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*Research Article*

# Topological Characteristics and Vulnerability Analysis of Rural Traffic Network

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Rural traffic network (RTN), as a complex network, plays a significant role in the field of resisting natural disasters and emergencies. In this paper, we analyze the vulnerability of RTN via three traffic network models (i.e., No-power Traffic Network Model (NTNM), Distance Weight Traffic Network Model (DWTNM), and Road Level Weight Traffic Network Model (RLWTNM)). Firstly, based on the complex network theory, RTN is constructed by using road mapping method, according to the topological features. Secondly, Random Attack (RA) and Deliberate Attack (DA) strategies are used to analyze network vulnerability in three rural traffic network models. By analyzing the attack tolerance of RTN under the condition of different attack patterns, we find that the road level weight traffic network has a good performance to represent the vulnerability of RTN.

## 1. Introduction

Complex networks play an important role in real life. With the development of China's economy, the nationwide transportation network has been continuously improved, and more emphasis has been placed on the construction and management of township, town, and county transportation networks, and the overall goal of the construction of the "Four Good Rural Roads" has been comprehensively promoted. The improvement of Rural Traffic Network (RTN) can improve the connectivity of urban traffic network and promote the overall economic development. At present, the national expressway and the dry line network are basically fixed, and the depth of the urban road network is expanded by continuously improving the RTN.

For the study of the network characteristics of complex networks, V. Latora and M. Marchiori describe cost as a measure of the cost (time, money, manpower, material resources, etc.) needed to build a network, thereby analyzing the results of economic development in weighted and unweighted networks in the topology [1]. Ake J. Holmgren models the network of the Northern European and Western European power transmission networks, calculates the eigenvalues of the network topology, and compares its errors and attack tolerance (structural vulnerability) [2]. P. Luathep, A. Sumalee, and H. W. Ho propose a sensitivity analysis-based approach to improve computational efficiency and allow for large-scale applications of road network vulnerability analysis [3]. J. Wu, Z. Gao, and others' discovery of scale-free characteristics are reported on the network constructed from the real urban transit system data in Beijing. It is shown that the connectivity distribution of the transit network decays as a power-law, and the exponent $\lambda$ is about equal to 2.24 from the simulation graph [4]. A. Q. H. Tran and A. Namatame have shown that some topological properties of complex networks have a great impact on their stability. This observation study aims to understand the organization principle of these networks and the interaction between topology and network dynamics [5]. R. M. May, S. A. Levin, et al. mainly evaluated the reliability and vulnerability of the network. The results showed that the failure of the network caused by errors, interference of environmental conditions, or attacks may lead to global economic losses and social order destruction [6, 7]. O. Woolley-Meza, T. Verma, et al. have studied the high socioeconomic costs of large-scale disasters that interfere with global social and technological infrastructures (such as mobile and transport networks) and have made considerable efforts to understand how networks respond to damage [8, 9]. X. Yang, A. Chen, B. Ning, et al.'s definition of routes and route diversity and a solution algorithm based on characteristics of metro networks are described to calculate the route diversity index and also develop the route diversity index for measuring passenger route choice and network vulnerability [10]. Q. H. Tran and Akira Namatame describe the application of complex network analysis in the Worldwide Aviation Network (WAN) to clarify the hidden characteristics of the network and provide insights on building stable networks and improving network recovery capabilities [11]. M. Liu et al. developed a hierarchical model of road circuit cluster formed at various granularity levels of road network and proposed a vulnerability index to measure a series of events in failure scenarios and the damage consequences caused by these events [12]. Based on the complex network theory, Li Chengbing et al. analyzed the complex traffic network structure of urban agglomeration, constructed the road-track complex traffic network model, and analyzed the topological characteristics and vulnerability of the complex traffic network [13]. In summary, the existing methods always analyze the urban traffic network by using multiple models without considering the property of roads, especially the characteristics of rural traffic networks.

Generally speaking, the contributions of this paper are twofold. Firstly, according to the characteristic of the present rural traffic network in China, we build a proper rural rating system, including National Road (G), Provincial Road (S), County Road (X), Rural Road (Y), and Special Road (Z). Secondly, three static networks (No-power Traffic Network Model (NTNM), Distance Weight Traffic Network Model (DWTNM), and Road Level Weight Traffic Network Model (RLWTNM)) are modeled in order to explore the vulnerability of the RTN in Zhangwu in China. By employing different attack patterns, we analyze the ability of three constructed networks in maintaining their connectivity after being attacked.

## 2. The Vulnerability Analysis of RTN

In this section, we analyze the vulnerability of RTN in Zhangwu. The construction processes of three static networks are introduced in Section 2.1. Section 2.2 gives the topological feature analysis of the three networks. Section 2.3 implements the vulnerability analysis by three networks under the condition of two kinds of attacks.

*2.1. Rural Traffic Network Construction.* The construction methods of traffic network mainly include Road Mapping Method (RMM) and Site Mapping Method (SMM) [14–16]. The RMM is road intersection to the node of the traffic network according to the actual geographical location, and the section connecting the intersection to the edge of the traffic network; the SMM is road intersection to the edge of the traffic network according to the actual geographical location, and the section connecting the intersection to the node of the traffic network. For the RTN, the SMM cannot be used to connect the whole network well because some township roads or village roads have no stations so that SMM cannot express the connectivity of the traffic network. RMM can reflect the characteristics of the RTN more intuitively. All the intersections of the traffic network are the nodes (N), and the lines connecting the nodes are the edges (M), constructing a topology model of the RTN.

Three traffic network models are established based on the actual situation of the existing rural traffic network. There are few important infrastructure and economically developed areas in rural transportation network, which is generally the scope of People's Daily travel activities, and the overall transportation network has few special properties. Therefore, the NTNM is established to analyze the characteristics of the overall rural transportation network. The most obvious measurement index of rural traffic network is distance factor, so a DWTNM is established to further analyze the characteristics of the overall rural traffic network. Considering the fact that the current rural traffic network includes National Road, Provincial Road, County Road, and Rural Road, a RLWTNM is established to analyze the current situation of the rural traffic network in a more specific way, which is more in line with the actual application of the rural traffic network, and the analysis results are more accurate (the weight of road level is set according to China's highway engineering technical standards (JTG B01-2014)).

*(1) No-Power Traffic Network Model (NTNM).* All road networks exist in the study area; there is no weight on the road side; roads are restricted without direction, constructing the NTNM.

*(2) Distance Weight Traffic Network Model (DWTNM).* Based on NTNM, considering the influence of the spatial distance on the traffic, the longer walking time of the road affects the traffic efficiency. The traffic network is weighted by the actual spatial distance; the road traffic has no direction restriction, constructing the DWTNM.

*(3) Road Level Weight Traffic Network Model (RLWTNM).* The traffic road network is classified to five categories according to the road administrative level, which are divided into National Road (G), Provincial Road (S), County Road (X), Rural Road (Y), and Special Road (Z). Considering the RTN integrity, the Special Roads are exclusively used for factories, mines, forests, farms, oil fields, tourist areas, military sites, etc. Special Roads are built, maintained, and managed by special units that may cover National Road, Provincial Road, County Road, and Rural Road. Therefore, instead of using Special Roads in this study, Village Roads (C) are used to improve the overall traffic network. According to the traffic volume, task, and nature of China's highway engineering technical standards (JTG B01-2014), different levels of traffic network have different annual average daily traffic volume (ADT). National Road is a highway connecting important political, economic, and cultural centers. It can generally adapt to ADT = 15,000-55,000 vehicles; Provincial Road is the trunk highway connecting the political and economic center or large industrial and mining areas. It can generally adapt to ADT = 3000-7500 vehicles; County Road is a branch road linking county or above cities, which can adapt to ADT = 1000-4000 vehicles; Rural Road and Village Road are branch roads connecting counties or towns and townships, which

Table 1: Road level weight value.

| Road level | National Road (G) | Provincial Road (S) | County Road (X) | Rural Road (Y) | Village Road (C) |
|---|---|---|---|---|---|
| Weight | 0.4 | 0.3 | 0.2 | 0.05 | 0.05 |

can adapt to ADT less than 1500 vehicles. So the weights of different levels of traffic network are set as shown in Table 1 (which meets the criterion of weights sum of 1).

Assume that RTN construction is defined as $G = (V, E)$, where $V = \{v_1, v_2, v_3, \cdots, v_n\}$is a set of all road nodes; $E = \{(v_i, v_j) | v_i, v_j \in V \text{ and } i \neq j\}$ represent the traffic network edge. The weighting matrix $W$ is defined with the number of road nodes as the size of $N \times N$. $V_i$ and $V_j$ are any nodes in the road network, respectively; the adjacency matrix of graph $G = (V, E)$ is $A = (a_{ij})_{n\times n}$, and it is defined as follows:

$$a_{ij} = \begin{cases} W_{ij} & V_i \text{ is directly connected to } \mathrm{V}_j \text{ (Use weight to indicate liquidity)} \\ 0 & \text{Not directly connected} \end{cases} \quad (1)$$

*2.2. Topological Characteristics Analysis.* Currently, it is difficult to evaluate the vulnerability with a universal metric. A proper way to quantify the vulnerability of a network should be designed based on the demand of a real-world system. Therefore, considering the commuting efficiency and the underlying network structure, we use three evaluation metrics to estimate the vulnerability of RTN. The three metrics include average distribution, clustering coefficient, and average path length. The definitions of the three metrics are given as follows.

*(1) Average Distribution.* At present, many complex networks have a heterogeneous topology phenomenon; that is, some network nodes have a very large number of edges connected, but most network nodes only connect several edges. The degree $k_i$ represents the number of connection edges of the network node $i$, and the network node degree is characterized by a distribution function $P(k)$, which gives a probability that the randomly selected network node has $k$ edges. Thus, for a large value $k$, the degree distribution is as follows: $P(k) \sim k^{-\gamma}(if\ k \longrightarrow \infty, P(k)/k^{-\gamma} \longrightarrow 1)$. Therefore, the average distribution of RTN graphics is

$$\langle k \rangle = \frac{2M}{N} \quad (2)$$

where $N$ is the number of road nodes and $M$ is the number of road links between road nodes.

*(2) Clustering Coefficient.* Many complex networks now show a tendency to cluster. In social networks, this represents a circle of friends that each member knows about each other. The meaning of the clustering coefficient is to express the local attribute of the triangle "density" in the captured graph. The two vertices connected to the third vertex are also directly connected to each other. The degree $k_i$ of node $i$ in the network simultaneously expresses $k_i$ neighbor nodes. The maximum number of edges between neighbor nodes is $\binom{k_i}{2} = k_i(k_i - 1)/2$. The clustering coefficient $C_i$ of the network node $i$: the ratio of the number of edges $M_i$ actually existing between the $k_i$ neighbor nodes to the maximum number of edges is $C_i = 2M_i/k_i(k_i - 1)$. The clustering coefficient of the entire network is

$$C = \left(\frac{1}{N}\sum_i C_i\right) \quad (3)$$

$C = 0$ indicates that all nodes are isolated nodes; $C = 1$ indicates that the network is globally coupled; that is, any two nodes are connected.

*(3) Average Path Length.* The average path length, represented as $\ell$, refers to the average distance between a pair of nodes in the giant component. It is defined as follows:

$$\ell = \langle \ell_{ij} \rangle = \left[\frac{1}{N(N-1)}\sum_{i\neq j\in V} \ell_{ij}\right] \quad (4)$$

where $\ell_{ij}$ is the distance between nodes $i$ and $j$ in a network. In particular, $\ell_{ij}$ is equal to finite value only if the $i$ and $j$ both exist in the giant component. A short average path length means a high effective connectivity of RTN.

*2.3. The Vulnerability Analysis of RTN.* At present, domestic and foreign research scholars have no clear concept of vulnerability, and some scholars will combine the words of vulnerability, stability, and risk. Combined with the current research conclusions, the road network suffers from the unexpected external events, resulting in the loss of the use of some road nodes and road sections, resulting in the redistribution of load within the road network. The nature of the ability to resume normal traffic is vulnerability. Therefore, each road node and road section in the transportation network have different traffic levels, and the vulnerability analysis of the traffic network needs to consider the overall network (global analysis). The traffic level at the time of no accidents is taken as the initial value, and the traffic volume is redistributed at the fastest speed after the accident. The traffic level after the traffic returns to normal operation is used as a vulnerability analysis value compared with the initial value to analyze the severity of the vulnerability.

(a) (b)

Figure 1: Traffic network structure diagram of the experimental area ((a) traffic network containing nodes; (b) traffic network road level).

Table 2: Detailed parameters of the traffic network model.

| Traffic Network Model | Nodes number (N) | Links number (M) | Average degree (K) | Clustering coefficient (C) | Average path length (L) | Network efficiency (E) |
|---|---|---|---|---|---|---|
| NTNM | 1840 | 2054 | 2.177 | 0.031 | 25.836 | 0.039 |
| DWTNM | 1840 | 2054 | 2.177 | 0.031 | 41.181 | 0.024 |
| RLWTNM | 1840 | 2054 | 2.177 | 0.031 | 15.203 | 0.066 |

Based on the research in this paper, $N$ is the number of road nodes in the overall road network. The road length between road nodes $i$ and $j$ is $d_{ij}$, and $\ell_{ij}$ is the shortest path length from node $i$ to $j$. That is, $\ell_{ij} = \min_{V(i,j)} d_{ij} (d_{i\longrightarrow j} = d_{j\longrightarrow i}, \ell_{i\longrightarrow j} = \ell_{j\longrightarrow i} = \ell_{ij})$; therefore, the road network efficiency between road nodes $i$ and $j$ is defined as

$$\varepsilon_{ij} = \frac{1}{\ell_{ij}} \tag{5}$$

Under the overall analysis of the traffic network, consider the efficiency of all networks:

$$E = \frac{1}{N(N-1)} \sum_{i \neq j} \varepsilon_{ij} = \frac{1}{N(N-1)} \sum_{i \neq j} \frac{1}{\ell_{ij}} \tag{6}$$

Considering the occurrence of an unexpected event, $E_0$ is the initial efficiency of the initial network traffic state, $E_i$ is the efficiency of the traffic state after the accident, and $D$ is the difference between the efficiencies of the traffic network before and after; that is, the traffic network vulnerability:

$$D = \frac{E_i - E_0}{E_0} \times 100 \tag{7}$$

The result is a dynamic response to the failure of the entire network system, and how the location of the fault propagates as well as the consequences for the entire traffic network.

## 3. Experimental Data Analysis

*3.1. Experimental Data and Statistical Characteristics.* Zhangwu County, which is affiliated to Fuxin City, Liaoning Province, is located in the northwestern part of Liaoning Province, with a total area of 3,641 square kilometers. Among them, three National Roads pass through the county; the actual mileage is 250 kilometers; there are two Provincial Roads; the actual mileage is 169 kilometers, and the total mileage of the county's transportation network is 2875 kilometers as shown in Figure 1.

*3.2. Statistical Analysis of Traffic Network.* We use the aforementioned method in Zhangwu rural road network to build up a topological model. By *Matlab* and *Pajek* software, the basic topological characteristics of three models are obtained, as shown in Table 2.

In Table 2, the number of network edges is 2054, and the number of nodes is 1840. The average value of the vertex degree is 2.1766, which shows that the intersections are mostly connected with 3 or 4. The average path length of RLWTNM is 15.203. It shows that the rural roads account for a large proportion of Rural Roads, mostly broken roads, and the road network connection relationship is relatively simple; the distribution of traffic network degree and the probability distribution of the node degree are shown in Figures 2 and 3, respectively. As shown in Table 2, the clustering coefficient of the RTN is C=0.0313. Generally speaking, there are fewer connecting lines between road nodes in the RTN; thus the overall accessibility is poor, and the degree of grouping is not

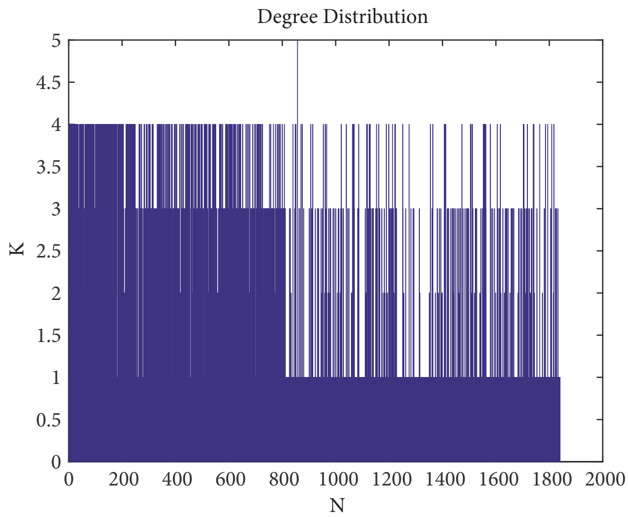



Figure 2: Distribution of traffic network degree.

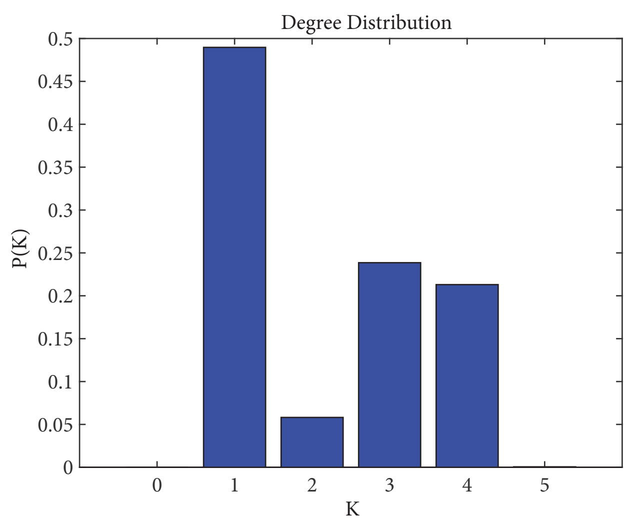



Figure 3: Probability distribution of traffic network degree.

high; by comparing the average shortest path lengths of the three traffic network models, the average shortest path length of the DWTNM has the best performance, indicating that the RTN connectivity is relatively poor. The average shortest path length of the RLWTNM is the smallest, indicating that the RTN connectivity is relatively good; the RLWTNM has the highest efficiency value of the whole network. Comparing with the other two traffic network models, different road levels in the RTN have different traffic carrying capacity and usage efficiency.

*3.3. Analysis of Two Attack Strategies for RTN.* In this paper, we use two attack strategies: Random Attacks (RA) and Deliberate Attacks (DA). Based on the RTN structure, there is no protection measure, and the attack cost and capacity limitation are not considered. When an attack is completed, the attacked road node can be invalidated, and the connected road link is disconnected; the road node is deleted, and the connected road link is deleted. RA randomly selects road nodes for attack each time until all road nodes have finished attacking. DA selects attack strategies, which are based on node-first attack strategies with high efficiency until the road nodes are attacked.

*(1) Random Attacks (RA).* The road vulnerability computed by NTNM is shown in Figure 4(a), and the highest vulnerability value is generated when the 50th road node is randomly attacked; the vulnerability of the DWTNM is shown in Figure 4(b). The vulnerability value of the entire RTN varies with the increase of the distance weight. Compared with the NTNM, the vulnerability value of the overall RTN has increased; the vulnerability of the RLWTNM is shown in Figure 4(c). The traffic network with road level weights constraint improves the efficiency and carrying capacity of high-level road networks. Compared with the NTNM, the trend of vulnerability changes is basically the same, but

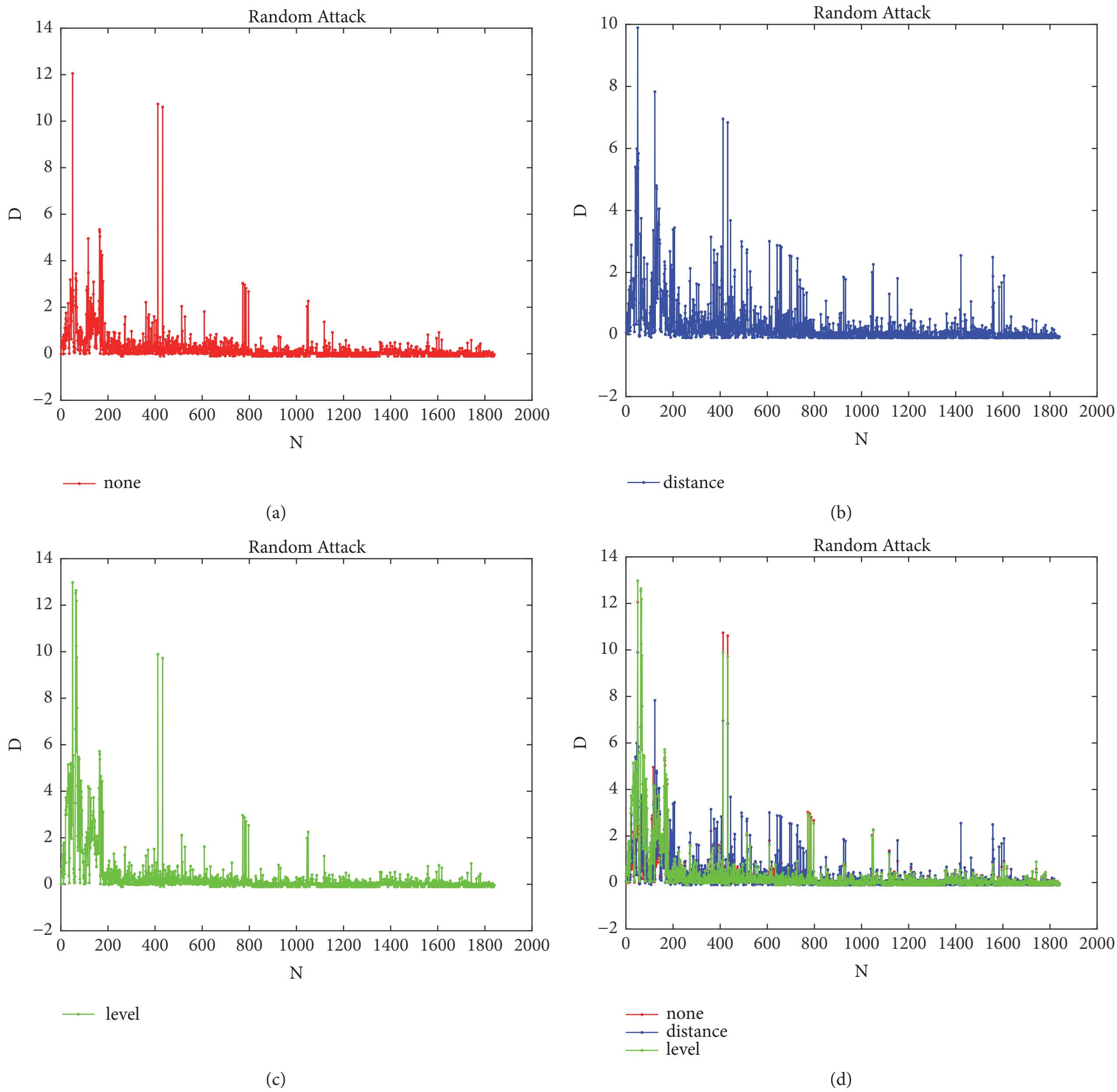



Figure 4: Random Attack traffic network ((a) NTNM; (b) DWTNM; (c) RLWTNM; (d) three traffic network model comparison graphs).

the road node vulnerability of high-level road networks is enhanced. As shown in Figure 4(d), the three traffic network models show that the vulnerability value calculated by the DWTNM changes greatly, and the value of the RLWTNM has a large contrast.

*(2) Deliberate Attacks (DA)*. Figures 5(a)–5(c) show the vulnerability calculated from the RTN. The three traffic network models have the same trend, and the attacks are performed in descending order of the link efficiency. The higher the efficiency, the greater the vulnerability of the road link. Traffic links with high vulnerability and high risk needs to be maintained.

In Figure 5(d), the slope of the vulnerability curve of the RLWTNM is higher than the other two traffic network models. In line with the actual traffic conditions, when the important road sections fail, it will quickly lead to the overall RTN. The vulnerability of different levels in actual traffic networks is different. The utilization rate and carrying capacity of high-level road networks are relatively high, and they also have high vulnerability.

*3.4. Vulnerability Analysis of RTN.* With the topological statistics, the vulnerability of traffic networks can be learned from the decline of their performance compared to the initial state. Different network characteristics can be used

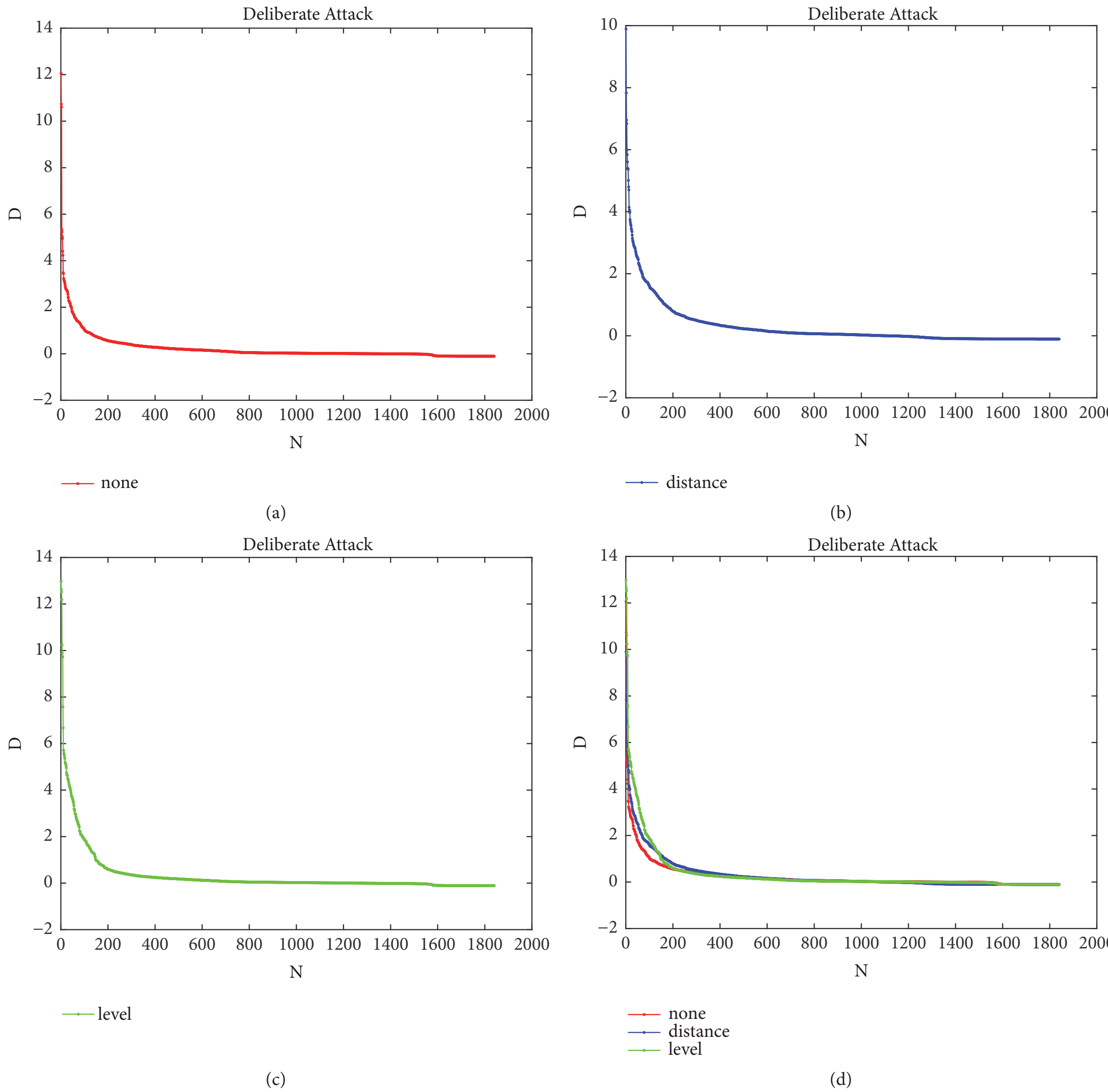
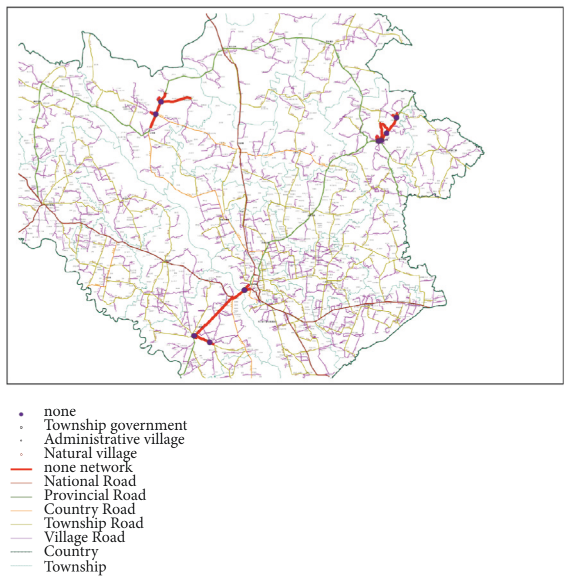
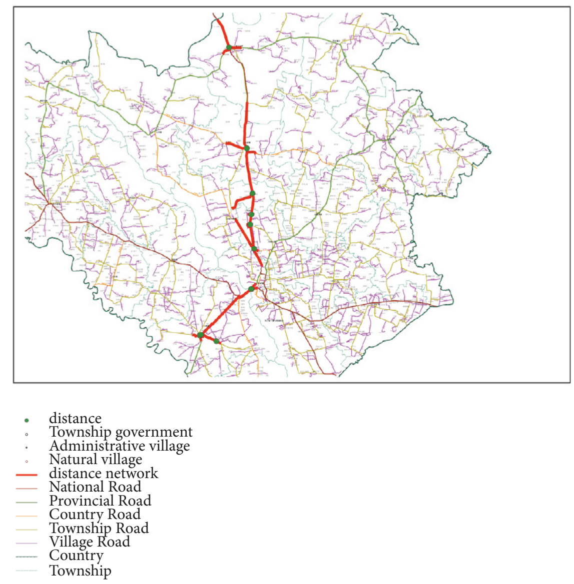



Figure 5: Deliberate Attack traffic network ((a) NTNM; (b) DWTNM; (c) RLWTNM; (d) three traffic network model comparison graphs).

for describing the performance of network. In this section, we analyze the vulnerability of RTN via those three models, as described in Figure 6. The results of the vulnerability analysis of the traffic network in the experimental area show the following. In the traffic network constructed by the NTNM, the most vulnerable link of the experimental area is shown in Figure 6(a). The constructed traffic network is based on the theoretical model of European space. The highly vulnerable road link is generated by the high efficiency of the theoretical road link, so the location of the vulnerable link is deviated from the actual traffic situation. In the traffic network constructed by the DWTNM, the most vulnerable link of the experimental area is shown in Figure 6(b). The weight assignment of the RTN is based on the length of the actual distance, so the road link with high vulnerability is caused by the actual distance length. In the traffic network constructed by the RLWTNM, the most vulnerable link of the experimental area is shown in Figure 6(c). The constructed traffic network divides the weight value according to the road level, and the high-level road link has a higher utilization rate and a higher relative weight assignment. Therefore, the highly vulnerable road links are distributed on the National Road, G101 Jingshen Line; and the utilization rate is high and the bearing capacity is strong, which is in line with the actual traffic conditions.




(a)

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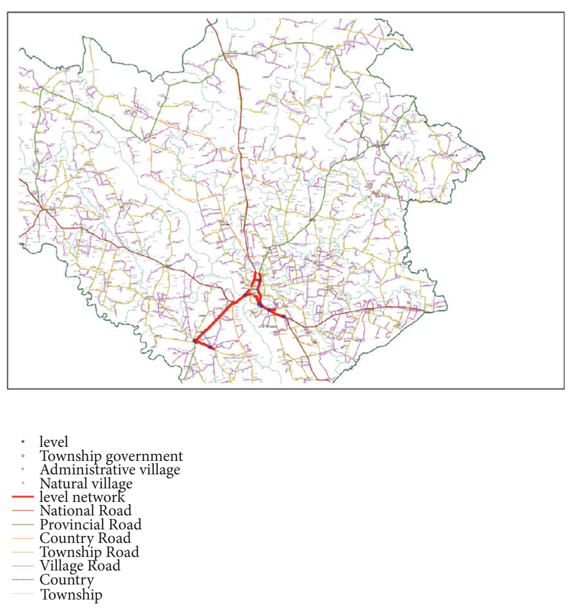


(c)

Figure 6: The severe traffic link of the RTN in the experimental area ((a) NTNM; (b) DWTNM; (c) RLWTNM).

## 4. Conclusion

Based on the existing complex network theory, this paper constructs the No-power Traffic Network Model (NTNM), the Distance Weight Traffic Network Model (DWTNM), and the Road Level Weight Traffic Network Model (RLWTNM). By analyzing the distribution results of the Rural Traffic Network (RTN), the traffic network of Zhangwu County showed no scale phenomenon. The three types of traffic network models were attacked by two kinds of manners in order to analyze the vulnerability. The results show that the average degree of the three traffic network models is 2.1766, and the overall trend of single link connection is relatively simple. The clustering coefficient is 0.0313, indicating the poor accessibility of the transportation network in Zhangwu. The average path length of the Road Level Weight Traffic Network Model is 15.2032, and the median value of the three models is the minimum. It is most suitable to analyze the actual traffic network of Zhangwu county (the actual traffic network of Zhangwu county is not as bad as the other two models). The road network efficiency of the Road Level Weight Traffic Network Model is 0.0658, and the median value of the three models is the largest, which better reflects the actual application efficiency of the traffic network in Zhangwu county. The Road Level Weight Traffic Network Model of Zhangwu county reflects the actual traffic situation more, and the road links with high vulnerability were analyzed on the high-level traffic network (National Road, G101 Jingshen Line). It is necessary to take protective measures for high-vulnerability road links, which prevented natural disasters or unexpected events from affecting traffic. In the future, we would consider more factors that affect the Rural Traffic Network and optimize the expansion direction of the Rural Traffic Network.

## Data Availability

The Zhangwu County Traffic Network data used to support the findings of this study have not been made available because the original road network data is the traffic situation of the real county location in China, and it is real and effective reality data. It can reflect the real data of China's geographical location. Therefore, it cannot be made public. However, the results of the later results can be referenced and applied.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

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