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Research Article

Calculating Node Importance Considering Cascading Failure in Traffic Networks

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Abstract: The traffic network is a scale-free network. In selective attack, invalidation of few key nodes may lead to network failure so it is important to find these key nodes. In this study, the key nodes are determined by establishing calculating methods of node importance based on cascading failure behaviors. First, a cascading failure model of traffic network is posed. Its differences from current models are as follows: 1) The upper travel network and lower road network are influenced each other, 2) Capacity of nodes and links are given at first but not in direct proportion to initial flow that is related to initial capacity, 3) Travel time is used to describe status of links, 4) Capacity of links may change. The evaluation method of node importance of traffic network considering cascading failure is proposed then based on node deletion. It uses congestion status of cascading failure network to describe the node importance and algorithm procedures are designed to estimate importance of all nodes. At the end, the experiment analysis shows that network structure and traveler behaviors have in significant influence on node importance.

Keywords: Bi-level network, cascading failure, node importance, traffic network

INTRODUCTION

As the infrastructure of social economy activities, traffic network is the intranets for communications and transportation. From some researches, it is discovered that the traffic network is a complex system characterized by a small world. It is a scale-free network (Gao and Chen *et al.*, 2007; Zhang and Yang, 2008). The scale-free network has fault tolerance of random attack. In random attack, even a majority of nodes have been damaged, the rest network may still form an integrate cluster to maintain connectivity. Scale-Free Network is of vulnerability under calculated attacks: in selective attack, deficiency of a few key nodes may lead to failure of network, which is called "robust and vulnerable" character (Albert *et al.*, 2000). Therefore, node importance in the traffic network is of significance to be estimated. By estimation, "key nodes" can be found. In this way, these key nodes can be protected to improve the reliability of the whole traffic network and vulnerable links may be attacked to fulfill the purpose of destroying the whole traffic network by attacking these vulnerable links.

Three kinds of method for estimation of node importance have been established so far:

- The determination method based on relationship between node importance, social economy and traffic volume of passengers and cargoes (Liu *et al*., 2004; Wang *et al*., 2001; Miao *et al*., 2005). Its fundamental idea is to comprehensively assess the node importance using multiple indexes by social economy characteristic and traffic distribution analysis. This method is commonly used in traffic network planning.
- The determination method that the node importance is equivalent to conspicuousness. Its fundamental idea is to highlight different between network nodes by finding something useful characteristic information from the network, that is to say, fully reflecting the position features of nodes in network, which amplifies the conspicuousness of network nodes to define their importance. Indexes measuring nodes' importance are mainly degree, degree of approach, betweenness, degree of agglomeration, information, eigenvector and cumulated nomination, etc. The degree involves the number of links adjacent to nodes; the degree of approach is the reciprocal of distance sum from nodes to all other nodes, reflecting centralization degree of the node in network; the betweenness reflects the controlling affect of communication between the node and all other nodes; the degree of agglomeration is the ratio between nodes and average path length, reflecting the degree of agglomeration after contraction of nodes; the information involves all information flow delivered in all paths; the eigenvector carries out linear combination that the reputation of single member is

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regarded as that of all other members, from which a linear equations set can be obtained. The eigenvector corresponding to the maximum eigenvalue of the set; the cumulated nomination only improves the solution of eigenvector with the fundamental principles same as that of eigenvector.

- The determination method that the node importance is equivalent to destructiveness. Its fundamental idea is to determine the node importance by measuring the destructive extent to network connection after the nodes (set) have been deleted. The more serious the network connection is damaged, the more important the deleted nodes are. After nodes (set) of undirected connecting network are deleted, as Li Depeng puts it, there are three aspects of damage to the whole network connection status:
  - The deleted nodes (set) cannot connect with other nodes.
  - Concentrated nodes of the deleted nodes cannot connect with each other.
  - Concentrated nodes of the rest nodes cannot connect with each other.

Therefore, to define the total damage means that the whole destructive extents to the whole network connection after nodes are deleted, so as to determine the importance of deleted nodes (set). Liu poses the preferential equivalent method to estimate the node importance that, after the nodes are deleted, is the sum of the number of branches of connected graph and priority level coefficient of nodes directly or indirectly connected with the deleted nodes. Gao argues that stops in public transit network are deleted in descending order according to flow of stops. If 90% of travel demands cannot be assigned, those deleted stops set are the most important ones. Wu suggests an assessment method for importance of complicated loading network nodes considering cascading failure10.

In current researches, the first method determining node importance only begins from external adaptability of road network, without considering topological structure and dynamic behavior of traffic network itself. The second and third method determining node importance begins from the topological structure, in which node failure are assumed to be independent each other without considering network dynamic behavior, network loading and influence of travel network on node importance, that is, ignoring the external adaptability of road network. Especially, the literature determining node importance begins from cascading failure. Although it considers the dynamics behavior of loading network, it ignores the influence of travel network on node importance. Moreover, it determines node load according to between's, which is inconsistent with loading mode of road network. The literature determines node importance only beginning from network's travel need adaptability. It only can determine the most important node sets and cannot differentiate importance of each node. It cannot explore the influence of network's topological structure and dynamic behavior on node importance.

Actually, the traffic network is a "network of network" consisting of road network (including road system and management system) and travel network. The travel network and road network are affected each other. Therefore, two networks should be considered in measuring node importance. In this study, it is proposed that bi-level network is established to describe characteristic of mixed network and node importance of traffic network is determined based on cascading failure behavior of traffic network. On the one hand, this method considers the influence of network's topological structure and dynamic behavior on node importance. On the other hand, it considers the particularity of traffic network and determines node importance from the interplay of road network and travel network.

CASCADING FAILURE MODEL OF TRAFFIC NETWORK

In actual network, failure of few nodes in the network will lead to failure of other nodes via connection relationship with other nodes, creating chain effect to finally cause failure of the majority of network or even the whole, which is call cascading failure. Cascading failure models may be divided into four categories: load-capacity model, two-value influence model, sand-pile model and other models (such as OPA model and CASCADE model). The load-capacity model generally assigns some load and capacity to each node (link) in the network. If one node's capacity is exceeded, it will fail. According to a strategy, the loads of fault nodes are assigned to other nodes in the network. Because of these additional loads, the total loads may grow beyond their capacity, thus causing another reassignment of loads. Upon this repetition, the influence nodes expand gradually, which leads to cascading failure. Figure 1 for load-capacity cascading failure model.

In current researches of cascading failure of traffic network, the cascading failure model that has been used is load-capacity model. Still, there have been some problems so far for this model in application in traffic network such as follows:

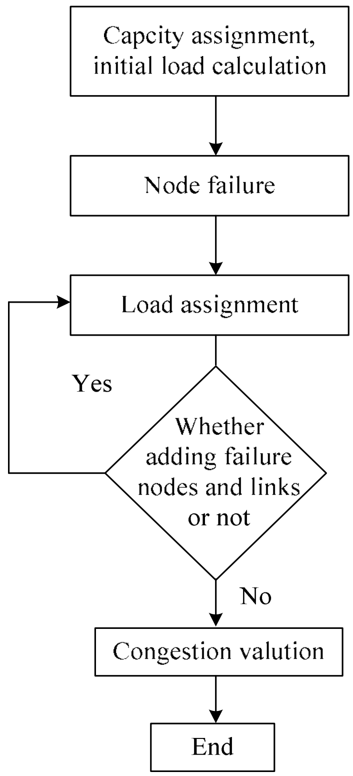


Fig. 1: Load-capacity model of cascading failure

- The influence of travel network structure on cascading failure is not considered.
- It assumes that the initial capacity of nodes (links) in road network is in direct proportion to initial flow of those. Actually, nodes (links) capacity depends on the road network, but independent to the flow it bears.
- Only two states occur for links in road network: if link flow is less than flow, the link is considered normal or become invalid otherwise. Those invalid links will be deleted from the network. In fact, even in case of high density, the majority of links are not blocked off. Therefore, the majority of links are in a medium state between normal and invalid state. As the flow declines, the links in medium state may still turn into normal. To simply delete links in medium state is not appropriate.
- It assumes the capacity of links in road network is constant, which does not comply with actual status. The congestion of downstream nodes, in fact, will affect the capacity of upstream sections.

Based on these problems, such improvements are made in this study as follows:

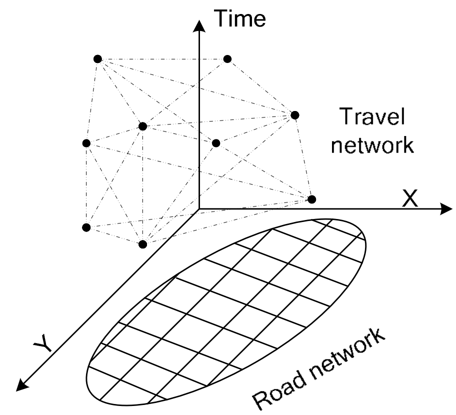


Fig. 2: Bi-level network model

- A bi-level network model is established to describe the mixed network characteristic of traffic network in cities. The lower network is the road network with nodes representing intersections and links representing roan sections that connect intersections; the upper network is the travel network with nodes representing travel generating or attracting points and links representing interrelation of nodes, as shown in Fig. 2. The upper network and lower network interact: the upper travel network determines node or link loads in the lower road network through traffic assignment. At the same time, the variations of the lower road network will influence travel path choices of the upper travelers.
- Based on road network state, the initial capacity of each link is given at first and values are assigned according to initial capacity. The initial flow of road network is obtained in accordance with a traffic assignment principle.
- Travel time is used to describe the state of links, which adopts travel time function from Bureau of Public Road of USA:

$$t_{ij}(\tau) = t_{ij}(0)\left[1 + \alpha \frac{q_{ij}(\tau)}{C_{ij}(\tau)}\right]^{\beta} \tag{1}$$

where, t_{ij} (τ) is the travel time at time step τ, t_{ij} (0) is the free flow time of link ij, q_{ij} (τ) is the flow of link ij at time step τ and C_{ij} (τ) is the capacity of link ij at time step τ.

- The capacity of link uses the changing rule in literature [14]:

$$C_{ij}(\tau+1)=\begin{cases}C_{ij}(0)\dfrac{C_j(\tau)}{q_j(\tau)}, & if\ C_j(\tau)<q_j(\tau)\\ C_{ij}(0), & otherwise\end{cases} \quad (2)$$

where,

C_j (τ) = The capacity of node j at time step τ (in this study it is assumed the capacity of intersections is 0.9 times the capacity of intersecting roads.

q_j (τ) = The inflow of node j at time step τ:

$$q_j(\tau)=\sum_i q_{ij}(\tau)$$

- The congestion index J in literature to describe consequence after the failure of cascading failure:

$$J=\sum_{ij}q_{ij}(\tau)t_{ij}(\tau)/\sum_{ij}q_{ij}(0)t_{ij}(0) \quad (3)$$

CALCULATING METHOD OF NODE IMPORTANCE

In case of considering cascading failure, it is assumed that if a node become invalid, it will be deleted. If this node is a key node, its invalidation will trigger cascading failure, which will lead to decline of network's performance that means the congestion index J is becoming bigger. Therefore, we can consider that the bigger the congestion index J after cascading failure of network is, the more important the node.

Calculating steps for estimate importance of all nodes are as follows:

Step 1: Give travel network, road network; give links' initial capacity, free flow time; calculate initial capacity of nodes; traffic assignment; obtain initial flow of each link in road network; calculate initial flow of node; calculate travel time of each link according to Eq. (1).

Step 2: Delete node j.

Step 3: Assign traffic after the capacity of links and capacity of nodes are updated according to Eq. (2) to obtain flow of each link in road network; calculate flow of nodes and travel time of each link.

Step 4: Judge if invalid nodes are renewed; if so, delete invalid nodes and link and return to step 3 or to step 5 otherwise.

Step 5: Calculate congestion index according to Eq. (3).

Step 6: If all nodes are traversed; if so, go to step 7, or return to step 2 by choosing other nodes.

Step 7: Determine importance of nodes according to the obtained congestion index J after the nodes are deleted.

For above algorithms, the traffic assignment methods may adopt User Equilibrium (UE) and Stochastic User Equilibrium (SUE), etc.

This algorithm is also suitable to determine link importance if "delete node" change into "delete link" in step 2.

EXPERIMENTAL ANALYSIS

Road network adopted as shown in Fig. 3, it has 25 nodes and 40 links. See Table 1 for parameters of road network. Two travel networks with 25 nodes are established, respectively by means of WS (Watts Strogatz), Small-World Network (SWN) and BA (Barabasi Albert) Scale-Free Network (SFN), as shown in Fig. 4a and b. In respect of WS algorithm, first, a regular network is set up with each node connecting with adjacent 4/2 nodes on the right and left link. Then, the links are reconnected with a probability of 0.5. The average degree of scale-free network that has been established is 2.

Assume the total need is 100000 pcu/h and each OD needs same; in the small-world travel network as shown in Fig. 4a, the flow of each OD pair is 1667 pcu/h. In the small-world travel network as shown in Fig. 4b, the flow of each OD pair is 3125 pcu/h. In accordance with the algorithm in section 3, travel network of Fig. 4a and b are selected to evaluate node importance in road network as shown in Fig. 3 under conditions of cascading failure, which can be used to analyze the influence of network structure on node importance. In the same travel network, UE and SUE traffic assignment models are used to analyze the influence of path selection of traveler on node importance.

Importance of each node of road network shown in Fig. 3 is calculated based various path selection rules such as UE and SUE and various travel networks such

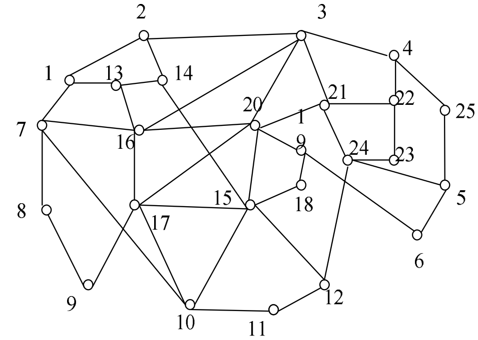


Fig. 3: Topology structure of road network

Table 1: Parameters of road network

Link	Free flow time (s)	Initial capacity (pcu/h)
1-2	28	4000
2-3	33	4000
3-4	23	4000
4-25	10	4000
25-5	7	4000
5-6	15	4000
6-19	13	6000
19-20	11	4000
1-7	15	4000
7-8	10	6000
8-9	24	6000
7-10	25	4000
10-11	17	4000
11-12	11	4000
1-13	17	2000
13-14	14	6000
2-14	13	6000
14-15	31	6000
10-15	22	6000
12-15	19	6000
15-17	26	6000
15-18	9	6000
18-19	7	6000
15-20	19	6000
3-16	30	4000
3-20	21	6000
3-21	20	6000
20-21	14	6000
21-22	7	6000
22-23	4	2000
23-24	4	2000
4-22	10	6000
5-24	16	4000
21-24	7	6000
12-24	15	6000
16-20	33	6000
17-20	20	6000
16-17	10	4000
13-16	14	4000
17-9	12	6000
10-17	24	6000
7-16	21	6000

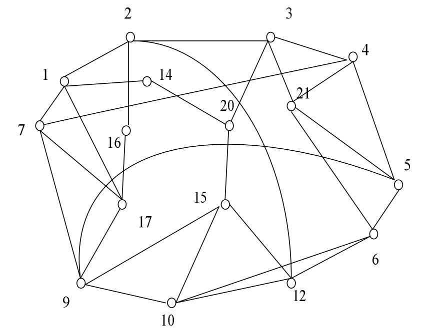
Table 2: Congestion analysis of the most important 4 nodes

Importance order		1	2	3	4
SWN	UE assignment	21	20	10	15
	Congestion status	0.929	0.794	0.787	0.782
	SUE assignment	11	20	21	16
	Congestion status	∞	1.084	1.055	0.951
SFN	UE assignment	7	16	15	12
	Congestion status	0.586	0.552	0.534	0.527
	SUE assignment	13	11	8	1
	Congestion status	1.139	0.958	0.944	0.833

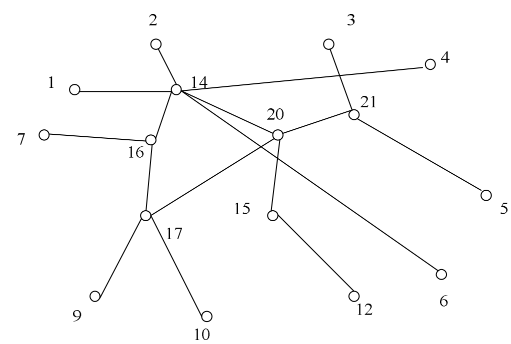
as small-world travel network shown in Fig. 4a and small-world travel network shown in Fig. 4b. Four most important nodes are selected. After these 4 nodes are deleted, the congestion status of the rest network is shown by Table 2.

As known from Table 2:

- The travel network structure has an important influence on node importance. Importance of each node is different obviously in small-world network and scale-free network.



(a) Small-world network



(b) Scale-free network

Fig. 4: Topology structure of trip network

- The path selection of travelers has an important influence on node importance. No matter what the network structure is, the path selection of UE and SUE leads to an obvious change of node importance.
- In this experiment of scale-world network, a calculated attack to key nodes leads to a greater damage. If the travel structure is a scale-free network, it helps the system resist calculated attacks. To select travel path by SUE, for instance, if the most important nodes is under attack, the road network in small-world travel network will fail while the road network in scale-free travel network has only a part to be blocked and the system will not fail.
- In this experiment, the more familiar the travelers know the road network, the stronger the road network resist the calculated attacks. Either in small-world travel network or in scale-free network, the network will be congested relatively slighter if travelers select paths by UE. Especially, in scale-free travel network, the road network will not be blocked even the most important nodes are under calculated attacks.

CONCLUSION

In this study, the key nodes are determined by setting up calculating methods of node importance based on cascading failure behaviors. First, a cascading failure model of traffic network is posed on the basis of bi-level network. The evaluation method of node importance of traffic network considering cascading failure is proposed then based on node deletion. At the end, the experimental analysis is performed to indicate that the travel network structure and behaviors of travelers have great importance on node importance. UE path selection and travel network of scale-free network help traffic system resist calculated attacks.
The further work is as follows:

- To study the cascading failure of traffic system when multiple nodes are under attack.
- To analyze the influence of travel structure and path selection on node importance.

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