critical links of urban road networks [9]. Iraklis reviewed measures of centrality in transportation networks and assessed their suitability for transportation-network studies. He pointed out that if critical nodes can be identified, the allocation of transportation resources in urban road networks can be more rational [10]. Li et al. proposed a method for identifying critical links considering the index of a traffic flow gap in a user equilibrium assignment model, aiming to improve the computational efficiency of the complete scanning method [11]. Taylor et al. introduced an indicator considering generalized travel costs, which was used to evaluate the risk and vulnerability of transportation networks [12]. Hansen's integral accessibility indicator and the Accessibility/Remoteness Index of Australia (ARA) have also been used to identify critical links [13]. Oliveira et al. ranked critical links through congestion and vulnerability indicators and studied the similarities and differences between ranks and ratings [14]. Victor et al. reviewed the existing literature and evaluated the quality of the proposed indicators [15]. Identifying critical links facilitates the assessment of the weak links of urban-road-network schemes. Therefore, carefully selecting evaluation indicators is crucial, as different indicators may yield different results in different models [16,17]. The identification accuracy of critical links can be improved by considering multiple levels and aspects comprehensively. Various indicators have been proposed to identify critical links of urban road networks, and the results obtained from different models also vary. Therefore, when identifying critical links, it is necessary to carefully select appropriate evaluation indicators and consider multiple factors comprehensively to enhance accuracy [18]. In this paper, the POI data of public facilities, road density, and accessibility are regarded as essential indicators for identifying critical links in urban road networks.

There have been numerous studies on the methods to identify critical links. Munikoti et al. proposed an expandable neural-network framework to identify critical links by predicting scores of road sections in network graphs using a model [19]. This approach can avoid excessive computational iterations. Scott et al. proposed an integrated method to identify critical links using traffic flow, link capacity, and network topology [20]. Chalkiadakis et al. conducted simulation experiments on central urban road networks, quantifying efficiency, vulnerability, and criticality indicators and studying the impact of these indicators on traffic-network efficiency [21]. Wang et al. proposed a global optimization-solving method to identify critical links by computing cost values in transportation networks [22]. Feng et al. comprehensively considered static network topology and dynamic traffic flow characteristics, along with the visualization of spatial–temporal variations of traffic flow using GPS data, enabling the more accurate identification of critical links in urban road networks [23]. Rupi et al. proposed a hybrid indicator to identify critical links by analyzing the connectivity of road sections and the impact of their discontinuation on the entire network. Amirmasoud developed a new measurement method that simultaneously considered traffic characteristics and network topology to identify critical links [24]. Eduardo utilized TransCAD (version 7.0) with GIS features to identify critical links by analyzing congestion indicators with equal weights assigned to two attributes. However, assigning equal weights to attributes may lead to varying results. Thus, assigning weights after indicator analysis is a more rigorous analysis approach. Sohn used the distance and traffic flow volume as parameter indicators for calculating accessibility to identify critical links in Maryland's highway network [16]. However, in the calculation, he replaced county areas with city center points and only considered the highway road network, resulting in significant discrepancies between the computed accessibility values and actual values. In summary, a comprehensive consideration and analysis from multiple perspectives can facilitate the faster and more accurate identification of critical links [25–27].

The commonly used evaluation indicators for critical links often reflect specific characteristics of urban road networks from a single perspective, resulting in potential discrepancies between the evaluation results and actual outcomes. Moreover, most methods for identifying critical links rely on iterative approaches, where each node in the graph is repeatedly explored, leading to high computational complexity. To address these issues, this study analyzes and evaluates the distribution of transportation infrastructure, road density, and network accessibility in the Anning District of Lanzhou City from micro, meso, and macro levels, based on GIS. Subsequently, by establishing a network topology, the comprehensive scores of each road section are calculated to identify the critical links of the urban road network. This method considers indicators from multiple levels, enabling a more accurate assessment and identification of critical links. Furthermore, this approach avoids the iterative process, reducing computational complexity. This research proposes a new method for identifying critical links of urban road networks using GIS tools and spatial analysis methods, taking Lanzhou City as an example. By conducting analysis and evaluation from micro, meso, and macro perspectives, this study provides a theoretical basis for decision making and measures related to transportation optimization, resource allocation, infrastructure planning, land use planning, and traffic safety, thus achieving sustainable and efficient urban development.

This method provides necessary theoretical support for urban planning and development by optimizing urban road planning, enhancing traffic flow, improving transportation network accessibility, and supporting decision making. By evaluating the distribution of road facilities, the road density, and network accessibility, and conducting a comprehensive assessment and ranking of critical links, this method assists planners in adapting to urban growth, reducing congestion bottlenecks, improving transportation efficiency, and providing scientific foundations for decision making. Ultimately, it contributes to cities' sustainable development and enhances residents' transportation quality.

Section 1 of this paper introduces the research background and comprehensively reviews domestic and international studies. Section 2 primarily focuses on the research area and data processing, and evaluation methods for distributing public facilities, the road density, accessibility, and a total evaluation. In Section 3, critical links are identified, and the comprehensive scores of each section are evaluated from the micro, meso, and macro levels. Sections 4 and 5 are dedicated to the discussion and conclusions, respectively.

2. Materials and Methods

This study aims to identify critical links by comprehensively analyzing urban road networks at the micro, meso, and macro levels. The analysis process is illustrated in Figure 1 below.

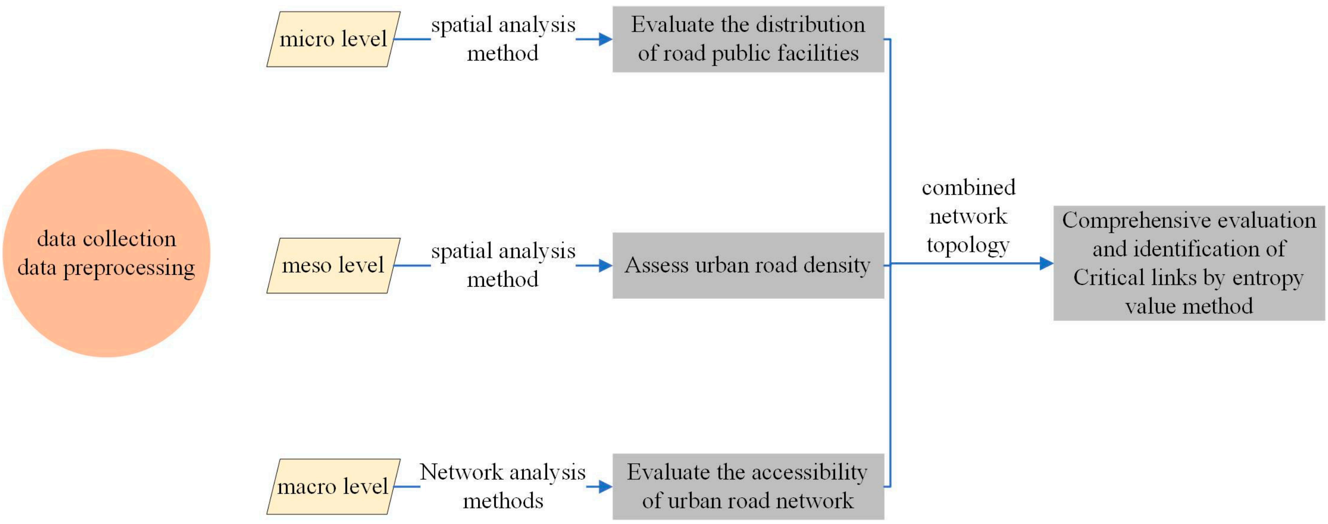

Figure 1. Analysis process.

2.1. Research Area and Data Preprocessing

Lanzhou, located in the northwest region of China, is the capital city of Gansu Province. This study focuses on the road segments in the Anning District of Lanzhou City, Gansu Province, to identify critical links within the urban road network.

The data for this study were sourced from OpenStreetMap, an open-source mapping platform, which includes vector electronic maps of the road network and point-of-interest (POI) data. The vector data were in a UTM WGS1984 coordinate system with 48S projection, and the units were in meters. Preprocessing of POI data mainly involves data cleaning and standardization. Firstly, duplicated, missing, or erroneous POI data entries are removed. Then, the categories of POI data are standardized, and facilities are classified and labeled accordingly. Data scaling and unit conversion are also performed to ensure consistent units and meters for subsequent spatial analysis and visualization [28].

The road network data covered 2086 ground road segments within the Anning District of Lanzhou City, including arterial roads, collector roads, and local roads, distributed primarily within a concentrated length range. The dataset also included 591 traffic-infrastructure data points consisting of intersections and transportation stations, and 121 data points representing locations with a high population concentration, such as restaurants and supermarkets. The data included information such as names, categories, and coordinates.

2.2. Distribution Evaluation of Public Facilities

Urban transportation infrastructure consists of facilities and equipment that support the regular operation of a city's transportation system. Around critical links, there are typically numerous transportation infrastructures such as roads, bus stops, subway stations, and parking lots. The presence of these facilities increases the traffic volume in those sections, thus affecting traffic flow and congestion. Commercial facilities refer to buildings or locations used for conducting business activities. The distribution of commercial facilities also influences the demand for the road network, with more commercial facilities leading to increased traffic flow. Failure to effectively manage traffic can result in congestion in those critical links.

At the micro-level, this study utilized a GIS network and buffer-analysis tools to accurately calculate the distribution and quantity of the transportation infrastructure and commercial facilities on each road. Currently, many scholars employ buffering techniques for micro-level accessibility assessment. This paper uses buffer analysis techniques to identify critical links at the micro-level. Creating usable areas around roads based on linear distances makes the impact of public facilities within a 100 m range on both sides of the road significant [29].

Firstly, buffer analysis tools were used to generate a 100 m buffer range as the standard for the extent of influence. Subsequently, spatial joins were employed to aggregate the number of transportation infrastructures and commercial facilities within the buffer zones formed by each road. Then, the attribute table of the road data was processed through a merge operation to obtain the total value of facilities within the impact range of each road. Finally, the statistical results were classified using the natural-breaks method to obtain a specific evaluation of each road. The specific process is illustrated in the following figure, Figure 2.

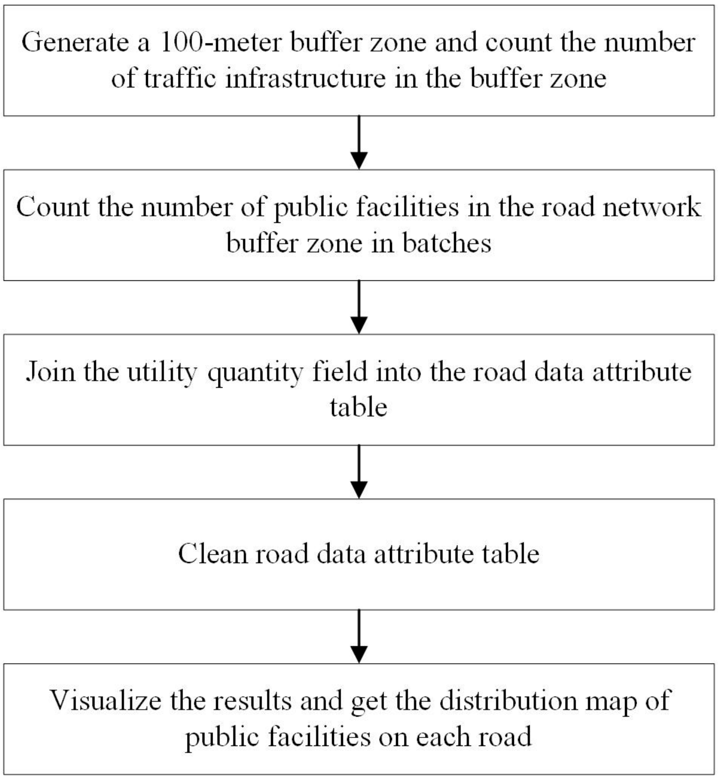

Figure 2. Evaluation Process of Public Facilities Distribution.

The research method combines network-analysis tools and buffer-analysis tools in GIS to achieve accurate calculations of the distribution of transportation infrastructure and commercial facilities around roads. Using these tools makes it possible to accurately calculate the quantity of facilities and determine the impact range of the roads. While traditional micro-level evaluations primarily utilize buffering techniques, this study proposes a novel approach to employing buffer analysis for identifying critical links. Critical links can be identified by quantifying the transportation infrastructure and commercial facilities within the buffer zones formed by each road. Moreover, this research method comprehensively considers the influence of the transportation infrastructure and commercial facilities. By integrating spatial data and statistical results, an overall assessment of the situation of each road can be conducted, enabling the evaluation of the importance of road sections.

The micro-level analytical approach allows for the precise calculations of the distribution of transportation-related elements on each road, providing a reliable basis for further analysis and the identification of critical links. Through integrating spatial data and statistical results, a comprehensive evaluation of the transportation infrastructure and commercial facilities for each road can be conducted, enabling an understanding of the importance of road sections.

2.3. Road Density Evaluation

The road density refers to the ratio of the total length of roads in a particular area to the area of the area. It is one indicator for evaluating the area's traffic conditions. Its formula is as follows:

$$D_i = L_i / A_i, i \in (1, 2, 3, \cdots, n) \quad (1)$$

where D_i is the road density in area i (m/m^2), L_i is the road length (m) in area i and A_i is the land area in area I confirm i (m^2).

The road density is an essential concept in urban planning and transportation planning. It provides information about the level of development and congestion of a transportation network, assisting in assessing the load and capacity of the road system. By analyzing the road density, the degree of road congestion, the locations of traffic bottlenecks, and recommendations for new road additions or improvements to existing ones can be determined. The concept of road density plays a crucial role in improving road conditions. By increasing road density, congestion can be alleviated, and traffic efficiency can be improved.

Furthermore, the rational planning and design of road density can also reduce traffic accidents and enhance road safety. In summary, road density is critical for evaluating the transportation network and road conditions. It can help address traffic congestion, optimize traffic flow, and improve road safety.

At the mesoscopic level, the calculation and analysis of road density distribution are carried out in GIS using fishnet tools [30]. Specific steps are shown in Figure 3.

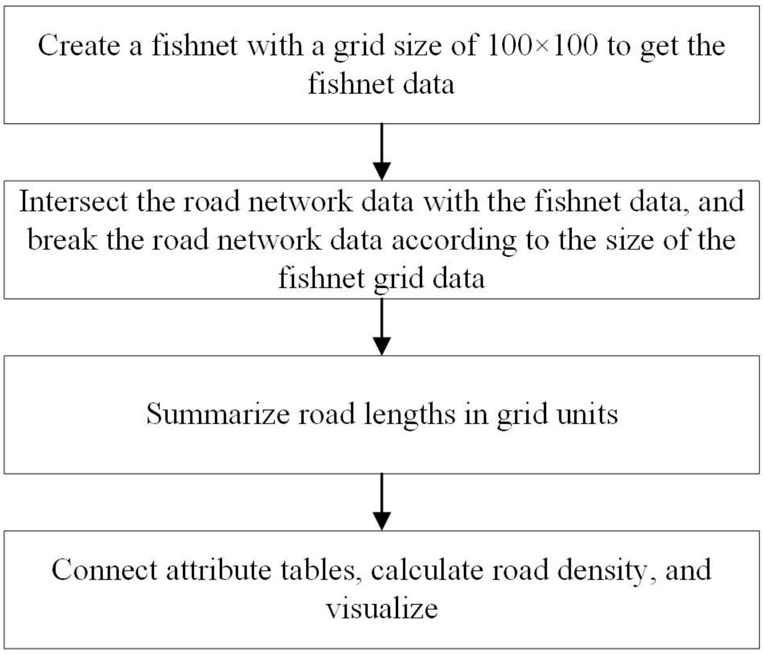

Figure 3. Evaluation Process of Road Density Distribution.

Step 1: The road network length is measured in meters, and the urban planning layer of the city is used as the source layer. The fishnet data and parameters are set, and the total area of the administrative district is divided into 100 × 100 grid cells as the unit for data processing and analysis. Vector fishnet data are created, and the "network" and "network center points" are generated. The road-network vector data are divided by grid cells, using road intersections as boundaries.

Step 2: After road fusion, the attribute table of the road density map is obtained through attribute table joining. The road density is calculated in the attribute table. The natural-breaks method is used to classify and display road density values, resulting in a road-network density distribution map for the Anning district.

The above research method utilizes the fishnet tool for calculating and analyzing the distribution of road density. It employs attribute table joining and the natural breaks method for classification and display. Compared to traditional point density methods, using the fishnet tool allows for a more detailed spatial-scale analysis of road density. Integrating attribute tables and classification displays provides a more precise understanding and visualization of the variation and distribution of road density. Additionally, this research method can reflect the aggregation of the road network. By examining the road density map, areas with a higher road density can be identified, enabling an assessment of the degree of road-network aggregation.

2.4. Road-Network Accessibility Evaluation

Road-network accessibility refers to the ease of reaching other destinations through the road network from a specific location [31,32]. Critical links often have high accessibility and significant impacts on the entire road network. By identifying critical links with poor road-network accessibility [33], traffic bottlenecks can be identified, leading to the recognition of road sections that require better connectivity or improved transportation infrastructure. This aids in developing more rational road planning and transportation layouts to optimize the overall efficiency and accessibility of the transportation system.

The specific process of calculating accessibility at the macro level is depicted in Figure 4.

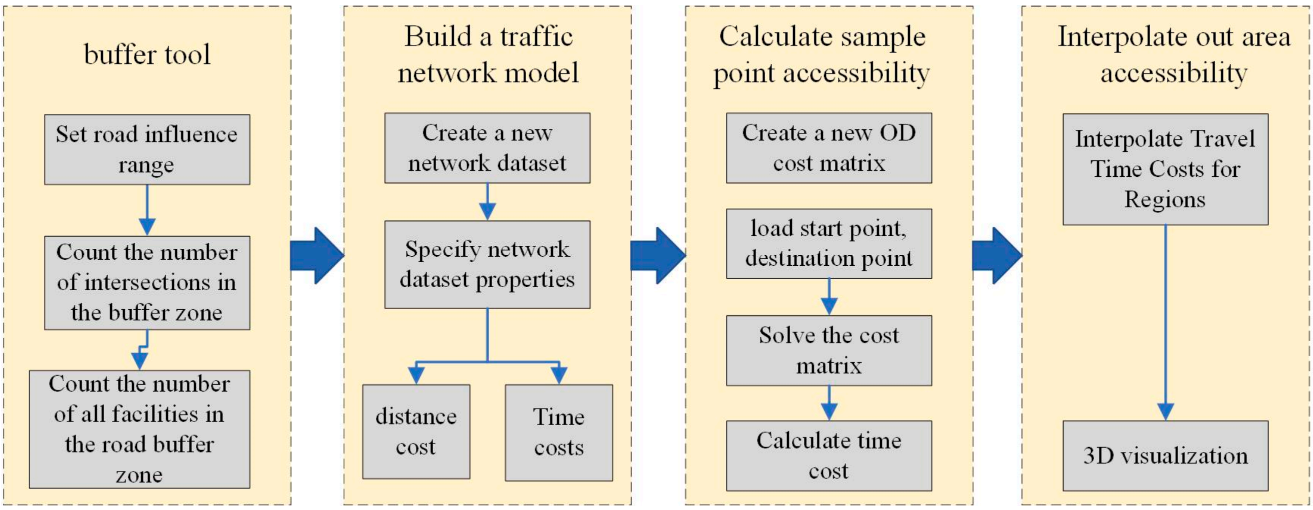

Figure 4. Evaluation Process of Road Network Accessibility.

Step 1: A network dataset is created, and road network features are imported into the dataset. The connectivity and directionality between road network features are established. GIS-network analysis tools are used to set time and distance costs, assigning cost values to each road segment. Considering different design speeds on arterial roads, sub-arterial roads, and local roads, this study set the design speed for arterial roads as 60 km/h, sub-arterial roads as 30 km/h, and local roads as 20 km/h. Finally, a network topology is established to construct the urban road network traffic model.

Step 2: Since this study focuses on road segments, the centroid of each road segment represented the segment. Then, using network analysis tools, an OD cost matrix was created, loading the locations of the origin and destination points.

Step 3: Using the time cost as the indicator value, the statistical results of accessibility for OD points are obtained. The time-cost values of accessibility are input, and interpolation analysis is conducted using the inverse distance weighting method, with the influence range of other points on the elevation values of the interpolation points decaying as the distance from the interpolation points increases.

Computing the accessibility of a traffic-network node can be used to evaluate its connectivity and importance, and the traffic accessibility of the entire road network is the average of the traffic accessibility of each node [34]. In this paper, the spatial barrier model was used to solve the traffic accessibility of each node, and the formula is as follows:

$$H_i = \frac{1}{n-1} \sum_{j=1(j \neq i)}^{n} (d_{ij}) \tag{2}$$

where H_i represents the accessibility of network node i; d_{ij} represents the minimum impedance between nodes i and j.

This study quantified minimum impedance by using the time cost of the shortest path from each node to other nodes. The accessibility indicator value of each node was quantified by calculating the average time cost of the shortest paths from that node to all other nodes. The calculated accessibility indicator values were discrete and multiple. Therefore, spatial-data processing techniques in the GIS were employed to infer the accessibility values of unknown locations, thereby estimating the accessibility values of the entire road network. Interpolation analysis, which can transform discrete data points into a smooth surface, was used to visualize the accessibility of the entire road network by applying the inverse distance weighting method.

The formula for calculating the inverse distance weight is as follows:

1. Calculate the distance from other nodes to the interpolation point:

$$d_i = \sqrt[2]{(x - x_i)^2 + (y - y_i)^2} \tag{3}$$

where x_i, y_i is the coordinate value of other points.

2. Calculate the weight of other points:

$$w_i = \frac{1/d_i}{\sum_1^n 1/d_i} \tag{4}$$

3. Calculate the elevation value of the interpolated point:

$$Z_0 = \sum_{i=1}^{i=n} w_i \cdot Z(x_i, y_i) \tag{5}$$

where $Z(x_i, y_i)$ is the time-cost value of other points.

From the perspective of transportation networks, a transportation network model is constructed by establishing a network dataset, setting time and distance costs, and assigning cost values to indicator costs. This allows for the creation of a transportation network. The road network can be analyzed and simulated using traffic models and network analysis tools to identify critical links with necessary paths, connectivity, or transfer functions.

This research method utilized network analysis tools for connectivity and importance analysis of the road network, evaluated the accessibility of transportation network nodes using a spatial impedance model, and visualized the accessibility of the road network using inverse-distance-weighting interpolation analysis. Compared to traditional methods, network analysis based on network-analysis tools is more accurate and comprehensive. By quantifying the traffic accessibility of nodes and analyzing the time cost of the shortest paths, the accessibility of nodes can be better evaluated. Additionally, visualization through interpolation analysis can intuitively display the accessibility of the entire road network.

2.5. Comprehensive Evaluation of Entropy Value Method

The distribution of the number of transportation infrastructures and catering facilities, the distribution of road density, and the accessibility of the road network were, respectively, analyzed at the micro, meso, and macro levels, providing multiple indicators for comprehensive evaluation. To determine the weight of the indicators, the entropy method was used [35]. The entropy value method is based on the concept of information entropy. By calculating the entropy value and weight of the index, the importance and contribution of each index in the comprehensive evaluation are determined. This method can objectively measure the importance of indicators and give a more accurate weight value [36,37]. By comprehensively analyzing the weight values of these indicators, a comprehensive evaluation result can be obtained to evaluate the traffic situation more comprehensively and provide decision-making reference. The steps of the entropy method are as follows:

Step 1: Normalize each factor according to the number of each option:

For positive indicators:

$$x'_{ij} = \frac{X_{ij} - \min(X_{1j}, X_{2j}, \ldots, X_{nj})}{\max(X_{1j}, X_{2j}, \ldots, X_{nj}) - \min(X_{1j}, X_{2j}, \ldots, X_{nj})} \tag{6}$$

For negative indicators:

$$x'_{ij} = \frac{\max(X_{1j}, X_{2j}, \ldots, X_{nj}) - X_{ij}}{\max(X_{1j}, X_{2j}, \ldots, X_{nj}) - \min(X_{1j}, X_{2j}, \ldots, X_{nj})} \tag{7}$$

Step 2: Calculate the entropy value of the j indicator:

$$e_j = -k\sum_{i=1}^{n} p_{ij}\ln(p_{ij}),\ j = 1, \ldots, m \tag{8}$$

$k = 1/\ln(n) > 0, e_j \geq 0;$

Step 3: Calculate information entropy redundancy:

$$d_j = 1 - e_j,\ j = 1, \ldots, m \tag{9}$$

Step 4: Calculate the weight of each indicator:

$$\omega_j = \frac{d_j}{\sum\limits_{j=1}^{m} d_j},\ j = 1, \ldots, m \tag{10}$$

Step 5: Calculate the comprehensive score of each sample:

$$s_i = \sum_{j=1}^{m} \omega_j x_{ij},\ i = 1, \ldots, n \tag{11}$$

where x_{ij} is the normalized data. According to the score of each influencing factor, the importance ranking of the above three factors can be obtained.

3. Results

3.1. Identification of Critical Links Based on Distribution of Public Facilities

The intersections are the crucial points where road traffic converges, often serving as bottlenecks in urban transportation. Managing traffic volume and congestion at intersections is of paramount importance. Traffic stations, including bus stops and subway stations, are vital origins and destinations for public-transportation users, directly impacting the accessibility and convenience of a road network. Food and entertainment establishments provide dining and leisure services, cultural and sports venues host cultural events and sports competitions, and supermarkets offer daily necessities and essential household items. To assess the distribution of public facilities along roadways, we took Anning District in Lanzhou City as an example and classified them based on the service types and user demands, as shown in Figure 5.

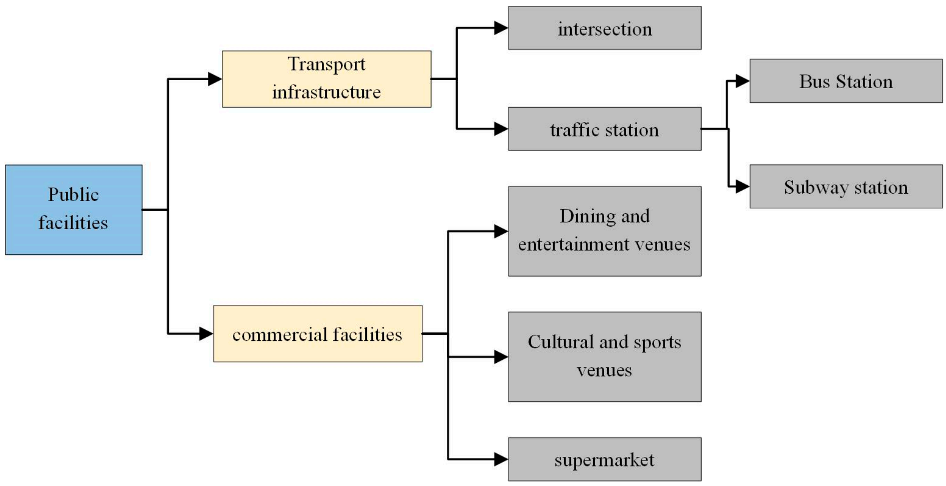

Figure 5. The distribution of public facilities.

This study divided public facilities into transportation infrastructure and commercial facilities. The sum of these two categories could initially reflect the region's transportation-infrastructure distribution. There were 591 transportation-infrastructure facilities, including 444 intersections and 147 transportation stations. The transportation stations were further divided into 144 bus stops and 3 subway stations. There were also 121 commercial facilities, including 75 dining and entertainment venues, 13 cultural and sports venues, and 23 supermarkets. These facilities are related to identifying key road sections in the urban road network because they play essential roles and serve as connections in the urban transportation system. By analyzing and identifying these facilities, we can help determine key road sections with a high traffic flow, dense transportation nodes, and efficient traffic in the urban road network, and optimize urban transportation planning accordingly. The distribution of these facilities in the Annin District Road network is shown in Figure 6.

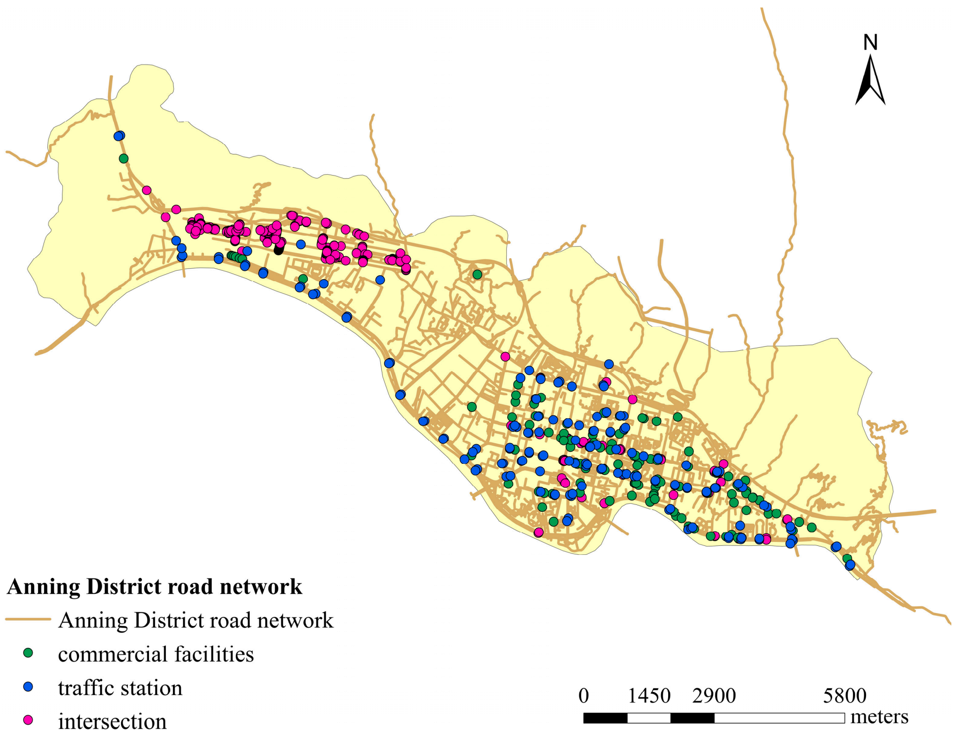

Figure 6. Distribution map of road network and public facilities in Anning District.

Through GIS analysis, the distribution number of public facilities on each road on the road network of Anning District can be obtained. The specific distribution is shown in Figure 7 below:

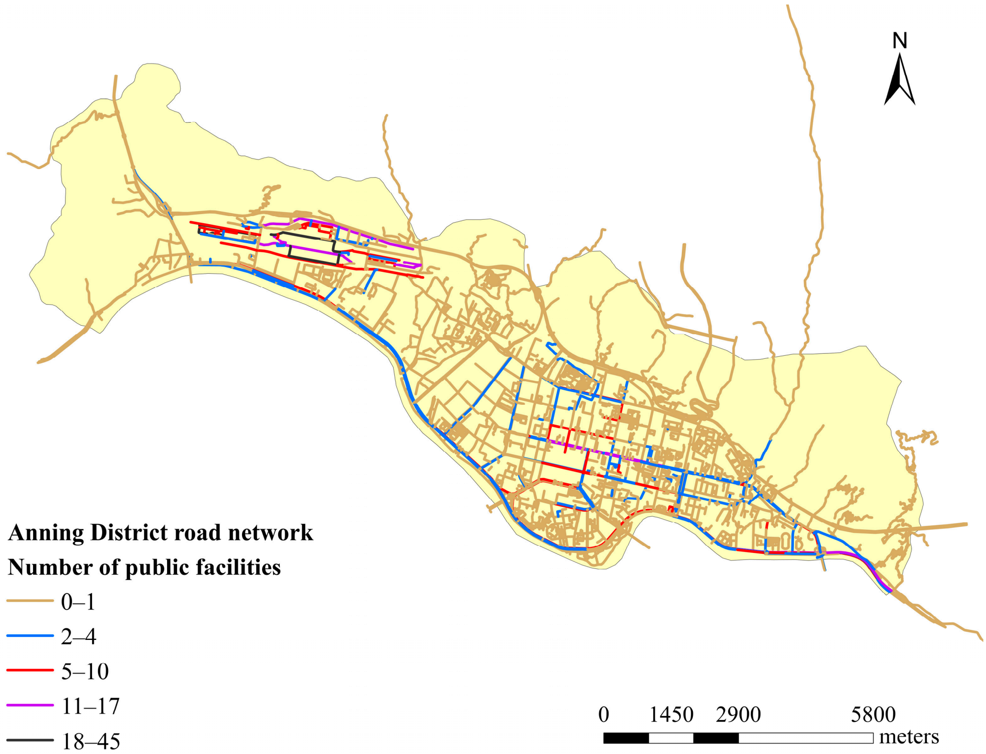

Figure 7. Distribution map of road-network traffic elements in Anning District.

As seen from the above figure, there are many intersections in the west of Anning District but few commercial facilities. The reason is a marshaling yard at Lanzhou North Station in the west. This article did not analyze and evaluate the marshaling yard. Commercial facilities are mainly distributed in the central part of Anning District, with a higher population density, better transportation convenience, and commercial-development potential.

Spatial analysis based on a GIS can visually display the distribution and quantity of public facilities. By using the buffer tool to calculate the number of public facilities on the road, we can better analyze the distribution of public facilities to understand the distribution of public facilities on different transportation networks. According to the attribute table in the GIS, the indicators near Lanzhou North Railway Station were excluded. The top ten roads and their numbers of public facilities are counted in Table 1.

Table 1. Statistical table of public facilities.

Serial Number	Road Name	Number of Public Facilities
1	Anning East Road	30
2	Beibinhe West Road	29
3	Jianning West Road	22
4	Anning East Road	19
5	Jianan West Road	12
6	Jianning West Road	9
7	Kyushu Tong East Road	9
8	Wanxin North Road	8
9	Zaolin Road	6
10	Fuqiang Road	5

3.2. Identification of Key Road Sections Based on Road Density

Road density directly or indirectly affects the traffic flow and operation of critical links. The distribution of traffic roads in urban areas can be understood by analyzing the road density. Typically, a higher road density means more roads for vehicles, which helps to spread traffic flow and reduce congestion. In this case, the traffic flow carried by critical links was relatively low, and the traffic operation was relatively stable. However, if the road capacity of key road sections was limited and could not meet the high-density traffic flow, congestion and traffic problems were still prone to occur. Conversely, with a low road-network density, roads with relatively less traffic flow may be more likely to form critical links.

Based on the analysis of GIS, the distribution of road density in Anning District, Lanzhou City, is shown in Figure 8.

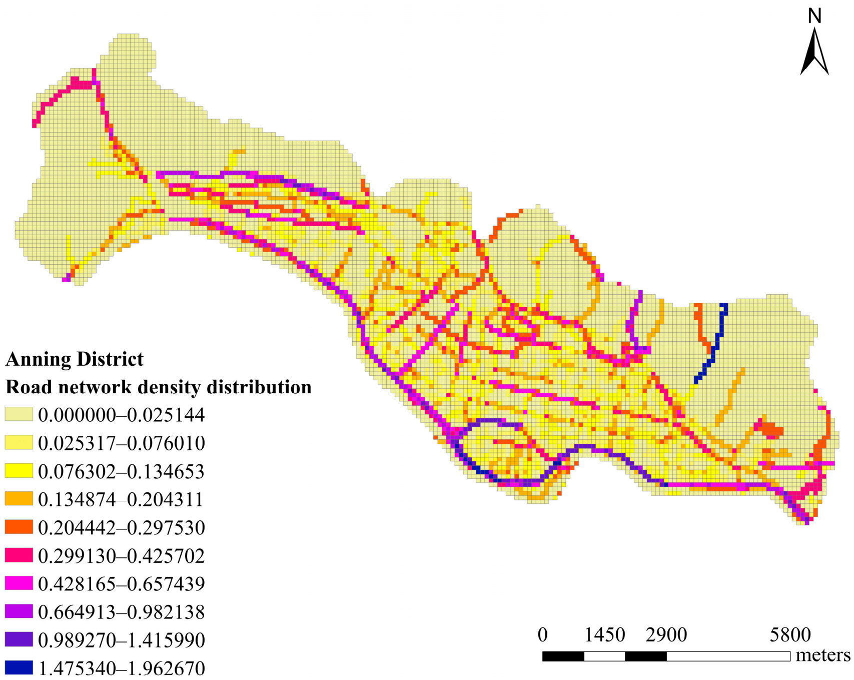

Figure 8. Road-density distribution map of Anning District.

In this paper, the administrative area of Anning District was divided into 100 × 100 grids, and the road density was calculated in units of grids. Therefore, the specific density of each road needed to accumulate the grid density where the road was located. Through calculation, we discovered the top-ten densest roads, which, with their densities, are shown in Table 2.

Table 2. Statistical table of road density.

Serial Number	Road Name	Road Density (m/m^2)
1	Beibinhe West Road	44.13483
2	Anning East Road	13.869955
3	Anning West Road	12.1052553
4	Jian'an West Road	10.6642629
5	Yin'an Road	6.13525
6	Jianning East Road	4.387306
7	Silver Beach Bridge	3.54354
8	Jianning West Road	3.152289
9	Xing'an Road	2.918937
10	Fuqiang Road	1.881789

3.3. Identification of Critical Links Based on Road-Network Accessibility

Network accessibility is a crucial indicator to identify the importance of road sections, which directly affect the development of cities and regions. Through micro- and meso-level analysis, it was calculated that, excluding the Lanzhou North Railway Station area, the distribution of traffic elements in Anning District and places with high road network density was concentrated in the middle of Anning District. This paper selected the road network in this area as an example to identify and analyze critical links.

Using GIS network-analysis tools, a traffic-network model of an urban road network in Anning District, Lanzhou City, was constructed. Then, we used network-analysis tools to create a new OD cost matrix and load location information. There were 192 starting points and 192 destination points after loading.

There were 36,864 paths from the starting point to the destination point. We summarized the statistics, calculated the average time cost from each starting point to other destination points, and obtained the accessibility table. We then inputted the time-cost value of accessibility, used the existing 192 points to estimate the value of other locations, and performed interpolation analysis. Finally, the calculated elevation values were displayed hierarchically through the natural breakpoint method, and Figures 9 and 10 were obtained.

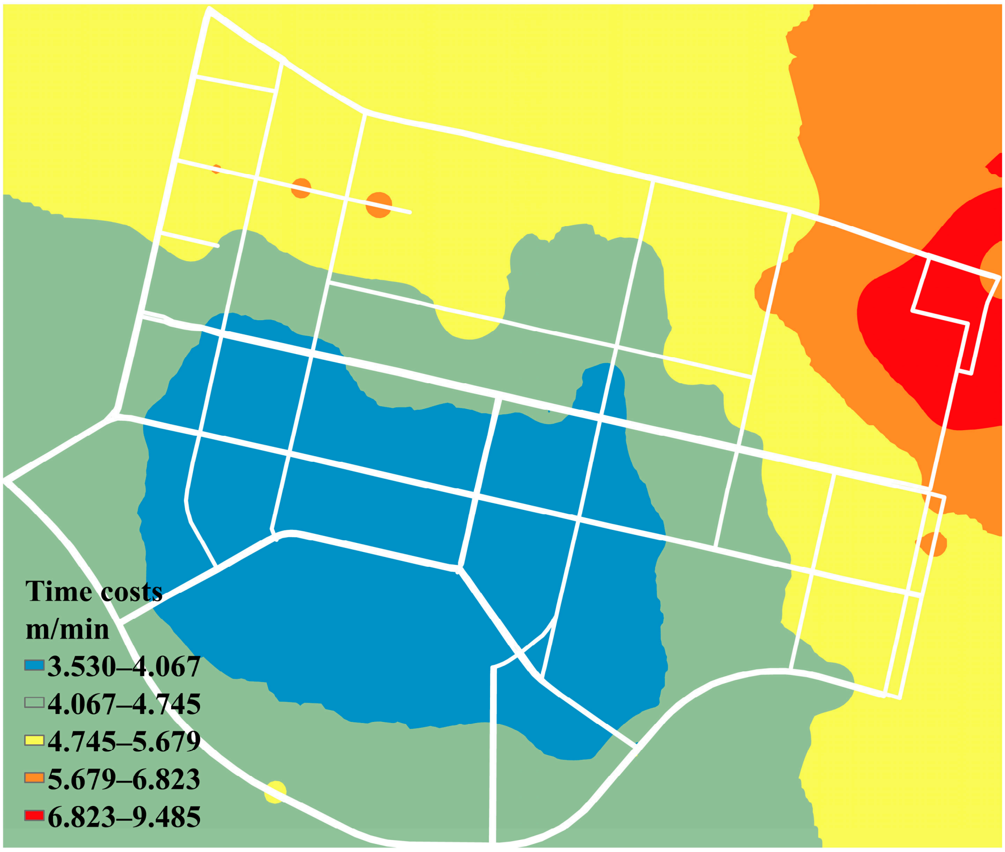

Figure 9. Accessibility.

The accessibility index values are displayed hierarchically using the natural breakpoint method, and the time-cost values increase sequentially from blue to red. The smaller the time cost value, the less the average time spent from each road segment to the other 192 road segments, indicating that the road segment is more accessible and it is likely to be a critical link in this area. According to the graph of accessibility results, the areas with low time costs were mainly distributed near Jianning West Road.

According to the analysis, the top ten roads in terms of accessibility are shown in Table 3.

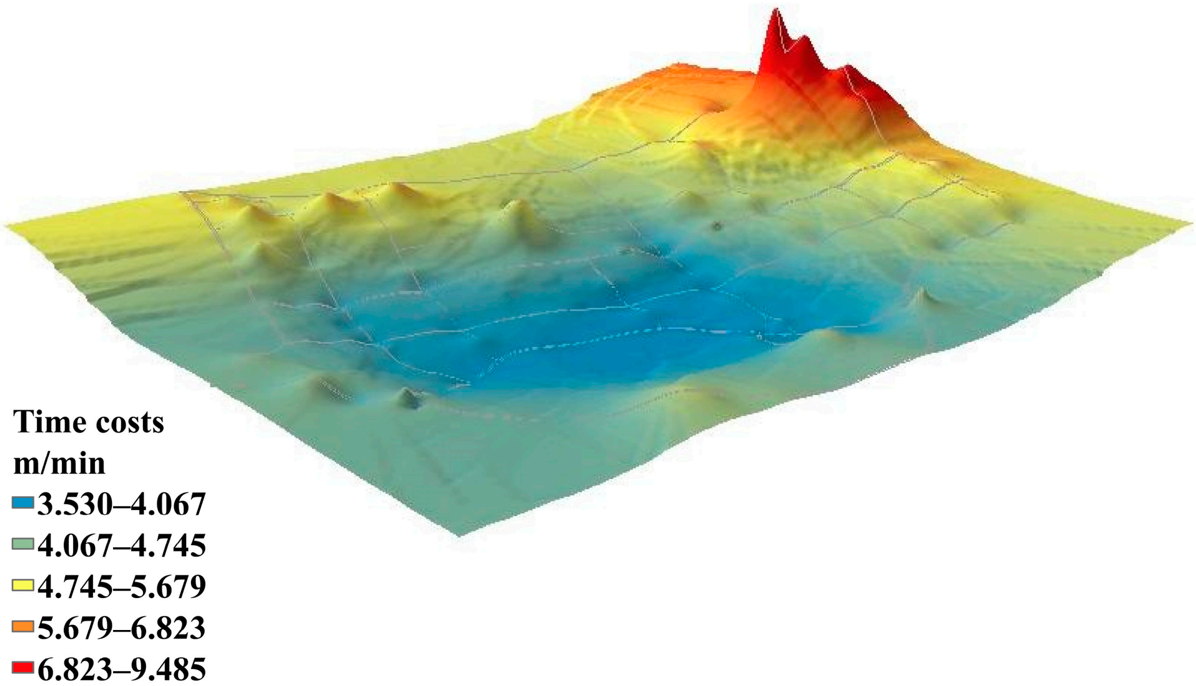

Figure 10. Three-dimensional visualization display.

Table 3. Accessibility statistics table.

Serial Number	Road Name	Time Costs (m/min)
1	Yin'an Road	3.529315
2	Jianning East Road	3.539626
3	Fuqiang Road	3.665739
4	Wanxin South Road	3.675806
5	Silver Beach Road	3.702214
6	Anning West Road	3.753501
7	Silver Beach Bridge	3.779115
8	Taolin Road	3.816274
9	Zaolin Road	3.859619
10	Jianning West Road	4.011422

3.4. Comprehensive Evaluation Analysis

Based on the results of accessibility analysis, this study focused on a road network in the Annin District of Lanzhou City, consisting of 18 roads, including Jian 'an West Road, Jian 'an East Road, Zhongbang Avenue, Xuehua Road, Mogao Avenue, Taolin Road, Anning West Road, Wanxin North Road, Xuefu Road, Xing 'an Road, Yin 'an Road, Baoshihua Road, Beibin Hexi Road, Yin 'an Road, Changxin Road, Jianning West Road, Jianning East Road, and Anning East Road. This area was selected by removing the road sections with the worst accessibility, lowest road density, and fewest public facilities. The road network encompassed 63 road sections and 39 intersections. Each road section was numbered for the identification analysis of critical links. The network structure of the study area was constructed using the original method, treating intersections as nodes and road sections as edges. This was carried out based on the distribution of intersections and the interconnected relationships between road sections, as shown in Figure 11 below.

We calculated the weight and comprehensive score according to the entropy method, and finally obtained the top five road sections, roads, and their index information values in the comprehensive score, as shown in Table 4.

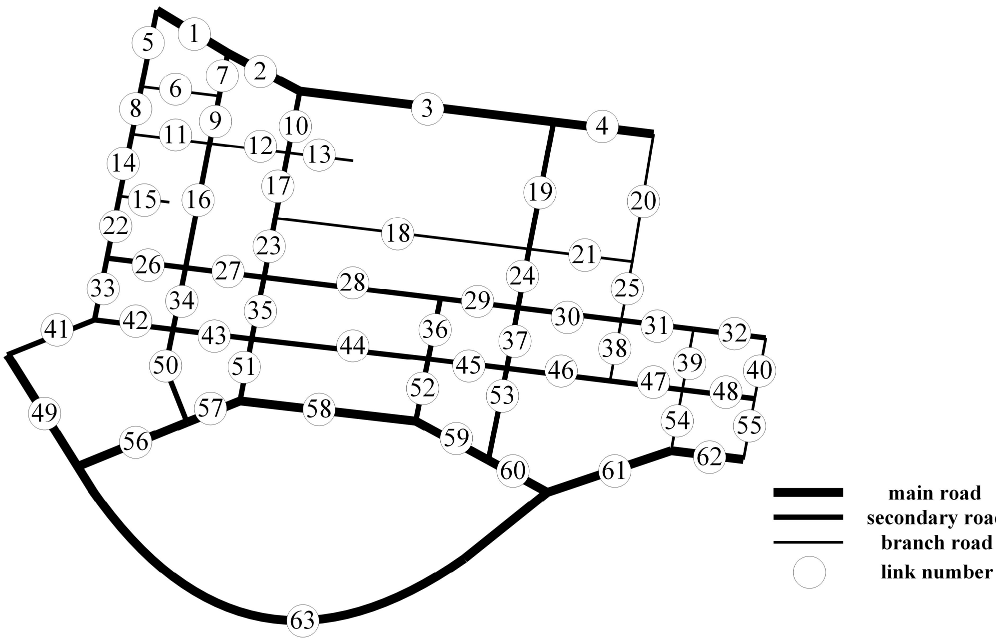

Figure 11. Road-network structure diagram.

Table 4. Critical-link identification results.

Link Number	Road	Number of Public Facilities	Time Costs (m/min)	Road Density (m/m^2)	Overall Ratings
44	Jianning West Road	5	3.543	3.024257	0.641
30	Anning West Road	5	4.698	3.336491	0.571
29	Anning West Road	5	4.349	3.025451	0.570
28	Anning West Road	4	4.521	3.615964	0.519
18	Xing'an Road	4	5.504	2.104771	0.508

4. Discussion

According to Table 1, the top five roads in terms of the number of public facilities in the Annin District of Lanzhou City are Anning East Road, Beibin Hexi Road, Jianning West Road, Anning West Road, and Jian'an West Road, with 30, 29, 22, 19, and 12 public facilities, respectively. However, as observed in Figure 2, the areas where Zhongbang Avenue, Renshou Mountain Street, and Lanke Road are located had a lower distribution of public facilities. Nevertheless, Figure 8 shows that these areas have a high road density. Therefore, urban planners may consider adjusting the route layout, increasing the number of public transportation routes, or adding facilities such as dining venues in these areas to improve the accessibility of public transportation.

From Table 2, the top five roads with the highest road density in the Annin District of Lanzhou City are Beibin Hexi Road, Anning West Road, Anning East Road, Jian'an West Road, and Yin'an Road, with road densities of 44.13483, 13.86996, 12.10526, 10.66426, and 6.13525, respectively. As shown in Figure 8, Beibin Hexi Road had the highest road density, mainly due to its role as a major expressway. However, despite its high road density, Beibin Hexi Road had relatively lower accessibility and fewer public facilities, so it was not identified as a critical section. Planners could consider extending public transportation routes near expressways to provide more convenient and efficient transportation options. Additionally, it is essential to plan and construct public facilities in suitable locations to meet the daily needs of residents and commuters. However, the construction of these facilities should consider the traffic flow and speed of the expressways to ensure a reasonable layout and convenience of transportation facilities.

As seen in Table 3, the top five roads in the Annin District of Lanzhou City with the lowest to highest time cost values are Yin'an Road, Jianning West Road, Fuqiang Road, Wanxin South Road, and Yintan Road, with values of 3.529315, 3.539626, 3.665739, 3.665739, and 3.675806 m per minute, respectively. Based on Figures 10 and 11, it is evident that the area near Yin'an Road has the highest network accessibility. However, this area has a relatively minor number of public facilities and was not identified as a critical section. Therefore, road planners may consider collaborating with private enterprises or other partners to develop commercial complexes near Yin'an Road.

Based on the research results, as shown in the network topology diagram in Figure 11, using the entropy method, five critical links were identified in the Annin District of Lanzhou City, namely Jianning West Road, Anning West Road, and Xing'an Road, with section numbers 44, 30, 29, 28, and 18, with comprehensive scores of 0.641, 0.571, 0.570, and 0.519, respectively. These critical links significantly impact the stability of the city's road network. In particular, the main arterial road, Anning West Road, experiences a high traffic volume in the Annin District, necessitating careful planning and management by road planners and administrators.

In urban planning, the layout of public facilities, road density, and network accessibility are crucial factors that need to be considered comprehensively. Selecting these three indicators is based on their importance and practical feasibility in urban transportation planning and management. Public facilities, the road density, and network accessibility are essential elements in urban transportation systems, as they mutually influence and collectively determine the criticality of road sections. However, solely considering public facilities, road density, or network accessibility has limitations. By solely focusing on public facilities, the traffic-flow situation of road sections may be overlooked. Some roads may have more public facilities but still experience congestion due to heavy traffic volumes. If only road density were emphasized, the connectivity and timeliness of road sections may be disregarded. Some roads may have a high density but do not necessarily carry significant traffic flow, thus lacking criticality. Likewise, only focusing on network accessibility may neglect factors like the traffic flow and road density.

A single indicator cannot accurately and comprehensively identify critical road sections. The comprehensive evaluation using the entropy method can quantify and compare the impact of different indicators, yielding a comprehensive score to identify critical links. This approach adequately considers the weights and relationships of different indicators, thereby avoiding biases caused by a single indicator. Hence, comprehensive evaluation can provide more objective and accurate results in identifying road sections and provide valuable support for urban public transportation development and transportation planning. Furthermore, this research presented a novel method for identifying critical road sections in the urban road network and analyzed the road network from the micro, meso, and macro perspectives. It also reveals the distribution of public facilities and road density and analyzes the factors influencing the identification of road sections in urban areas. These results offer valuable information and guidance for urban transportation planning.

However, this study still has some issues that need further exploration. This study mainly considered indicators such as the number of public facilities, road density, and network accessibility, but did not incorporate factors such as traffic flow. Additionally, more limitations in data availability restrict opportunities to validate network and POI data, making obtaining permits more challenging. Future research could expand on studying traffic flow and distribution to identify critical road sections more accurately.

In conclusion, by considering multiple indicators comprehensively and using the entropy method to analyze the urban road network, this study provided valuable information and guidance for urban transportation planning and management. It also presented a new approach to identifying critical road sections. However, further research is necessary to broaden its scope and depth, enabling a comprehensive assessment of the criticality of urban road networks.

5. Conclusions

This study used GIS to analyze the characteristics of the urban road network from the micro, meso, and macro perspectives. It assessed the distribution of public road facilities, the road density, and network accessibility. A comprehensive evaluation and analysis of the features and underlying mechanisms of critical links in the urban road network were conducted, considering multiple factors. The main conclusions are as follows:

(1) At the micro level, the distribution of public facilities on roads was analyzed to consider the coverage of services at different locations. At the meso level, the distribution of road density was considered the distribution of road resources. At the macro level, the analysis of network accessibility evaluated the importance of the urban road network.
(2) The spatial relationships between road sections were analyzed by combining spatial analysis methods with network analysis methods and considering multiple indicators of the urban road network. The results were visualized to improve the accuracy and intuitiveness of identifying critical links.
(3) Taking the Annin District of Lanzhou City as an example, this study identified five critical links with section numbers 44, 30, 29, 28, and 18, with comprehensive scores of 0.641, 0.571, 0.570, 0.519, and 0.508, respectively. The roads associated with these critical links are Jianning West Road, Annin West Road, and Xing'an Road.
(4) Identifying critical links in the urban road network holds significant importance for urban planning. It can provide technical support and a theoretical basis for alleviating traffic congestion planning urban traffic flow, facilities, and safety, ultimately enhancing residents' travel experience. This will contribute to realizing the overall optimization of the urban road network, improving the reliability of the transportation system, the sustainable development of a city, enhancing the quality of life for its residents, and increasing urban accessibility.

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References

1. Thill, J.C. Geographic information systems for transportation in perspective. *Transp. Res. Part C Emerg. Technol.* **2000**, *8*, 3–12. [CrossRef]
2. Gianfranco, F.; Mariangela, D.; Patrizia, S.; Edoardo, P.; Massimiliano, P. A GIS-supported methodology for the functional classification of road networks. *Transp. Res. Procedia* **2023**, *69*, 368–375. [CrossRef]
3. Deloukas, A.; Kokkinos, I.; Kiousis, G.; Zannou, D. GIS-Based Transportation Planning and Analysis: A Practical Implementation. *IFAC Proc. Vol.* **1997**, *30*, 417–426. [CrossRef]
4. Gerges, F.; Nassif, H.; Herrington, T.; Boufadel, M.C. A GIS-based approach for estimating community transportation exposure and capacity in the context of disaster resilience. *Sustain. Horiz.* **2022**, *3*, 100030. [CrossRef]
5. Kucukpehlivan, T.; Cetin, M.; Aksoy, T.; Kurkcuoglu, M.A.S.; Cabuk, S.N.; Pekkan, O.I.; Cabuk, A. Determination of the impacts of urban planning of the urban land area using GIS hotspot analysis. *Comput. Electron. Agric.* **2023**, *210*, 107935. [CrossRef]

6. Khahro, S.H.; Talpur, M.A.H.; Bhellar, M.G.; Das, G.; Shaikh, H.; Sultan, B. GIS-based sustainable accessibility mapping of urban parks: Evidence from the second largest settlement of Sindh Pakistan. *Sustainability* **2023**, *15*, 6228. [CrossRef]
7. Truden, C.; Kollingbaum, M.J.; Reiter, C.; Schasché, S.E. A GIS-based analysis of reachability aspects in rural public transportation. *Case Stud. Transp. Policy* **2022**, *10*, 1827–1840. [CrossRef]
8. Ahmadzai, F. Analyses and modeling of urban land use and road network interactions using spatial based disaggregate accessibility to land use. *J. Urban Manag.* **2020**, *9*, 298–315. [CrossRef]
9. Sullivan, J.L.; Novak, D.C. A method for evaluating accessibility in transportation problems considering social vulnerability. *Eur. J. Oper. Res.* 2023, *in press*. [CrossRef]
10. Stamos, I. Transportation Networks in the Face of Climate Change Adaptation: A Review of Centrality Measures. *Future Transp.* **2023**, *3*, 878–900. [CrossRef]
11. Li, F.; Jia, H.; Luo, Q.; Li, Y.; Yang, L. Identification of critical links in a large-scale road network considering the traffic flow betweenness index. *PLoS ONE* **2020**, *15*, e0227474. [CrossRef]
12. Taylor, M.A.; Sekhar, S.V.; D'Este, G.M. Application of accessibility-based methods for vulnerability analysis of strategic road networks. *Netw. Spat. Econ.* **2006**, *6*, 267–291. [CrossRef]
13. Hansen, W.G. How accessibility shapes land use. *J. Am. Inst. Plan.* **1959**, *25*, 73–76. [CrossRef]
14. de Oliveira, E.L.; da Silva Portugal, L.; Junior, W.P. Determining critical links in a road network: Vulnerability and congestion indicators. *Procedia-Soc. Behav. Sci.* **2014**, *162*, 158–167. [CrossRef]
15. Knoop, V.L.; Snelder, M.; van Zuylen, H.J.; Hoogendoorn, S.P. Link-level vulnerability indicators for real-world networks. *Transp. Res. Part A Policy Pract.* **2012**, *46*, 843–854. [CrossRef]
16. Sohn, J. Evaluating the significance of highway network links under the flood damage: An accessibility approach. *Transp. Res. Part A Policy Pract.* **2006**, *40*, 491–506. [CrossRef]
17. Venkatalaxmi, A.; Padmavathi, B.S.; Amaranath, T.J.F.D.R. A general solution of unsteady Stokes equations. *Fluid Dyn. Res.* **2004**, *35*, 229–236. [CrossRef]
18. Du, M.; Jiang, X.; Cheng, L. Alternative network robustness measure using system-wide transportation capacity for identifying critical links in road networks. *Adv. Mech. Eng.* **2017**, *9*, 1687814017696652. [CrossRef]
19. Munikoti, S.; Das, L.; Natarajan, B. Scalable graph neural network-based framework for identifying critical nodes and links in complex networks. *Neurocomputing* **2022**, *468*, 211–221. [CrossRef]
20. Scott, D.M.; Novak, D.C.; Aultman-Hall, L.; Guo, F. Network robustness index: A new method for identifying critical links and evaluating the performance of transportation networks. *J. Transp. Geogr.* **2006**, *14*, 215–227. [CrossRef]
21. Chalkiadakis, C.; Perdikouris, A.; Vlahogianni, E.I. Urban road network resilience metrics and their relationship: Some experimental findings. *Case Stud. Transp. Policy* **2022**, *10*, 2377–2392. [CrossRef]
22. Wang, D.Z.; Liu, H.; Szeto, W.Y.; Chow, A.H. Identification of critical combination of vulnerable links in transportation networks–a global optimization approach. *Transp. A Transp. Sci.* **2016**, *12*, 346–365.
23. Feng, H.; Bai, F.; Xu, Y. Identification of critical roads in urban transportation network based on GPS trajectory data. *Phys. A Stat. Mech. Its Appl.* **2019**, *535*, 122337. [CrossRef]
24. Almotahari, A.; Yazici, M.A. A link criticality index embedded in the convex combinations solution of user equilibrium traffic assignment. *Transp. Res. Part A Policy Pract.* **2019**, *126*, 67–82. [CrossRef]
25. Li, Q.; Wang, F.; Wang, Y.; Forson, K.; Cao, L.; Zhang, C.; Zhou, C.; Zhao, B.; Chen, J. Experimental investigation on the high-pressure sand suspension and adsorption capacity of guar gum fracturing fluid in low-permeability shale reservoirs: Factor analysis and mechanism disclosure. *Environ. Sci. Pollut. Res.* **2022**, *29*, 53050–53062. [CrossRef]
26. Li, Q.; Han, Y.; Liu, X.; Ansari, U.; Cheng, Y.; Yan, C. Hydrate as a by-product in CO2 leakage during the long-term sub-seabed sequestration and its role in preventing further leakage. *Environ. Sci. Pollut. Res.* **2022**, *29*, 77737–77754. [CrossRef]
27. Wang, F.; Xiao, Z.; Liu, X.; Ren, J.; Xing, T.; Li, Z.; Li, X.; Chen, Y. Strategic design of cellulose nanofibers@ zeolitic imidazolate frameworks derived mesoporous carbon-supported nanoscale $CoFe_2O_4$/CoFe hybrid composition as trifunctional electrocatalyst for Zn-air battery and self-powered overall water-splitting. *J. Power Sources* **2022**, *521*, 230925. [CrossRef]
28. Pan, C.; Wu, S.; Li, E.; Li, H.; Liu, X. Identification of urban functional zones in Macau Peninsula based on POI data and remote information sensors technology for sustainable development. *Phys. Chem. Earth Parts A/B/C* **2023**, *131*, 103447. [CrossRef]
29. Tanishita, M.; Sekiguchi, Y.; Sunaga, D. Impact analysis of road infrastructure and traffic control on severity of pedestrian–vehicle crashes at intersections and non-intersections using bias-reduced logistic regression. *IATSS Res.* **2023**, *47*, 233–239. [CrossRef]
30. Wang, S.; Yu, D.; Kwan, M.P.; Zheng, L.; Miao, H.; Li, Y. The impacts of road network density on motor vehicle travel: An empirical study of Chinese cities based on network theory. *Transp. Res. Part A Policy Pract.* **2020**, *132*, 144–156. [CrossRef]
31. Minaei, M. Evolution. Density and completeness of OpenStreetMap road networks in developing countries: The case of Iran. *Appl. Geogr.* **2020**, *119*, 102246. [CrossRef]
32. Luo, L. Analyzing accessibility of car campgrounds through road network structure software in Beijing. *Comput. Electr. Eng.* **2023**, *109*, 108716. [CrossRef]
33. Martin, B.; Ortega, E.; Cuevas-Wizner, R.; Ledda, A.; De Montis, A. Assessing road network resilience: An accessibility comparative analysis. *Transp. Res. Part D Transp. Environ.* **2021**, *95*, 102851. [CrossRef]
34. Papilloud, T.; Keiler, M. Vulnerability patterns of road network to extreme floods based on accessibility measures. *Transp. Res. Part D Transp. Environ.* **2021**, *100*, 103045. [CrossRef]

35. Gu, Y.; Chen, A.; Kitthamkesorn, S. Accessibility-based vulnerability analysis of multi-modal transportation networks with weibit choice models. *Multimodal Transp.* **2022**, *1*, 100029. [CrossRef]
36. Chan, J.; Papaioannou, I.; Straub, D. Bayesian improved cross entropy method for network reliability assessment. *Struct. Saf.* **2023**, *103*, 102344. [CrossRef]
37. Banadkouki, M.R.Z. Selection of strategies to improve energy efficiency in industry: A hybrid approach using entropy weight method and fuzzy TOPSIS. *Energy* **2023**, *2023*, 128070. [CrossRef]