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Vulnerability of Long-Distance Bridges and Tunnels in Urban Roadway Networks

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Abstract

The increasing incidence of traffic congestion and road mishaps has underscored the vulnerability of road networks. However, measuring such vulnerability lacks a comprehensive and reasonable index because of the large scope and variability of these networks, especially the long-distance bridges and tunnels that serve as the key links of an entire road network. This study employed congestion propagation theory and performed a dynamic traffic assignment to evaluate the degree of damage sustained by these structures. A vulnerability evaluation index was then proposed based on the current traffic conditions and topology of the road network. Thirteen river-crossing tunnels and four river-crossing bridges within the scope of the Outer Ring Expressway in Shanghai were investigated from the network perspective using TransCAD and Gephi. The Lupu Bridge and Nanpu Bridge sustained the most serious damage as reflected in their vulnerabilities of 10.68% and 10.62%, respectively. Large bridges are more vulnerable than tunnels, while the bridges and tunnels within the Inner Ring of Shanghai are more vulnerable than the surrounding bridges. This finding may be attributed to the geographical location and the number of lanes of these structures, thereby highlighting the importance of these factors in assessing road network vulnerability. This study also proposes some suggestions for optimizing the vulnerability of road networks.

Keywords: Network Vulnerability, Congestion Propagation, Dynamic Traffic Assignment, Large Tunnels and Bridges

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1. Introduction

Since the 1990s, the Shanghai government has been actively building expressways to solve the traffic congestions in downtown areas. Among these expressways, the “three vertical and three horizontal” arterial roads comprise a 3D network of city trunk roads in Shanghai that connect the two sides of the Huangpu River [1]. Another highway network layout called “two rings, nine emittings, one vertical, one horizontal and two links” has also been formed in Shanghai. The city has experienced a rapid increase in its number of vehicles and population in response to its accelerated urbanization, all of which threaten the operation safety of its road networks. Many road sections in Shanghai are gradually becoming saturated and unable to absorb new traffic, thereby diffusing traffic congestion throughout the city especially during peak hours. The trunk road network capacity of Shanghai also faces several risks, such as accidents, fluctuations in traffic demand, earthquakes, floods, large-scale activities, and terrorist attacks, and the failure to control such risks may lead to local crash and overall network paralysis [2].

The two sides of the Huangpu River are connected by cross-river bridges and tunnels with four bidirectional lanes that ease the road network pressure and save the travel time for motorists. However, as special components of the whole road network, these large structures create a bottleneck in guiding traffic flow [3]. Meanwhile, the destruction of large bridges and tunnels can substantially damage the entire road network. Apart from preventing these structures from performing their functions, the occurrence of weather disasters or other incidents may also result in traffic accidents and wide traffic congestion diffusion.

Therefore, a highly systematic and comprehensive method for assessing road network vulnerability must be proposed to maintain normal traffic operations, manage a large traffic flow, and facilitate rescue work during emergency situations.

2. State of the art

Foreign scholars have mainly examined road network vulnerability from a purely theoretical perspective, while domestic scholars prefer to combine theories with case studies in investigating such topic. Berdica argued that the vulnerability of transportation networks is easily affected by certain events and can substantially reduce the quality of road network services [4]. Road network vulnerability can be roughly divided into two categories. The first category is related to the consequences of failure in some parts of the network. D’Este et al. argued that when assessing vulnerability, one should consider the consequences of a disaster, such as how the severity of failures at small road sections can significantly reduce the accessibility of nodes (with node vulnerability acting as the accessibility index) [5]. The second category is related to risks. Therefore, the consequences and probability of link failure must be

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considered simultaneously when assessing road network vulnerability. Jenelius et al. divided the concept of vulnerability into two parts, namely, the probability for hazardous events to occur and the consequences of events that occur in a specific location [6]. Husdal argued that network vulnerability is not only related to the structure of the network but also to network traffic and environmental factors [7]. This study supports the argument that both risks and consequences contribute to road vulnerability. Section 3 reviews the related literature based on this idea. The vulnerability of road networks has been assessed in previous research using two methods. First, the main sections of the road network are fractured individually, and then those sections with the highest vulnerability are determined based on the decline in the service capacity of the entire network [8]. Second, game theory analysis is used to establish a model for analyzing road network vulnerability [9]. This study adopts the first approach for convenience.

Zhao et al. [10], Feng et al. [11], and Huang et al. [12] studied the vulnerability of the road networks from the network topology perspective in two attack modes, namely, random and deliberate attacks. Eduardo et al. used travel distribution data to analyze the vulnerability of the Madrid metro network in Spain [13]. Ye et al. used a broad travel cost growth parameter as an index for measuring vulnerability [14], while Li et al. introduced the travel time delay parameter in road vulnerability assessment [15]. However, these vulnerability assessment methods are not comprehensive enough, and the algorithms proposed in the literature are only validated in a small scale than in the city scope. Moreover, dynamic traffic assignment (DTA) is viewed as a day-to-day rather than a within-day adjustment process [16]. This study employs DTA theory to determine a dynamic process of allocating traffic volume during emergency situations.

This study proposes a novel method for evaluating the vulnerability of large bridges and tunnels in urban road networks in consideration of road topology and traffic conditions. This method is basically a more systematic and comprehensive version of the traditional vulnerability assessment method. This study chooses the main road network within the Shanghai Outer Ring as its research scope and the 4 cross-river bridges and 13 tunnels as its main objects to understand further the correlation between certain features and improve the overall efficiency of road networks in Shanghai. Large bridges and tunnels serve as link segments in a road network. Given that the operating statuses of bridges and tunnels are independent from one another, the failure conditions of these structures are also unrelated to one another. The road sections are fractured individually during the evaluation process, and an iterative traffic assignment procedure is performed to evaluate the influence of failures on the road network.

The rest of this paper is organized as follows. Section 3 presents the congestion propagation model and the proposed method for evaluating the vulnerability of bridges and tunnels from the road network perspective. Section 4 demonstrates the applicability of this method through case studies. Section 5 concludes the paper.

3. Methodology

3.1 Failure model of the road network based on congestion propagation

The propagation of traffic congestion is analyzed through a failure model simulation. The model assumes that the edges and nodes in a road network may assume either a normal or a failure status. The running status of roads is related to two random variables, namely, traffic capacity C and demand flow V. The road running function Z is computed as follows:

$$Z = C - V \tag{1}$$

Real capacity and distributed demand flow are random variables that meet the normal distribution. Rodríguez–Núñez et al. argued that when a center link is interrupted, the motorists may choose another route to their destination [13]. The road running function is a random variable according to theory of probability. Given the instability of road running, a road unit saturation of less than 0 may be treated as a failure. The following situations can be used to describe the reliability of a road unit [17]:

$$\begin{cases} Z>0 & \text{the road unit is reliable} \\ Z<0 & \text{the road unit fails} \\ Z=0 & \text{the road unit is in critical state} \end{cases} \tag{2}$$

The road network may be expressed as G = (N, A). If the load on the edges and nodes exceeds their capacity, then these edges and nodes are in a “failed status” and are removed from the network for the next flow distribution. This work employs such assumption to simulate the propagation of traffic congestion in road networks and to estimate the convergence condition. By allocating time-varying traffic volume in DTA, this work performs a re-allocation whenever a failure node is detected in the network. No failed nodes are detected in the network after several iterations of traffic assignment. The structural indexes of the traffic network under the final equilibrium state are then computed to measure the degree of damage to the whole network. Fig. 1 presents the road network failure model based on congestion propagation:

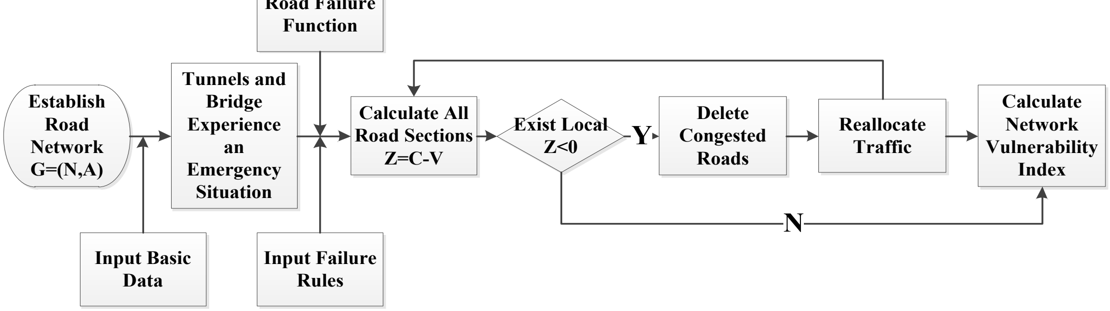

Fig. 1. Network failure model based on congestion propagation

3.2 Stochastic user equilibrium model

The user equilibrium model is commonly used in traffic assignment. This model assumes that vehicle drivers show the same behavior characteristics and are able to choose the shortest path to their destination. However, travelers cannot accurately estimate their travel time, especially in crowded metropolises such as Shanghai, thereby producing huge deviations in the distribution results. The actual traffic demands also interact with the running status of the road network operation. The stochastic user equilibrium (SUE) model considers random distribution and Wardrop equilibrium simultaneously to provide a more realistic theoretical framework.

Travelers make their travel choices in hopes of maximizing utility. Therefore, the SUE problem based on the logit model can be described using the following minimization model [18]:

$$\min \sum_{a\in A}\int_0^{x_a} t_a(w)\,dw + \frac{1}{\theta_2}\sum_{i\in I}\sum_{j\in J}\sum_{r\in R_{ij}} f_r^{ij} l_n f_r^{ij} \tag{3}$$

$$\text{s.t.}\, x_a = \sum_{i\in I}\sum_{j\in J}\sum_{r\in R_{ij}} f_r^{ij}\delta_{ar}^{ij} \quad a \in A$$

$$\sum_{r\in R_{ij}} f_r^{ij} = q_{ij} \quad i \in I, j \in J$$

$$f_r^{ij} \geq 0 \quad i \in I, j \in J, r \in R_{ij}$$

where A denotes a collection of sections, x_a denotes the traffic volume on road a, $t_a(w)$ denotes the travel time function of section a on time w, θ_2 denotes the travel time estimation error of travelers, R_{ij} denotes the path set between the OD pairs (i, j), and f_r^{ij} denotes the traffic volume on path r that is located between the OD pairs (i, j). δ_{ar}^{ij} is a 0-1 variable that equals to 1 when the path r between the OD-pair (i,j) passes through road a. q_{ij} denotes the traffic volume between the OD pairs (i, j).

3.3 Vulnerability analysis indicators of cross-river bridges and tunnels

Large bridges and tunnels are not the most sensitive parts of a network topology. However, given their special geographical features and significant influence, the failure of large bridges and tunnels will substantially damage the entire network operation. Therefore, to understand further the risks being faced by the whole road network, the vulnerability of bridges and tunnels to congestion and fragile topology must be considered.

3.3.1 Congestion vulnerability indicators

Previous studies have mostly used traffic volume as an indicator of traffic network condition. However, this indicator ignores the differences in the capacity of various road sections. This work selects the V/C ratio of roads during peak hours to evaluate the health of the entire network, uses TransCAD to realize the distribution of traffic in the entire network, and evaluates transport network vulnerability from the road congestion perspective.

V/C ratio, or the ratio of traffic volume to road capacity, can directly reflect vulnerability based on the capacity of the traffic congestion facility. V/C ratio has been widely used in transportation system assessments for indirectly inferring the service level of roads [19].

As a dimensionless parameter, the traffic congestion index (TCI) is computed after quantifying the congestion intensity of a single road section, a graded road, or the whole network in a certain region and time [20]. By examining the traffic running state and congestion intensity from a single section to the whole road network, the value of TCI can reflect the operation quality of an entire road network. TCI is a continuous variable with values ranging from 0 to 5, with each value corresponding to a certain operational status and traffic congestion intensity. A greater TCI corresponds to a worse operating status and severe congestion intensity.

Table 1. Relative indexes corresponding to road congestion

TCI_{road}	V/C	Road congestion
1	0–0.25	Very Smooth
2	0.25–0.5	Smooth
3	0.5–0.75	Slightly Congested
4	0.75–1	Moderately Congested
5	>1	Seriously Congested

For easy calculation, this study discretizes TCI and links TCI, congestion, V/C ratio together. The congestion performance (TCP) of the network is then computed as follows:

$$TCP = \sum_{i\in N}\sum_{j\in N} TCI_{ij} \bullet \frac{V_{ij}}{C_{ij}} \tag{4}$$

3.3.2 Vulnerability index for road topology

To achieve a highly comprehensive measure of road network topology, the plurality of the network topology parameters must be considered. Given that the dimensions of each index may vary, all indicators are normalized to the tradeoff weights of each index with to achieve a unified comparison.

$$\begin{aligned}\phi_i &= \frac{S^i_{After\ failure} - S^i_{Before\ failure}}{S^i_{Before\ failure}} \\ &= \frac{S^i_{After\ failure}}{S^i_{Before\ failure}} - 1\end{aligned} \tag{5}$$

where $S^i_{\text{After failure}}$ and $S^i_{\text{Before failure}}$ are the values of index i after and before failure, respectively.

The degree, betweenness, and clustering coefficient of the network, all of which offer the same contribution to vulnerability, reflect the vulnerability of the network topology from different aspects. The road congestion condition and the characteristics of the road network topology must be considered to establish a comprehensive and objective evaluation index for the vulnerability of bridges and tunnels. Therefore, the vulnerability index for network topology (VIT) is expressed as follows:

$$
\begin{aligned}
VIT &= \frac{1}{3}\left(\phi_{\overline{k_l}} + \phi_{\overline{b_l}} + \phi_{\overline{c_l}}\right) \\
&= \frac{1}{3}\left(\phi \frac{1}{N}\sum_{j \in N} a_{ij} + \phi \sum_{k,j \in N} \frac{D_{kj}(i)}{D_{kj}} + \phi \sum_{i=1}^{N}\sum_{j=1}^{N} \frac{2L_{ij}}{N(N-1)}\right)
\end{aligned}
\tag{6}
$$

3.3.3 Overall vulnerability evaluation of bridges and tunnels

$$
\begin{aligned}
w_a &= \lambda_1 \times q_a + \lambda_2 \times C_a \\
&= \lambda_1 \times \phi_{TCP} + \lambda_2 \times \phi_{VIT}
\end{aligned}
\tag{7}
$$

where λ_1, λ_2 are the weights, q_a is the traffic flow indicator of road section a, and C_a is the topology index of the network after normalization.

Formula 7 shows the combined indexes for the operation and topological structure of a road network [21]. Based on this formula, the traffic flow index is used to represent the TCP of the entire network, while average network degree, average clustering coefficient, and average betweenness are selected as indexes to describe the network topology. Following common practice, given the large weight of the operation index of a network, the weight of the network operation index (λ_1) is set to 0.6 while that of the topology structure index (λ_2) is set to 0.4 to calculate vulnerability [22]. All operation indexes are non-dimensional. The fragility of the bridges and tunnels in a road network is calculated by integrating formulas 4, 6, and 7 as follows:

$$
V = 0.6\left(\frac{\sum_{i \in N'}\sum_{j \in N'} TCI_{ij} \bullet \left(\frac{v_{ij}}{c_{ij}}\right)'}{\sum_{i \in N}\sum_{j \in N} TCI_{ij} \bullet \left(\frac{v_{ij}}{c_{ij}}\right)} - 1\right) + 0.4 \times \frac{1}{3}\left\{\left(\frac{\sum_{k,j \in N'} \frac{D_{kj}(i)'}{D_{kj}'}}{\sum_{k,j \in N} \frac{D_{kj}(i)}{D_{kj}}} - 1\right) + \left(\frac{\sum_{i=1}^{N'}\sum_{j=1}^{N'} \frac{2L_{ij}'}{N'(N'-1)}}{\sum_{i=1}^{N}\sum_{j=1}^{N} \frac{2L_{ij}}{N(N-1)}} - 1\right) + \left(\frac{\frac{1}{N'}\sum_{j \in N} a_{ij}'}{\frac{1}{N}\sum_{j \in N} a_{ij}} - 1\right)\right\}
\tag{8}
$$

where V denotes vulnerability, the denominator position indicates the topological structure parameters and the network congestion evaluation coefficient obtained after a multiple re-distribution of the entire road network when a certain bridge-and-tunnel is broken, and the molecular position indicates the original state of the corresponding parameters.

4 Result Analysis and Discussion

4.1 Tools and topology modeling

The original data for the case study are collected from the Shanghai Road Council. These data mainly include the average flow in the main sections of highways and expressways as well as the annual average daily traffic volume of motor vehicles in large bridges and tunnels in the urban areas of Shanghai in 2014. The main sections of highways and expressways refer to influential road sections, such as large intersections. The flow data are counted bi-directionally. The flow unit used in this study is expressed in “passenger car unit.”

The transportation planning module of TransCAD is used for the traffic allocation and congestion analysis. When inputting all road section information and OD trip generation data in TransCAD, this software calculates the V/C ratio of all road sections [23]. The light and dark colors indicate the severity of congestion, with bright red indicating the most severe congestion and dark green indicating the least severe congestion. Gephi is an open-source network analysis and visualization software package written in Java on the NetBeans platform [24]. This software evaluates the network structure using several complex network theory indexes, such as degree, betweenness centrality, and closeness centrality, and by focusing on the nodes in the network. Pajek and Ucinet are useful topology analysis software with similar functions [25].

This study builds an abstract model of the topological structure of the major road network in Shanghai (including 13 large cross-river tunnels and 4 cross-river bridges, which are treated as the key sections of this network). The edges in the network are mostly bidirectional. The intersections are abstracted as nodes, while the segments between the intersections are abstracted as the edges of two nodes. Gephi is then used to establish the topology model of the full road network in Shanghai (Fig. 2) and to evaluate the vulnerability of large bridges and tunnels. To represent different network characteristics, the top five nodes, including those tied to be the fifth, are marked with different colors in the graph.

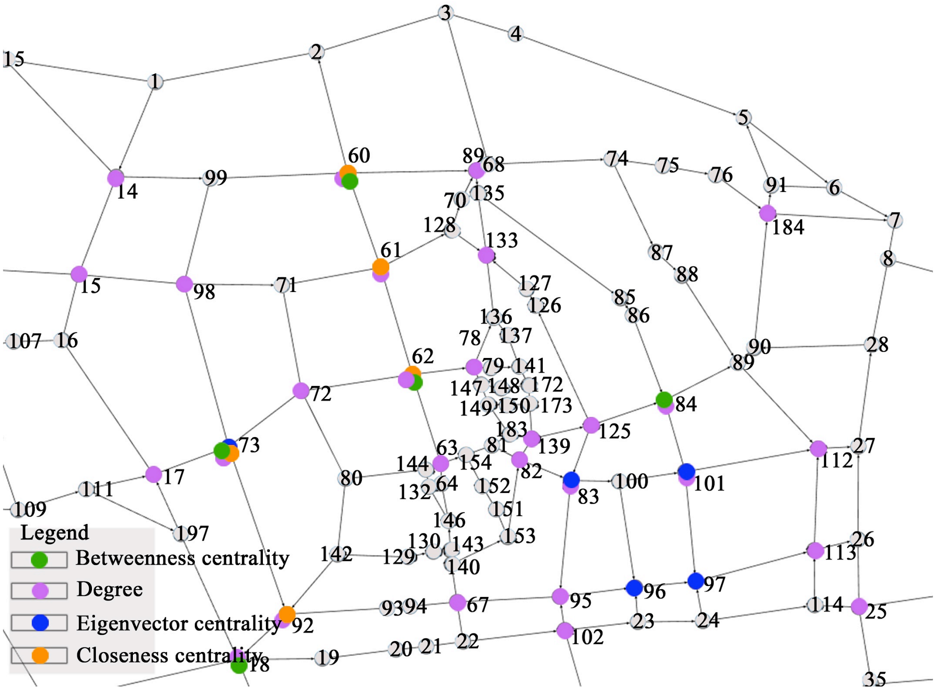

Fig. 2. Topology of the major road network in Shanghai (modeled using Gephi)

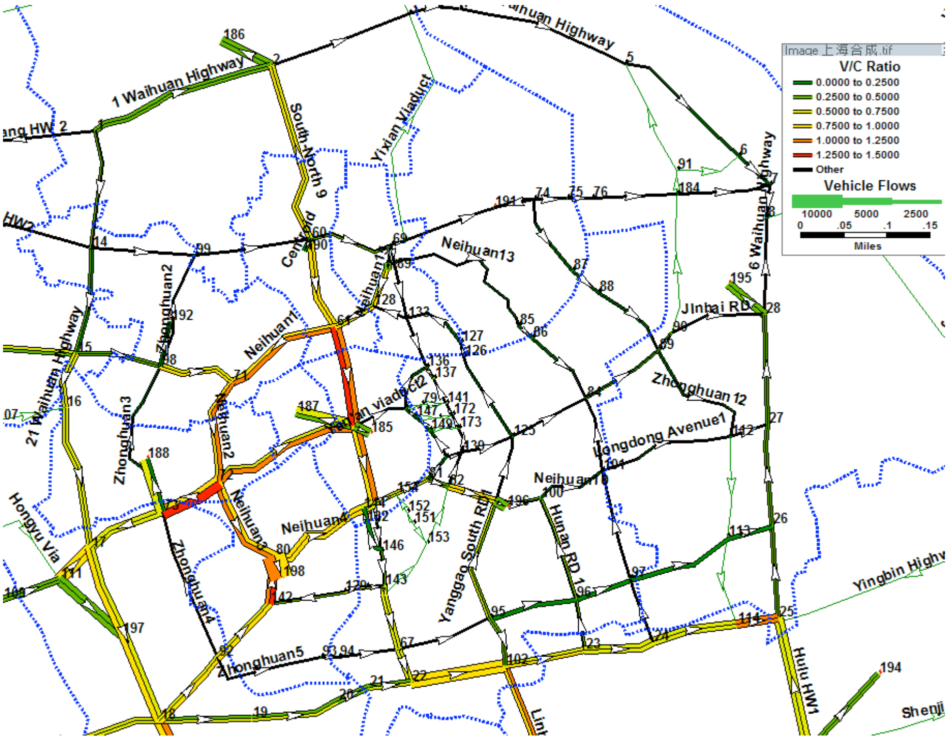

Fig. 3. Original traffic assignment scheme within the Shanghai Outer Ring under a normal condition (modeled using TransCAD)

4.2 Traffic assignment based on network congestion theory

The entire trunk road network of Shanghai, including the key large bridges and tunnels, is modeled using TransCAD. The essential road traffic information collected from the Shanghai Road Council is inputted into this model, the traffic zone is divided based on the Shanghai administrative partition and specific geographical units, and OD-Estimation is conducted according to the traffic flow information of each cross section. Table 2 shows the production attraction (PA) matrix of the entire network, which will be used for the succeeding traffic assignment. Fig. 3 presents the traffic allocation under a normal condition, where different colors indicate the severity of congestion in certain roads.

To study the vulnerability of large-scale bridges and tunnels, each bridge or tunnel was fractured with the connected roads and traffic assignment is subsequently conducted using SUE to reflect the actual situations. According to congestion propagation theory, after each allocation, those road sections with a V/C ratio of less than 1 are deleted, and the allocation process continues until all failures are removed from the road network.

Table 2. PA matrix estimated via OD-estimation

District	1	5	6	7	8	10	14	15
1	0	108.82	135.7	183.73	123.82	134.09	39.14	70.04
5	55	0	369.15	622.82	149.84	169.11	51.05	58.93
6	98.47	2274.45	0	1092.88	98.83	132.8	83.78	88.8
7	113.11	671.56	242.95	0	15.28	55.6	96.4	180.03
8	93.26	209.67	82.57	32.17	0	247.73	83.24	145.57
10	106.5	226.27	123.16	90.4	289.53	0	94.74	155.14
14	12.35	66.96	86.67	118.6	89.31	99.45	0	132.02
15	51.26	82.36	100.29	130.25	99.85	108.88	288.6	0
16	72.75	88.27	104.17	131.16	103.01	111.13	218.82	171.23
18	110.89	102.93	447.67	492.79	851.86	681.75	234.97	232.8
136	55.69	226.53	647.38	768.51	14.08	18.51	30.85	551.95
138	209.23	209.36	15.06	10.49	8.76	13.91	151.22	228.97
139	79.64	209.36	15.06	10.49	8.76	13.91	59.25	182.16
140	1099.84	185.34	23.06	18.08	16.85	22.58	823.16	570.48
141	37.53	188.59	23.69	18.74	17.64	23.42	22	168.74
143	1099.84	197.92	27.75	22.64	21.92	27.96	823.16	541.35
144	465.45	158.95	25.32	20.68	19.83	25.24	341.09	706.51

District	16	18	136	138	139	140	141	143	144
1	78.83	139.7	65.1	148.77	61.95	874.7	41.55	874.7	396.67
5	62.64	86.08	191.74	232.25	232.25	196.24	199.71	183.43	173.27
6	89.35	489.66	600.67	16.68	16.68	24.98	25.48	25.36	27.6
7	167.06	449.48	597.45	9.95	9.95	17.32	17.8	17.93	20.14
8	139.28	902.16	14.82	9.35	9.35	17.76	18.39	18.52	21.02
10	148.22	741.97	19.61	14.98	14.98	23.95	24.6	24.51	26.95
14	117.48	210.42	40.54	108.6	45.24	769.77	26.12	769.77	300.52
15	110.01	268.95	289.66	196.78	119.02	537.56	103.14	656.8	1165.62
16	0	472.29	257.73	248.56	248.56	417.59	711.17	355.46	530.47
18	289.98	0	1176.11	300.52	300.52	951.05	740.76	220.15	2059.8
136	381.13	1165.62	0	40.64	40.64	120.4	4.26	268.88	94.06
138	262.39	383.24	41.61	0	1	572.83	147.17	452.63	110.51
139	262.39	205.89	41.61	1	0	230.21	147.17	96.57	110.51
140	310.43	192.21	135.65	471.07	355.18	0	184.36	1	609.17
141	829.98	860.68	5.1	160.73	160.72	175.2	0	124.11	126.77
143	208.95	349.62	240.7	471.07	162.45	1	159.99	0	609.17
144	389.44	3266.29	82.42	103.23	103.23	378.7	117.95	378.7	0

4.3 Experiments on real-world networks

The final road congestion and topology parameters of each bridge and tunnel are calculated after the iterative traffic assignment using Gephi and TransCAD. Table 3 summarizes the results. The "Total number" column shows the frequency of DTAs.

After experiencing failure, most bridges and tunnels are reallocated for more than 10 times to eliminate the influence of congestion caused by failure. The vulnerability of bridges within the Outer Ring is relatively higher than that of tunnels, which may be attributed to the locations and traffic flows of these structures (Fig. 4). Based on "the greater the V, the greater the vulnerability" principle, Lupu Bridge shows the highest vulnerability of 10.68%, which suggests that the breakage of this bridge will greatly damage the entire road network. Nanpu Bridge and Xupu Bridge have vulnerabilities of 10.62% and 9.07%, respectively. Among the cross-river tunnels, Bund Tunnel, Fuxing East Road Tunnel, Xiangyin Tunnel, and Dapu Tunnel have the highest vulnerabilities, thereby suggesting that a tunnel located within the Inner Ring is more likely to influence the road network performance. Therefore, these tunnels warrant further attention. The number of lanes must be increased if possible, and a timely traffic diversion is necessary.

Table 3. Characteristics of the road network within the Outer Ring after the breaking of a bridge or tunnel

Failure section	Average degree	Network diameter	Average Betweenness	Average clustering coefficient
Original	2.953	15	0.0441	0.019
Lupu Bridge	2.866	15	0.0456	0.031
Nanpu Bridge	2.835	16	0.0484	0.03
Xupu Bridge	2.803	16	0.0444	0.032
Bund Tunnel	2.724	19	0.051	0.035
Yangpu Bridge	2.85	16	0.0464	0.032
Fuxing East Rd. Tunnel	2.756	16	0.0504	0.027

Xiangyin Rd. Tunnel	2.835	16	0.0462	0.032
Dapu Rd. Tunnel	2.819	17	0.047	0.031
Xinjian Rd. Tunnel	2.866	16	0.0458	0.031
Waihuan Tunnel	2.835	17	0.046	0.037
Yan’an East Rd. Tunnel	2.835	15	0.0451	0.031
Xizang South Rd. Tunnel	2.85	16	0.0469	0.031
Dalian Rd. Tunnel	2.873	16	0.0459	0.031
Longyao Rd. Tunnel	2.85	16	0.0474	0.031
Jungong Rd. Tunnel	2.85	16	0.0464	0.032
Shangzhong Rd. Tunnel	2.835	16	0.0484	0.031
Renmin Rd. Tunnel	2.866	16	0.047	0.031

Failure section	**Average path length**	**Congestion index**	**Total number**	**Index of vulnerability(V)**	**Ranking**
Original	6.644	361.82	/	/	/
Lupu Bridge	7.07	420.71	18	10.68%	1
Nanpu Bridge	7.369	412.48	19	10.62%	2
Xupu Bridge	7.452	410.26	15	9.07%	3
Bund Tunnel	7.821	385.9	13	7.41%	4
Yangpu Bridge	7.186	394.41	14	6.72%	5
Fuxing East Rd. Tunnel	7.604	379.92	16	5.94%	6
Xiangyin Rd. Tunnel	7.169	387.83	15	5.47%	7
Dapu Rd. Tunnel	7.263	384.63	13	5.30%	8
Xinjian Rd. Tunnel	7.104	386.71	14	5.17%	9
Waihuan Tunnel	7.23	381.97	12	4.56%	10
Yan’an East Rd. Tunnel	7.103	382.31	11	4.09%	11
Xizang South Rd. Tunnel	7.144	377.3	9	3.95%	12
Dalian Rd. Tunnel	7.064	377.64	8	3.65%	13
Longyao Rd. Tunnel	7.135	373.95	6	3.53%	14
Jungong Rd. Tunnel	7.182	374.13	7	3.35%	15
Shangzhong Rd. Tunnel	7.345	368.03	5	3.20%	16
Renmin Rd. Tunnel	7.158	371.03	5	3.04%	17

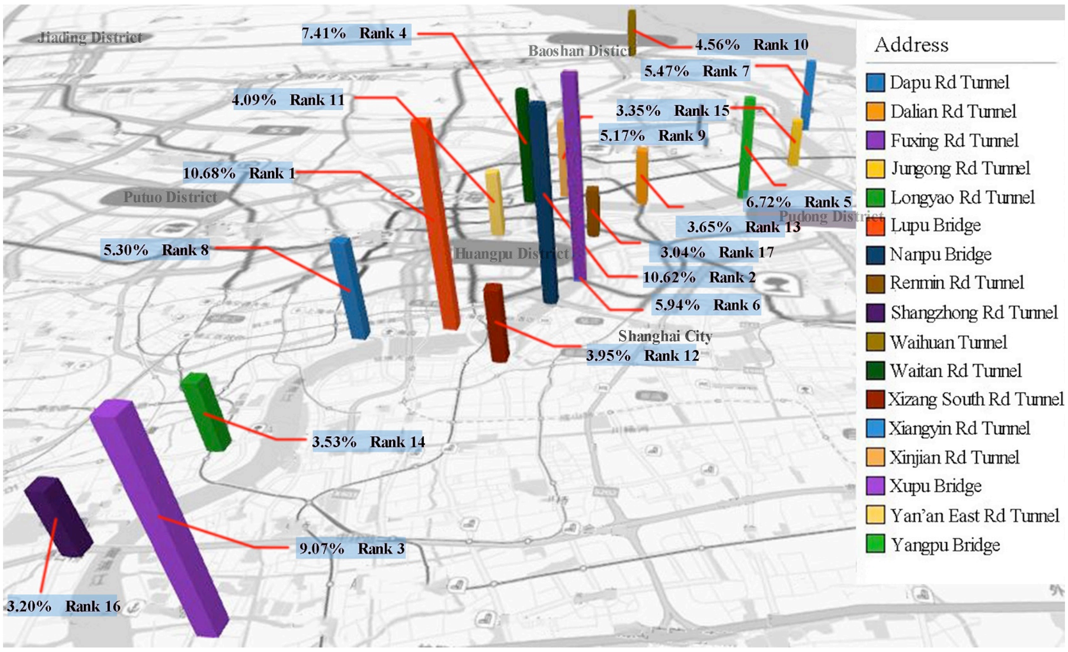

Fig. 4. Comparative list of indicators of the vulnerability of large bridges and tunnels

5. Conclusions

To control the risk of large-scale bridges and tunnels in an urban trunk road network, this study proposed a comprehensive evaluation index based on the traffic propagation model and by considering the present network topology and traffic conditions. A case study was conducted to confirm the feasibility of the proposed method. The vulnerability of the large-scale bridges and tunnels within the Shanghai Outer Ring was then evaluated. The following conclusions are drawn:

(1) The bridges and tunnels within the Shanghai Outer Ring show different degrees of vulnerability, which indicates that the proposed evaluation index can effectively assess the vulnerability of such structures and that both topology and traffic load significantly contribute to the evaluation process.

(2) The large-scale bridges have a relatively higher vulnerability than the tunnels because the former has more lanes, a higher roadway hierarchy, a simpler network topology structure, and a lower speed limit than the latter.

(3) Given their significant connecting functions, those bridges and tunnels with high vulnerability requires more iterations of traffic assignment. These structures must be located in high-density road networks with a significant effect of traffic congestion and an extensive failure response.

However, this work uses the annual average daily traffic and average peak hour traffic flow data provided by the Shanghai Road Council, which fail to reflect dynamic and real-time changes in traffic demand. Therefore, these data are not suitable for studying how network vulnerability changes in space and time. Future studies must investigate how the vulnerable segments in a network can be strengthened to improve the robustness of the entire network, satisfy the demands of motorists, and facilitate urban development.

Acknowledgements

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