Designing Post-Disaster Restoration Schemes for Traffic Networks based on Network Topological Indicators

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Abstract. Identifying key road segments and prioritizing their protection to enhance the resilience of road networks against crisis events remains a pressing issue. In this paper, complex network theory is adopted to determine the importance ranking of road segments and analyse how to select the road segments that need to be rehabilitated in the case of insufficient budget. This study will provide three different methods to assess the importance of road segments, and with the help of user equilibrium model for traffic demand allocation, calculate the system travel time after rehabilitation to evaluate, compare, and analyse different rehabilitation schemes, and then get the rehabilitation scheme with better performance. Meanwhile, it is investigated whether the optimal road segment rehabilitation combination will change under different budget levels. The results of the case study finally show that the rehabilitation set determined by the Clustering Coefficient and the betweenness is better, which can provide practical guidance on how to select the prioritized rehabilitation segments.

1. Introduction

Urban road transportation systems are vital lifeline systems that support a city's economic development and social prosperity. Their connectivity and efficiency are crucial for daily activities and essential for emergency responses. However, these systems are susceptible to various natural hazards and manmade events, including seismic activity, floods, explosions, intentional attacks, and more. Nowadays, the issue of emergency management of road networks oriented to emergencies has become a subject of global interest. This paper aims to utilize complex network theory to investigate the prioritization of system components during different disaster situations. It seeks to assess the overall efficiency of the system after restoration, considering the actual road network conditions. These analyses will help in devising an optimal transportation network restoration scheme.

Network topology refers to the relative structure of nodes and links layout in a networked system [1]. In the study of complex transportation networks, the impact of network topology on the overall network performance cannot be ignored [2]. Recent domestic studies have focused on specific cases to quantitatively evaluate the performance of transportation networks by analysing data in conjunction with real-world conditions in different cities. Research has primarily investigated railroads, highways, urban roads, urban railways, public transportation, and other systems, aiming to understand complexity [3], resilience [4], robustness [5], centrality [6], fragility [7], and reliability [8]. By analysing empirical data, these studies aim to give guidelines for transportation system design or operation.

There are three main types of current research on using complex network theory to study the topological characteristics and performance of transportation networks: The first category involves a generalized analysis of the topological network structure. Relevant literature extensively examines different types of networks and compares their distinctions. A random network refers to a network in which a link exists between any two nodes with equal probability, and the existence of a link is determined randomly. A scale-free network is a network in which the degree distribution obeys a power law distribution, i.e., the majority of nodes in the network have only a few links, whereas a few major nodes will have numerous links [9]. This can lead to varying importance of nodes within the network. These researches have combed the basic concepts related to the network in detail from a macro perspective [10], which provides a basic reference for the subsequent research. The second category of studies focuses on assessing the resilience of networked systems. Most of this literature leverages different topology indicators to assess the change in the performance of the networked system when nodes or links are removed. By varying the removal of nodes, different failure scenarios are modelled to expose the system's behaviour [11-13]. The third category of research focuses mainly on the characterization of complex networks. Many of these studies leverage stochastic networks, scale-free networks, or small-world networks as starting points to explore specific phenomena within transportation networks [14].

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The core focus of this paper lies in the application of complex network theory to rank the importance of network components. There are two key considerations in this study. Firstly, various network topology indicators exist for assessing the importance of road segments. Secondly, there is a practical limitation on the budget available for network restoration. Specifically, the total restoration cost must not exceed the allocated budget when selecting the set of road segments to be restored. To address these considerations, this study employs different network topology indicators to prioritize the damaged road segments based on their importance and design appropriate restoration schemes. Subsequently, the performance of various restoration schemes is evaluated by calculating the total travel time. This comprehensive analysis allows for the determination of the optimal restoration schemes.

2. Indicators for evaluating the importance of road segments

2.1. Network topological indicators

In the field of complex networks, a wide array of topology indicators is utilized to assess the importance of nodes or links. These indicators encompass various measures such as centrality, Clustering Coefficients, and others. Each topology indicator provides a distinct perspective for evaluating the significance of nodes or links within complex networks. Degree and betweenness and Clustering Coefficient in complex networks are defined as follows.

Definition 1 Degree
The degree of node \( i \) in the network is defined as the number of other nodes directly connected to node \( i \), i.e., the number of neighbouring nodes of node \( i \).

\[
C_D(i) = \sum_{j=1}^{n} A_{ij}
\]  \hspace{1cm} (1)

Definition 2 Betweenness
In a directed graph, the betweenness of node \( i \) is defined as:

\[
C_B(i) = \frac{\sum_{m=1}^{\text{deg}_i} H_{st,lm}}{\sum_{r=1}^{\text{deg}_i} H_{st,r}}
\]  \hspace{1cm} (2)

where \( H_{st,lm} \) denotes the sum of distance on the m-th shortest path that pass through node \( i \) between node \( s \) and \( t \), \( H_{st,r} \) means the sum of distance on the r-th shortest path between node \( s \) and \( t \), \( \text{deg}_i \) means the number of shortest paths between node \( s \) and \( t \) that pass through node \( i \), and \( n_{st,i} \) represents the number of shortest paths between node \( s \) and \( t \).

Definition 3 Clustering Coefficient
Clustering Coefficient is the coefficient used to describe the degree of clustering between the vertices of a graph. Specifically, it is the degree to which the adjacent points of a point are connected to each other. Suppose a graph \( G = (V, L) \) including \( V = \{v_1, v_2, ..., v_n\} \) said the set of nodes and \( E = \{e_{ij}; (i,j) \in S[1,2, ..., n]\} \) said the edge of the collection. \( L(i) \) is used to represent the set of edges connected to node \( i \). The number of edges in \( L(i) \) is the degree of node \( i \), \( k_i \): \( k_i = |L(i)| \). The local Clustering Coefficient \( CC(i) \) of node \( i \) in the directed graph is equal to the number of edges between all the nodes connected to node \( i \), divided by the maximum number of edges that can be connected between these nodes.

\[
CC(i) = \frac{||e_{jk}; v_j, v_k \in L(i), e_{jk} \in E||}{k_i(k_i-1)}
\]  \hspace{1cm} (3)

2.2. Restoration schemes

This paper conducts experiments to assess the importance of road segments using three topology indicators: degree, Clustering Coefficient, and betweenness. In this experiment, the degree index value of a road segment is obtained by averaging the in-degree of its start node and the out-degree of its end node. Similarly, the Clustering Coefficient index value is obtained by averaging Clustering Coefficients of the start and end nodes of each road segment. During the calculation process, several road segments may exhibit identical values for either the degree or Clustering Coefficient indicator. This results in an inability to differentiate their importance when determining the ranking order. To address this issue, the betweenness or TD (total travel time difference) value is introduced as a secondary basis. This helps avoid situations where a large number of road segments are ranked equally in terms of importance. The TD value represents the difference between the total travel time after the failure of the road segment and the original total travel time. To incorporate the influence of costs on the importance of road segments, the original secondary criterion of betweenness was replaced by the secondary criterion of costs. As a result, four new schemes were introduced. In light of situations where certain road segments possess identical TD values during the calculation process, an additional scheme was included, prioritizing TD value as the primary criterion and cost as the secondary criterion. All restoration schemes in this experiment are shown in Table 1.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Primary basis</th>
<th>Secondary basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Betweenness</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>Degree</td>
<td>Betweenness</td>
</tr>
<tr>
<td>3</td>
<td>Degree</td>
<td>TD</td>
</tr>
<tr>
<td>4</td>
<td>Clustering</td>
<td>Betweenness</td>
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<tr>
<td>5</td>
<td>Clustering</td>
<td>TD</td>
</tr>
<tr>
<td>6</td>
<td>Clustering</td>
<td>value&amp;Betweenness</td>
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<tr>
<td>7</td>
<td>Degree</td>
<td>Cost</td>
</tr>
<tr>
<td>8</td>
<td>Degree</td>
<td>TD value&amp;Cost</td>
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<tr>
<td>9</td>
<td>Clustering</td>
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<tr>
<td>10</td>
<td>Clustering</td>
<td>TD value&amp;Cost</td>
</tr>
</tbody>
</table>

Table 1. Summary of restoration schemes.
3. Methodology

3.1. Data preparation and network construction

Prior to conducting the experiment, thorough data preparation and complex network construction were undertaken. The initial step involved defining the fundamental information of the road network, including the number of road segments, node set, road segment set, and the set of starting and ending nodes. Subsequently, the topology indicators of the road segments were computed after constructing the network. For this study, the Anaheim inner-city road network provided by Ben Stabler on GitHub in 2020 was selected [15]. This road network consists of 416 road nodes and 914 road segments, along with the associated road segment data. The network is represented as a directed graph, where the entire urban road network is divided into 38 regions. Nodes 1-38 serve as the centers of their corresponding regions, forming a 38x38 demand matrix encompassing 1,406 pairs of starting and ending points. Furthermore, in this study, the Capacity Degradation Ratio is employed to indicate the extent of road segment damage within the network. The Capacity Degradation Ratio of 1.0 is assigned to a road segment in normal condition. If the capacity of a road segment is impaired, its Capacity Degradation Ratio is set to a value less than 1.0. These values are instrumental in reconstructing the network matrix representing various states, such as the damaged network and networks after different restoration schemes have been implemented.

Different complex network metrics are utilized to calculate the importance values and rank the road segments. This process enables the determination of the importance ranking of road segments for each restoration scheme. Subsequently, the restoration set of road segments is derived based on the importance ranking. The total restoration cost is obtained by summing the costs of the restoration set, which cannot exceed the budget. Following this, the restoration process is simulated, and the network performance after restoration is evaluated. These assessments facilitate a comparison of the advantages and disadvantages of different restoration schemes.

3.2. Restoration project situation setup

3.2.1 Disaster settings

To establish a practical and reliable theoretical foundation for post-disaster restoration schemes, it is crucial to accurately replicate the real-world conditions when modeling scenarios involving attacks on the road network. The simulation setup encompasses three key aspects: the attack mode, the probability of individual road segments being targets, and the extent of damage inflicted. This study focuses on optimizing strategies for rebuilding road networks after natural disasters by simulating random attacks on them. In the experiments, the attack probability is primarily defined as the proportion of damaged segments to the total number of segments. To prevent complete network paralysis resulting from excessive damage, the attack probability is intentionally kept moderate. In this paper, attack probabilities of 3%, 6%, and 9% are considered. Furthermore, it is recognized that the failure of roads could lead to unmet origin-destination (OD) demands. Thus, the damaged road segment is assumed to operate at only 50% capacity in terms of the degree of damage setting.

3.2.2 Restoration budget settings

Taking into consideration the actual post-disaster conditions and the limitations of the disaster relief budget, as well as the availability of human and material resources, this study imposes a constraint on the restoration budget. Consequently, there may be road segments that cannot be restored due to budgetary restrictions. Thus, determining the optimal set of road segments to be restored becomes particularly crucial. To analyze the impact of different levels of budgetary restrictions on the optimal restoration set, three budget levels were established in the experiment: a low budget level of 30%, a medium budget level of 50%, and a high budget level of 70%. Specifically, after identifying the set of randomly selected damaged road segments in the experiment, the total restoration cost of all damaged road segments is calculated. This result serves as the base budget and is multiplied by the corresponding percentage to establish the budgets for the three budget levels. The only constraint in this experiment is as follows:

$$\sum_{i \in I} C_i \leq B_i$$  \hspace{1cm} (4)

The sum of the restoration costs for the road segments in the restoration set must not exceed the total budget allocated for the disaster relief scenario.

4. Case Study

4.1. Obtaining collections of restored road segments

In the damaged network state, the Capacity Degradation Ratio of damaged segments is set to 0.5 and the road capacity becomes 50% of the original. The importance of the damaged road segments was ranked according to the ten importance assessment scenarios in Table 1. The restoration cost of all damaged road segments was then summed to obtain the base budget by multiplying the corresponding coefficients to obtain three levels of budget. In descending order of importance of the damaged road segments under different importance assessment scenarios, the road segments to be restored are selected sequentially and the restoration costs are accumulated until the budgets of different levels are reached to obtain the set of restored road segments under different budget levels for that importance leveling scenario. Finally, the set of restored segments and total restoration costs were obtained for the ten criticality assessment scenarios under the three budget levels. In order to avoid errors due to random sampling, this paper was repeated ten times to randomly select the set of damaged road segments and
perform the calculations, taking the mean of the results for analysis.

4.2. Performance analysis

In this experiment, the total travel time of the road network serves as the primary metric for evaluating network performance. However, the calculated total travel time values in the experiment were exceedingly large. To facilitate subsequent analysis and enhance comparability, the difference between the total travel time of the restored network and the total travel time of the unrestored network is calculated for comparison. Considering the issue of restoration efficiency, the total travel time difference is divided by the restoration cost to derive the unit cost benefit. This measure allows for further comparison of the efficiency advantages and disadvantages across different schemes. The results are shown in Figures 1 and Figures 2.

Fig. 1. Performance of 5 restoration schemes under three attack probabilities (3%, 6%, 9%).

Scheme 5 consistently outperformed other restoration schemes for 3% damaged road segments, based on Clustering Coefficients, TD value, and betweenness. Schemes 1 and 5 yielded higher travel time reductions for budget levels below 50%, while Schemes 2, 3, and 4 counteracted their benefits for budget levels between 50% and 70%. Scheme 4 had the highest returns, surpassing Schemes 1 and 5 significantly.

For 6% damaged road segments, Scheme 1 based on betweenness provided the highest benefits at a budget level below 50%, while Clustering Coefficient-based Schemes 4 and 5 approached Scheme 1’s benefits at a 70% budget level but remained relatively lower. Scheme 1 consistently had the highest gains in total travel time reduction for unit budget costs for budget level below 50%, while Clustering Coefficient-based Schemes 4 and 5 showed an increasing trend.

Fig. 2. Performance of 10 restoration schemes under three attack probabilities (3%, 6%, 9%).

Without considering Scheme 10, when 3% of road segments are damaged, Scheme 9, primarily based on Clustering Coefficient and secondarily on TD value and cost, demonstrates superior performance and notable advantages. When 6% of road segments are damaged, Scheme 1 based on the betweenness consistently performs optimally for budget levels below 50%. However,
Scheme 8, primarily based on Clustering Coefficient and secondarily on cost, becomes the optimal choice when the budget level exceeds 50%. Similarly, in the scenario where 9% of road segments are damaged, Scheme 1 based on the betweenness performs optimally at higher budget levels.

When considering Scheme 10, in the scenario where 3% of the road segments are damaged, Scheme 10, based primarily on TD values and secondarily on costs, consistently performs optimally, except when the budget level is equal to 50%. When 6% of the road segments are damaged, Scheme 10 also consistently performs optimally for budget levels above 50%. However, in the scenario with 9% of the road segments damaged, Scheme 10 consistently falls short of being the optimal choice.

5. Conclusion

To summarize, this study examines the impact of topology indicators and cost factors on scheme performance, aiming to provide guidance for optimizing road network restoration schemes.

1. In most cases, the betweenness and Clustering Coefficients are more suitable as primary criteria for selecting restoration targets. The betweenness metric proves more effective as a primary criterion when the road network is extensively damaged, whereas the Clustering Coefficient is more suitable when the road network is less affected.
2. With an increasing budget for restoration, the clustering coefficient-based scheme is more effective in enhancing network performance with a larger budget allocation.
3. Schemes with cost as a secondary criterion consistently outperform schemes with betweenness and TD values as secondary criteria. This highlights the superior performance of schemes based on cost as a secondary criterion for road network restoration.

Future work aims to refine the methodology presented in this paper, develop a model capable of handling large amounts of road data, incorporate advanced machine learning techniques, and ultimately achieve rapid detection of post-disaster transportation networks for early warning and the provision of corresponding restoration schemes.

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