Hierarchical Division Method of Road Network for Critical Points Identification

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Abstract. In order to increase the rationality and efficiency of critical points identification of road network, and improve safety monitoring level of the road network, the hierarchy division method of the road network was studied. Based on the analysis of influence factors of road hierarchical level, this paper presented four evaluation indexes: road safety, functional, traffic flow characteristics and road infrastructure features. Roads were evaluated and sorted using the utility function. The paper achieved a hierarchical division of road network using the sample clustering analysis method, showed the basic process of the hierarchical division method through an example, and provided the basis for the identification of the critical points of the road network in future.

1. Introduction
Safety security and emergency management level of road network rely heavily on real-time monitoring of road network operations, the effectiveness of safety monitoring however mainly depends on the location and number of monitoring devices in the road network. Ideally, deploying detectors in all sections of the road network can ensure the high precision and integrity of the collected data. However, it is not possible to deploy monitoring equipment on the entire road network due to the high installation and maintenance costs in practical applications [1]. In fact, when the number of monitoring points in a road network is more than a certain number, it can not effectively improve the accuracy of monitoring results by increasing the number of monitoring devices. In contrast, unnecessary waste will be caused if all the monitoring points in the road network are deployed by detectors [2]. If the monitoring equipment is placed at critical points that have a great influence on the road network, the deployed monitoring equipment will have a multiplier effect, which can not only ensure the accuracy of the collected data but also monitor efficiently the entire road network. Therefore, the identification of critical points of the road network is particularly important. In order to improve the rationality and efficiency of critical points identification in the road network, this paper introduces the idea of road network hierarchy division and divides roads in the road network into different levels. The roads belonging to different levels will have different weights which provide a basis for further critical points identification.
Currently, there are three main hierarchy division methods for road network: road classification based on road function and traffic volume [3-4], node importance degree method [5], and gray cluster theory for road network division [6]. The road classification method based on road function and traffic volume are simple and easy to understand, but it lacks certain comprehensiveness and does not fully reflect the road network characteristics. The node importance method has a good application for highway network planning, but the method is more macroscopic in the selection of indicators and incorporates subjective factors in the process of determining the weight of indicators and includes more qualitative components. The cluster analysis method is established on the basis of accurate quantitative calculation and can make up the deficiency of the node importance method [7-8]. The existing researches are mainly using the gray cluster analysis method which can achieve the purpose of various classifications. However, it is necessary to determine the classification level and each measurement function in advance, which may lead to a large subjectivity of the classification results.

In addition, the existing researches on the hierarchical division of road network are mainly applied to road network planning and are less applied to the hierarchical division of the entire road network for safety monitoring and monitoring equipment layout [4-8]. On the basis of the existing research methods and their applications, this paper investigated the hierarchy division method for road network used for critical points identification considering road safety. This paper presented four hierarchical division indicators for the road network, i.e., road safety, functionality, traffic flow characteristics, and road infrastructure characteristics, and sorted the roads in road network using the utility function comprehensive evaluation method. After then, the ordered sample clustering method is used for cluster analysis to hierarchically divide sorted roads in the road network into a different hierarchical category.

2. Determination of road network hierarchy index
There are many factors affecting the division of road hierarchy. This paper divides the road hierarchy from four aspects: road safety, functionality, traffic flow characteristics, and road infrastructure characteristics, and screens appropriate evaluation indicators to quantify and analyze various factors.

2.1 Road Safety
Ensuring road safety is the main purpose of road network monitoring and emergency management. Generally speaking, roads with poor safety in the road network often have more traffic accidents, resulting in traffic congestion, thereby reducing road traffic capacity and affecting the overall operational efficiency and safety level of the road network. Therefore, key points are more likely to be distributed on a road with poor safety and it is necessary to consider safety during the road network hierarchy. The accident rate is used to reflect the safety of the road. The higher the road accident rate, the worse its safety. The accident rate can be calculated according to Eq. (1) as follows [9].

\[
A_i = \frac{D_i}{\sum (L_i \times Q_i)} \times 10^8
\]

where, \(A_i\), the average number of car-kilometer accidents in the statistical year of a road; \(D_i\), the number of traffic accidents in the statistical year of a road; \(L_i\), the length of the \(i_{th}\) road segment; \(Q_i\), cumulative traffic volume in statistical year of the \(i_{th}\) road segment.

2.2 Road Functionality
The function of the road is to provide services for traffic travel. Different roads have different status and functions in the road network and have different functions in social and economic development. Therefore, road functionality can directly reflect the hierarchical level of the road in the road network and is an important factor that must be considered in the division of the road network. This paper will reflect the functionality of roads using road function classification levels by referring to existing studies. The United States is one of the early countries to classify road functions. It divides roads into principle arterials, minor arterials, collectors and local roads based on two service characteristics of road access and mobility [10]. Japan and other countries and regions have also proposed
corresponding road function classification guidelines. There is currently no clear definition and standard for the classification of highway functions in China. Based on the analysis of highway system functions and highway characteristics, Zeng and Cai proposed the idea of classification of highway functions in China by using hierarchical classification methods. They classified roads in China into three major types, i.e., arterial roads, collectors, local roads; or four major types, i.e., passageway roads, arterial roads, collectors and local roads [4]. Tang preliminarily analyzed the relationship between road function classification and safety, proposed the preliminary recommendations of highway function classification considering traffic safety in China, i.e., arterial roads, collectors and access roads [11]. Based on the analysis and comparison of the existing research results, the functional class proposed by Zeng was adopted here and the roads can be classified as passageway roads, arterial roads, collectors and local roads. The relationship between the functional classified roads and the administrative classified roads in China is shown in Figure 1. Grading each functional classified road using an expert scoring method and Table 1 shows the recommended values for the functional classified roads.

![Figure 1. Relationship between functional classified and administrative classified roads in China.](image)

**Table 1. Recommended evaluation values for each functional class road**

| Road types    | Passageway roads | Arterial roads | Collectors | Local roads |
|---------------|------------------|----------------|------------|------------|
| Values        | 7～9             | 5～7            | 3～5        | 1          |

2.3 Traffic Flow Characteristics

Traffic flow characteristics are a key consideration for road safety monitoring and emergency management. Traffic flow characteristics are mainly represented by traffic flow parameters such as traffic volume, vehicle speed, traffic density, and occupancy rate. Roads with large traffic volume, high speed, and high road capacity have a great influence on the safety and operation of the road network, and they are also at a high level in the road network. Therefore, this paper also used traffic flow characteristics as an evaluation factor to analyze the hierarchical nature of roads in the road network. Saturation can be used to measure the quality of road traffic services. It describes the degree of adaptation of road traffic capacity to road traffic demand [12]. The traffic saturation was used to describe traffic flow characteristics of roads and can be calculated as Eq. (2).

\[ S = \frac{V}{C} \]

where, \( S \), traffic saturation; \( V \), traffic volume, pcu/h/lane; \( C \), traffic capacity, pcu/h/lane.
2.4 Road Infrastructures
Road infrastructure is an important part of the road network, such as bridges, tunnels, slopes, traffic safety facilities, communication lighting, etc., which have a greater impact on the safe operation of road networks. If unexpected abnormal events occur in road infrastructure, such as bridge collapse, landslides, tunnel collapse, traffic accidents on bridges and tunnels, traffic disruptions will occur on the roads, which heavily affect the traffic conditions and the safe operation level of the road network. In particular, bridges and tunnels, as special structures, are important road facilities for the basic functions of road. If there are many bridges and tunnels in the road, the probability of traffic anomalies on the roads is large, and the impact on the operation of the road network is also large. Therefore, this paper chooses bridges and tunnels as important infrastructures to reflect the road hierarchy and measures the infrastructure characteristics of the roads using the proportion of the length of bridges and tunnels in the total length of the roads.

The Technical Standards for Highway Engineering (JTG B01-2003) divides bridges into the super large bridge, large bridge, medium bridge, small bridge and culvert according to the length of the span and divides tunnels into extra-long tunnels, long tunnels, medium tunnels and short tunnel [13]. It should be noted that super larger bridge, large bridge (or extra-long tunnel, long tunnel) not only have differences in length but also have great differences in structural characteristics compared with the medium bridge, small bridge (medium tunnel, short tunnel). Therefore, when calculating the specific gravity of bridge and tunnel structures, the super large bridge, large bridge (or extra-long tunnel, long tunnel) and medium bridge, small bridge (or medium tunnel, short tunnel) can not be simply superimposed by length and should be calculated considering their weights. Thus, the specific gravity of the bridge could be calculated based on Eq. (3).

\[
\gamma_B = \frac{\omega_B^1 \sum_{i=1}^{m_1} L_i^B + \omega_B^2 \sum_{i=1}^{m_2} L_i^B}{L^B}
\]  
(3)

where, \(\gamma_B\), the specific gravity of bridges; \(m_1\), number of super large and large bridges; \(m_2\), number of medium and small bridges; \(L_i^B\), the length of the \(i_{th}\) bridge in the road, m; \(L^B\), the length of the road, m; \(\omega_B^1\), weights of super large and large bridges; \(\omega_B^2\), weights of medium and small bridges. The specific gravity of the tunnel could be calculated based on eq. (4).

\[
\gamma_T = \frac{\omega_T^1 \sum_{i=1}^{n_1} L_i^T + \omega_T^2 \sum_{i=1}^{n_2} L_i^T}{L^T}
\]  
(4)

where, \(\gamma_T\), specific gravity of tunnels; \(n_1\), number of extra-long and long tunnels; \(n_2\), number of medium and short tunnels; \(L_i^T\), the length of the \(i_{th}\) tunnel in road, m; \(L^T\), the length of the road, m; \(\omega_T^1\), weights of extra-long and long tunnels; \(\omega_T^2\), weights of medium and short tunnels. The specific gravity of tunnel could be calculated based on Eq. (4). Thus, the specific gravity of bridges and tunnels can be expressed by \(\gamma\).

\[
\gamma = \gamma_B + \gamma_T
\]  
(5)

3. Hierarchy based on ordered sample clustering
Cluster analysis is a statistical method for classifying samples or indicators. It classifies samples or indicators based on the similarity between samples or indicators [14]. This paper focuses on the hierarchical classification of the roads in the road network. Therefore, the cluster analysis method is used to classify the hierarchical level of the road according to the similarity of the road in terms of safety, functionality, traffic flow characteristics and infrastructure characteristics. Cluster analysis can reasonably classify different samples, but it can not evaluate and rank the samples comprehensively. In order to make the roads in clustering results are hierarchical, it is necessary to first sort the roads
comprehensively and then, the ordered sample clustering method classifies each road in the road network. Thus, the road ranking is achieved by comprehensive sorting, and the similarity classification of each road is classified by cluster analysis, and the hierarchical division of the road network can be done well.

3.1 Comprehensive Evaluation Methods

For the multi-index comprehensive evaluation, the simplest evaluation idea is to quantify each evaluation index according to a certain method, and obtain a “quantized value” for measuring the evaluation problem, that is, the utility function value, and then calculate the total evaluation value based on a comprehensive model with weights [15]. Based on this idea, this paper will sort the roads in the road network. The general formula is expressed as Eq. (6)

$$Y = \sum_{j=1}^{m} \omega_j x_j$$

where, \(\omega_j\), weights of the \(j\)th factor; \(x_j\), the evaluation value of the \(j\)th factor, \(j=1, 2, \cdots, m\); \(m\), number of factors, \(m=4\) here, i.e., safety, functionality, traffic flow characteristics, and infrastructure characteristics. Non-dimensionalization of indicators using standardized calculation formula as Eq. (7).

$$x'_y = \frac{x_y' - \bar{x}}{s}$$

where, \(x'_y\), the non-dimensionalization value of the \(j\)th factor in the \(i\)th road; \(x'_y\), the original value of the \(j\)th factor in the \(i\)th road.

$$\bar{x}_j = \frac{1}{n} \sum_{i=1}^{n} x'_y, \quad s = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (x'_y - \bar{x}_j)}$$

The total evaluation value of each road is calculated according to Eq. (6), and the order of importance of the road can be obtained according to the value.

3.2 Basic Principle of Ordered Sample Clustering Analysis

Suppose the ordered sample is \(X(1), X(2), \cdots, X(n)\) (\(X(i)\) is \(m\)-dimensional vector). The roads in the road network after comprehensive evaluation are the ordered samples. \(n\) is the number of roads in the road network. \(X(i)\) is the \(i\)th road in the road network. \(m\) is a number of factors and actually denotes safety, functionality, traffic characteristics, and infrastructure characteristics.

3.2.1 Define Diameter of Cluster. The diameter of the cluster is used to reflect the degree of similarity of different class in the ordered samples. In this paper, the degree of similarity of each road hierarchy in terms of safety, functionality, traffic characteristics, and infrastructure characteristics.

Suppose \(X(i), X(i+1), \cdots, X(j)\) (\(j \geq i\)) are samples of a cluster, denoted by \(G\), and let \(G = \{i, i+1, \cdots, j\}\), \(\bar{X}_G\) is an average vector of cluster \(G\).[16].

$$\bar{X}_G = \frac{1}{j-i+1} \sum_{i=1}^{j} X(i)$$

\(D(i, j)\) denotes the diameter of the cluster and the common diameter can be expressed as Eq. (10).

$$D(i, j) = \sum_{i=1}^{j} \left( X(i) - \bar{X}_G \right) \left( X(i) - \bar{X}_G \right)$$

when \(m=1\), the diameter can also be expressed as Eq. (11), where \(\bar{X}_G\) is the median of this type of data.
\[ D(i, j) = \sum_{i=1}^{j} |X_{(i)} - \bar{X}_{c}| \]  

(11)

### 3.2.2 Loss Function of Classification.

\( b(n,k) \) denotes a classification method dividing \( n \) ordered samples into \( k \) classes [16], i.e.,

\[
G_1 = \{i_1, i_1 + 1, \ldots, i_2 - 1\} \\
G_2 = \{i_2, i_2 + 1, \ldots, i_3 - 1\} \\
\vdots \\
G_k = \{i_k, i_k + 1, \ldots, n\}
\]

and the split points are \( 1 = i_1 < i_2 < \cdots < i_k < n = i_{k+1} - 1 \), thus, \( i_{k+1} = n + 1 \). The loss function of the classification method \( b(n,k) \) can be defined as Eq. (13) [16].

\[
L[b(n,k)] = \sum_{i=1}^{k} D(i, i_{k+1} - 1) 
\]

(13)

when \( n \) and \( k \) are constants, the smaller the loss function, the smaller the squared sum of dispersion for each cluster and the more reasonable the classification. Therefore, it is important to find a classification method to minimize the loss function. Set \( P(n,k) \) as the classification method to minimize the loss function and Eq. (14) is the recursive equation of loss function according to Fisher algorithm [16].

\[
\left\{ \begin{array}{l}
L[P(n,2)] = \min_{2 \leq j \leq n} \{D(1, j-1) + D(j, n)\} \\
L[P(n,k)] = \min_{i,j} \{L[P(j-1, k-1)] + D(j, n)\}
\end{array} \right.
\]

(14)

To find the optimal segmentation that divides \( n \) samples into \( k \) classes, it should be based on the optimal segmentation that classifies \( j-1 \) samples into \( k-1 \) classes (where \( j = 2,3,\ldots,n \)).

### 3.2.3 Optimal Solution.

If the number of classifications, \( k \) (\( 1 \leq k \leq n \)), is known, the classification method, \( P(n,k) \), that minimizes the loss function can be obtained as follows.

First, finding the split point \( j_k \), to minimize the recursive equation using Eq. (15) and obtaining the \( k_{th} \) cluster, \( G_k = \{j_k, j_k + 1, \ldots, n\} \)

\[
L[P(n,k)] = L[P(j_k-1, k-1)] + D(j_k, n) 
\]

(15)

Then, finding the split point \( j_{k-1} \), to minimize the recursive equation using Eq. (15) and obtaining the \( k_{th} \) cluster, \( G_{k-1} = \{j_{k-1}, j_{k-1} + 1, \ldots, j_k - 1\} \). Using the same way to obtain all the clusters, \( G_1, G_2, \ldots, G_k \), and then obtain the optimal solution, i.e., \( P(n,k) = \{G_1, G_2, \ldots, G_k\} \).

### 4. Case analysis

Taking the 20 national and provincial roads of a regional road network as an example, the road network hierarchy was conducted based on calculation and analysis of the 20 national and provincial roads. The scores of each indicator were determined based on the quantitative calculation and expert scoring (see Table 2).
Table 2. Initial evaluation value of each evaluation index of the roads

| Numbers | Accident rate (times / 100 million car kilometers) | Functional scores | Saturation | Specific gravity of bridges and tunnels |
|---------|---------------------------------------------------|-------------------|------------|----------------------------------------|
| 1       | 34.6                                              | 5                 | 0.72       | 0.019                                  |
| 2       | 14.6                                              | 7                 | 0.79       | 0.079                                  |
| 3       | 24.3                                              | 4.5               | 0.84       | 0.049                                  |
| 4       | 8.6                                               | 8                 | 0.80       | 0.044                                  |
| 5       | 12.0                                              | 5                 | 0.72       | 0.064                                  |
| 6       | 14.5                                              | 5                 | 0.70       | 0.071                                  |
| 7       | 16.9                                              | 6                 | 0.68       | 0.075                                  |
| 8       | 18.5                                              | 5                 | 0.71       | 0.028                                  |
| 9       | 37.1                                              | 5                 | 0.75       | 0.068                                  |
| 10      | 12.5                                              | 6                 | 0.73       | 0.065                                  |
| 11      | 11.4                                              | 8                 | 0.87       | 0.016                                  |
| 12      | 13.3                                              | 8                 | 0.79       | 0.050                                  |
| 13      | 37.0                                              | 5                 | 0.82       | 0.013                                  |
| 14      | 29.7                                              | 5                 | 0.86       | 0.095                                  |
| 15      | 11.9                                              | 6                 | 0.78       | 0.034                                  |
| 16      | 21.4                                              | 6                 | 0.74       | 0.058                                  |
| 17      | 38.5                                              | 7                 | 0.69       | 0.022                                  |
| 18      | 25.0                                              | 6                 | 0.83       | 0.075                                  |
| 19      | 16.4                                              | 5                 | 0.73       | 0.025                                  |
| 20      | 17.4                                              | 5                 | 0.81       | 0.050                                  |

4.1 Comprehensive Evaluation Ranking

The analytic hierarchy process is used to determine the weight of each index, and the indicators are compared to determine the judgment matrix as follows.

\[ A = \begin{bmatrix}
1 & 1 & 3 & 5 \\
1 & 1 & 3 & 5 \\
1/3 & 1/3 & 1 & 5/3 \\
1/5 & 1/5 & 3/5 & 1
\end{bmatrix} \]

By calculation, the weight of indexes can be denoted by \( W = \{0.395, 0.395, 0.132, 0.079\} \). Thus, the comprehensive evaluation values and hierarchy ranks can be obtained based on Eqns. (7) and (8) and the results show in Table 3 and Figure 2.

Table 3. Comprehensive evaluation results of each road in the road network

| Road number | Evaluation values | Ranks |
|-------------|-------------------|-------|
| 1           | 1.110             | 8     |
| 2           | 0.818             | 11    |
| 3           | 0.806             | 12    |
| 4           | 1.476             | 1     |
| 5           | 0.851             | 10    |
| 6           | 0.752             | 14    |
| 7           | 0.419             | 19    |
| 8           | 0.542             | 18    |
| 9           | 1.435             | 2     |
| 10          | 0.566             | 17    |
| 11          | 1.386             | 4     |
| 12          | 1.243             | 5     |
| 13          | 1.228             | 6     |
| 14          | 0.921             | 9     |
| 15          | 0.775             | 13    |
It is known from Table 3 and Figure 2 that the road 4 has the highest rank, mainly because it is a national road, and has a more important role in the road network. The rank of road 9 is also relatively high. Although it is a provincial road, the accident rate is relatively large and the safety is poor. The proportion of infrastructure such as bridges and tunnels in the road network is relatively high, so its hierarchy rank is also high.

4.2 Hierarchical Clustering Analysis of Road Network

According to the comprehensive evaluation values, all roads are reordered in descending order and can be expressed as \{4, 9, 17, 11, 12, 13, 16, 1, 14, 5, 2, 3, 15, 6, 19, 20, 10, 8, 7, 18\}. According to the definition of ordered samples cluster, the number of clustered samples is 20, the accident rate, functional grade, saturation, and the proportion of bridge and tunnel structures are clustering factors, and the roads are divided into three classes: high, medium and low. That is, the classification method is $P(20,3)$, and then the cluster analysis can be conducted for the sorted roads mentioned above.

Based on the calculation of Matlab, the split points for the road network are number 11 and 15 which divide all roads into three clusters, i.e., high, medium and low. In other words, the roads belonging to the high level are roads with the total evaluation value from 1 to 11, and the corresponding roads are \{4, 9, 17, 11, 12, 13, 16, 1, 14, 5, 2\}. The roads belonging to the medium level are roads with the total evaluation value from 12 to 15, and the corresponding roads are \{3, 15, 6, 19\}. And the roads belonging to the low level are roads with the total evaluation value from 16 to 20, and the corresponding roads are \{20, 10, 8, 7, 18\}.
Through the cluster analysis of the sorted roads mentioned above, the roads in the road network are divided into three levels: high, medium and low. Roads with different levels have different weights. In addition, due to the reasons of funds and external environment, etc. the roads in the same cluster can also be given corresponding weights according to their ranks, which can provide the basis for further key point identification.

5. Conclusions
In order to improve the rationality and efficiency of key points identification in the road network, this paper introduces the idea of road network hierarchy division. Roads belonging to different levels will have different weights, which can provide the basis for key point identification. Based on the analysis of various factors affecting the level of road hierarchy, this paper proposed four evaluation indicators: road safety, functionality, traffic flow characteristics and road infrastructure characteristics, in which safety was characterized by accident rate, functional weight was obtained using experts scoring method, traffic flow characteristics were reflected by road saturation, and road infrastructure was represented by the proportion of equivalent bridge tunnel structures. The utility function comprehensive evaluation method was used to sort the roads in the road network and on the basis of this, the hierarchical clustering analysis method is used to realize the hierarchical division of roads in the road network. Case analysis was conducted and the results showed that the proposed method could classify roads in road network rationally and efficiently into different cluster according to their importance, which could provide the basis for further key point identification of roads.

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