Internet of Things Based Solutions for Transport Network Vulnerability Assessment in Intelligent Transportation Systems

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Abstract: Intelligent Transportation System (ITS) is essential for effective identification of vulnerable units in the transport network and its stable operation. Also, it is necessary to establish an urban transport network vulnerability assessment model with solutions based on Internet of Things (IoT). Previous research on vulnerability has no congestion effect on the peak time of urban road network. The cascading failure of links or nodes is presented by IoT monitoring system, which can collect data from a wireless sensor network in the transport environment. The IoT monitoring system collects wireless data via Vehicle-to-Infrastructure (V2I) channels to simulate key segments and their failure probability. Finally, the topological structure vulnerability index and the traffic function vulnerability index of road network are extracted from the vulnerability factors. The two indices are standardized by calculating the relative change rate, and the comprehensive index of the consequence after road network unit is in a failure state. Therefore, by calculating the failure probability of road network unit and comprehensive index of road network unit in failure state, the comprehensive vulnerability of road network can be evaluated by a risk calculation formula. In short, the IoT-based solutions to the new vulnerability assessment can help road network planning and traffic management departments to achieve the ITS goals.

Keywords: Internet of Things, Intelligent Transport Systems, vulnerability assessment, transport network.

1 Introduction

As an important functional component of cities and a carrier of urban traffic activities, the transportation system plays an invaluable role in the movements of urban residents and goods [Liu, Wang and Wang (2018); Liu and Wang (2019); Liu, Tang, Yang et al. (2019)] However, due to the rapid growth of car ownership and the lag in the construction of road

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Received: 12 November 2019; Accepted: 02 August 2020.

facilities in recent years, the urban transport network is in a severe overload state. The deteriorating traffic congestion has brought challenges to the stable operation of urban traffic, which has gradually become a focused issue. The vulnerability of urban transport network has become a hot and difficult problem in the current research on road network. Effective identification of vulnerable road sections of transport networks can help traffic management departments prevent, monitor and manage traffic incidents, and relieve traffic congestion, thus bringing huge social and environmental benefits.

Internet of things (IoT) can be used in the daunting task of quickly identifying vulnerable network sections. Such IoT based approaches have been evolving with the development of sensor and wireless communication technologies. Sensory data is processed in real time by remote handlers, and feedback is given to the clients. Such approaches, which are applicable to the development of increasingly effective ITS solutions by vehicular clients, are studied in this paper [Djajadi and Putra (2014); Zhu, Loo, Chen et al. (2016)]. Sensors are used in ITS to detect events induced by potential accidents, such as sudden braking, blind spot obstacle detection, assistance in lane change events, non-line of sight factors, and uneven road surface [Djajadi and Putra (2014)]. Traffic monitoring sensors also help real-time congestion management. IoT based processing is performed and alerts are conveyed to clients by a Wireless Sensor Network composed of vehicle-borne units, road side device/units and a centralized server. Vehicle-to-vehicle and vehicle-to-infrastructure-based communications are used between the nodes of the Wireless Sensor Network [Rawat, Bista, Yan et al. (2014)].

At present, domestic and foreign scholars have carried out increasing research on the vulnerability of urban road networks. However, there is no uniform definition and evaluation method for road network vulnerability. Road network vulnerability assessment methods are mainly classified int into two categories: vulnerability assessment methods based on road network topology and vulnerability assessment methods based on network performance. The former considers the connectivity performance of road networks, but neglects the probability of road unit failure. Relatively speaking, many evaluation methods are based on the operational performance of road networks. Scholars generally measure vulnerability by using supply-oriented reachability indicators. Scott et al. [Scott, Novak and Aultman (2006)] used transport network performance indicators to study the vulnerability of road networks and identified key locations in the road network. Moreover, they measured the importance of road segments based on NRI indicators. In the case of the known OD distribution matrix of the road network, Jenelius et al. [Jenelius, Petersen and Mattsson (2006)] continuously removed certain road segments. Consequently, some OD pairs in the road network were not connected to each other (the travel cost was infinite), or the total travel cost was greatly increased. The increase in travel cost after the failure of a road unit can indicate the importance of the link and evaluate the vulnerability. Taylor et al. [Taylor, Sekhar and D'Este (2006)] estimated the degraded consequences of the overall and remote road networks in Australia in three different ways: increased generalized cost, relative decline in Hessian accessibility indicators, and increased remoteness. Berdica et al. [Berdica and Mattsson (2010)] conducted a case study of the road network in Stockholm based on the flow-delay function, and analyzed the average travel time, path length, travel speed change and total cost estimate of the road network in 12 scenarios. On the basis of the complex network theory, Ye [Ye (2012)] study the vulnerability of rail transit stations to deliberate attacks from the perspectives of node degree, average path length and clustering coefficient. Zhou et al. [Zhou and Yi (2010)] studied the vulnerability of important network infrastructure based on network graph theory and further identified vulnerable road segments of traffic network systems.

The above research results demonstrate that the assessment of road network vulnerability is closely related to the consequences of road unit failure. The more serious the consequences of road unit failure, the more fragile the road network and the more critical the road unit. However, their research failed to consider traffic congestion and congestion propagation effects in road networks. The evaluation index of the increase in environmental costs brought about by road congestion cannot fully reflect the road network vulnerability. Considering this problem and the research status, this paper first discusses the definition of transport network vulnerability, and cascading failure of links or nodes detected by IoT monitoring system considering the congestion propagation effect. Second, a transport network vulnerability assessment method which comprehensively considers social benefit cost, energy cost and environmental cost with IoT based solutions is proposed. Finally, the vulnerability of road networks is assessed, and key road sections for traffic management departments are identified. The results are expected to provide reference for ITS improvement.

2 Methodology

2.1 Road network vulnerability

There is no authoritative definition of the road network vulnerability accepted in academic circles. Berdical [Berdica (2002)] was the first one who introduced vulnerability and applied it to road networks. He defined vulnerability as time sensibility caused by a sharp decline in service capability of road networks. It can be either spontaneous or passive, artificial or natural. It is also predictable to some extent. Husdal [Husdal (2004)] argued that the vulnerability of road networks is a feature of transportation networks in abnormal operation on specific situations. Taylor et al. [Taylor, Sekhar and D'Este (2006)] held that the concept of vulnerability is closely related to invalid consequence, instead of invalid probability. Based on the accessibility correlated with node vulnerability and node criticality of road networks, the definition is given under two conditions. If few road sections are invalid or the node accessibility of road networks decreases substantially, the net node is believed to be vulnerable. If some invalid road sections can depress the whole network or partial node accessibility, the road section is critical. Jenelius et al. [Jenelius, Petersen and Mattsson (2006)] believed that the road network vulnerability could be measured by the risk theory. In other words, vulnerability was composed of two parts, namely, invalid probability of road unit and consequences of invalidity. In terms of the consequences caused by invalid net units, Yang et al. [Yang and Qian (2018)] gave a definition of the road network vulnerability.

The most vital difference among scholars' definitions of the transport network vulnerability is whether the invalid probability of road unit should be included. However, they reach an agreement that the road network vulnerability is strongly associated with the consequences of invalid road units. The research believes that the index of road unit invalidity probability can hardly be calculated. Therefore, we should not only pay attention to road units with high probability and serious invalid consequences, but also focus on road units with low probability and serious invalid consequence. To this end, the research only takes the consequence caused by invalid road unit into consideration when evaluating the transport network vulnerability

2.2 Cascading failures conditions

In the actual transport network, when a section (or intersection) fails, especially during the morning rush hour, the traffic volume on the road section will exceed the possible capacity, and this section will lose its traffic function. Furthermore, the traffic of the surrounding roads will be affected, and even all local roads in the whole road network will fail. Therefore, it is of great practical significance to consider the impact of congestion propagation in the assessment of road network vulnerability. Based on the user balance model, the cascade failure is considered, and IoT monitoring system is used to simulate the running state of the transport network. To simplify the model, it is believed that there are only two types of road sections and intersections, namely, normal sections and failure sections in the road network. The road section is in a failure state when the distribution flow exceeds its possible capacity. In this case, the impedance function of the road section is changed to infinity, and the OD demand is redistributed. When failure occurs again, the above section impedance function will be changed until all the sections are in the normal state. If the OD pair cannot be disconnected, it will be discarded.

The cascading failure conditions are stated as follows: The urban road network dealing with the topological structure is abstracted into a network diagram with M edges and N nodes, which is represented by G，$[M, N]$. The impedance set of road network can be expressed as:

$$T=(t_1, t_2, t_3, \cdots, t_{m-1}, t_m) \quad (1)$$

Here t_i is the impedance function of each section of the road network, i=1,2,$\cdots, m$.

The impedance function t_i can be represented by a piece wise function, and its calculation formula is:

$$h_a = \begin{cases} h_a^0 \left[1+\mu\left(\frac{q_a}{C_{design}}\right)^\gamma\right], q_i \leq C_{possible} \\ \infty, \qquad q_i > C_{possible} \end{cases} \quad (2)$$

Here h_a^0 is free flow travel time;

q_a is section distribution flow;

C_{design} is design capacity of section I;

$C_{possible}$ is possible capacity of section i;

$C_{possible} = \emptyset C_{design}$, $\emptyset$ is design ratio, and the provisional value is 1.5;

μ, γ are section impedance parameter, taking the recommended value of the United States Federal Highway Administration, $\mu = 0.15$,γ=4;

2.3Transport network vulnerability assessment model

Travel delay, which has a great influence on the service level of road network, is highly sensitive to residents' travel time cost. When vehicles need to detour in the poor condition, the energy cost will increase substantially. Meanwhile, it can also have a strong impact on urban environment, leading to high environment costs. This study assesses the road network vulnerability synthetically from three aspects, namely, travel time cost, energy cost and environment cost caused by travel delay.

2.3.1 Travel time cost

The travel time cost is multiplied by the total time and the unit time spent by travelers on the road network (i.e., total delay).

This study is based on the difference value between the road section time of users' balanced allocation model and the zero-flow allocation, which is defined as road section delay.

$$\mathrm{d}_i = t_i - t_i^o \tag{3}$$

When one section fails and causes the failure of other sections, the total delay of the road network is

$$T_{\text{total}} = \sum_{i \in M} \theta_i q_i d_i \tag{4}$$

Type: when $\mathrm{q_i} \le C_{\text{possible}}$, $\theta_\mathrm{i} = 1$, whereas $\theta_\mathrm{i} = 0$; the other parameters are as mentioned before.

Assume that the per capital unit time cost of a region is p, and the travel time cost is

$$Q_1 = \lambda \mathrm{p} T_{\text{total}} \tag{5}$$

Type: p is per capital unit time cost, and the unit is yuan/(hour person);

λ is the unit traffic volume conversion factor, and the general value is 1.5~2.0.

2.3.2 Energy and environment cost

The energy cost of a road section can be multiplied by the traffic volume of road section $\mathrm{q_i}$, the length of road section L_i, the fuel consumption per hundred kilometers V and the unit price of the road network energy caused by the failure.

$$Q_2 = \sum_{\mathrm{i} \in M} \theta_\mathrm{i} q_i L_i V S_1 - \sum_{i \in M} q_i L_i^o V S_1 \tag{6}$$

Type: L_1^o is the length of road section in the zero-flow allocation;

the unit fuel consumption is L, the temporary value of V is 10.0; the unit of the unit price of fuel consumption S_1 is yuan/L, and its value is 6.0; other parameters are as mentioned earlier.

Transportation influences the ecological environment in the following aspects: the greenhouse effect, air pollution, traffic noise, waste pollution and the impact on the natural environment etc. In view of the feasibility of the assessment, this study only considers item 1 of the environment cost.

The calculation formula for the increase of road network environmental costs caused by the failure of a certain road section is:

$$Q_3 = \sum_{i \in M} \theta_i \, q_i L_i V C S_2 - \sum_{i \in M} q_i \, L_i^0 V C S_2 \tag{7}$$

where: C is the unit fuel consumption of greenhouse gas emissions, and the unit is kg. It can be obtained from relevant research, and the value is set to 2.3 temporarily. S2 is the carbon trading price, the unit is yuan/t. The weighted average of carbon trading in China is taken, and its temporary value is 45. Other parameters are as mentioned above.

When no cascade failure occurs, the total cost formula of road network is:

$$Q = \sum_{i \in M}(\lambda p q_i t_i^0 + q_i L_i^0 V S_1 + q_i L_i^0 V C S_2) \tag{8}$$

where: t_i^0 is zero traffic flow assignment time, and other parameters are as mentioned above.

Considering the unit of the indicator is yuan, the above formula is dimensionless and the road network vulnerability assessment model is obtained:

$$k = \frac{Q_1 + Q_2 + Q_3}{Q} \tag{9}$$

2.3.3 Evaluation step

For the urban road network map G [M, N], if a certain section is removed, this section is assumed to be sufficiently critical. Consequently, the traffic of the adjacent road section will exceed its possible traffic capacity, and cascade failure will occur. In this case, the invalid road section will be removed, and the traffic of the road network will be redistributed until the traffic of all road sections does not exceed its possible capacity. Taking the invalid road section as an example, the failure of a node can be regarded as the failure of all connected links. The steps are as follows.

1) Initialize the road network G [M, N]. Based on the user equilibrium assignment method, the EMME software is used for zero-stream allocation, and Q is calculated based on the travel time and the shortest path distance.

2) Set the impedance of the section to be evaluated to ∞. EMME software is used to allocate traffic distribution. If the traffic volume is beyond the possible traffic capacity, the impedance of this section is changed to ∞.

3) Continue the next OD allocation until the traffic of all sections of the road network does not exceed its possible capacity. If the connection cannot be reached between the OD pair, the OD distribution is changed to 0, that is, this OD pair is discarded.

4) Q1, Q2 and Q3 are calculated according to the newly generated road network, and the vulnerability k of the road is evaluated.

3 Experimental results and discussions

3.1 Transport network model construction

In this paper, the road network diagram is assumed to calculate the vulnerability of the transport network. Fig. 1. shows the example of transport network topology, which has 176 segments and 115 nodes.

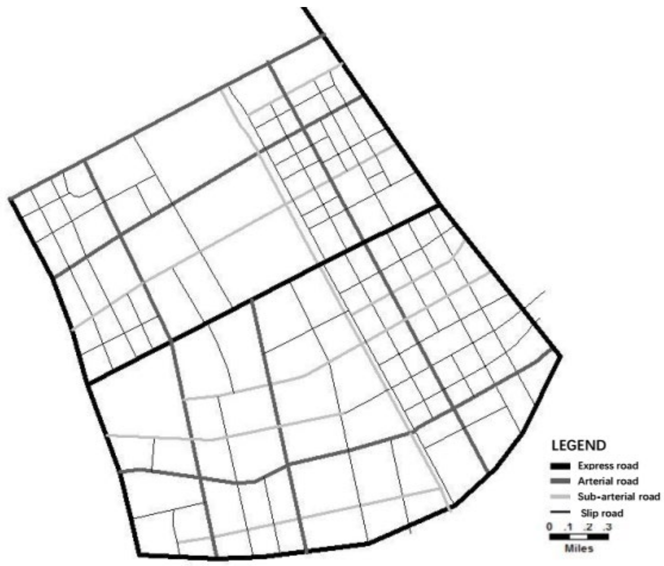

Figure 1: Example diagram of road network topology

By establishing the road network model using the original method, the geographical distribution characteristics of the road network can be completely preserved, so that the road network structure is clear and easy to analyse. This provides a prerequisite for screening key units and calculating failure probability of the key units. In the road network, the basic properties of each section are shown in Tab. 1.

Table 1: Road network attribute table

Road grade	Type	Traffic capacity for single line (pcu/h)	Design speed (km/h)
Express road	K1	2000	100
	K2	1750	80
	K3	1400	60
Arterial road	Z1	1500	70
	Z2	1400	60
	Z3	1200	50
Sub-arterial road	C1	1400	60
	C2	1000	40
	C3	1000	40
Slip road	B1	750	40
	B2	750	30
	B3	600	30

3.2 Key segments selection

The key road segments of above transport network can be detected by IoT monitoring system which collects wireless data by using vehicle-to-infrastructure-based channels. Vehicle-to-infrastructure communication is used to effectively manage traffic and improve the overall driving experience of motorists. The roadside units controlled by the centralized server with data processing capability manage client requests and collect data from road side sensors and on-board sensors placed. The roadside unit provides location-based alerts, weather related precautions, recommended speed for road sections, enforcement of speed limits and implementing variable road signs [Cao, Zheng, Wang et al. (2018); Wang, Ju, Kim et al. (2019); Wang, Gao, Liu et al. (2019); Wang, Gao, Zhou et al. (2020); Wang, Gu, Liu et al. (2019)]. Fig. 2. shows the Wireless Sensor Network describing the vehicle-to-infrastructure communication channel.

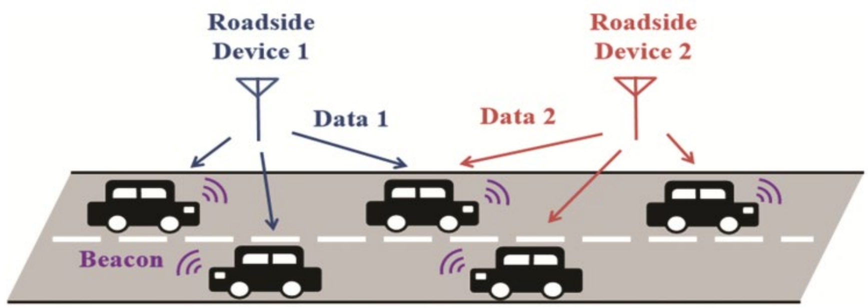

Figure 2: Wireless Sensor Network containing the vehicle-to-infrastructure communication channel

Figure 3: Selected key segments by IoT-based solutions

The key road elements and their failure probability can be monitored by IoT monitoring system (Fig. 3 and Tab. 2). The results show the positive correlation between the importance of the key elements of the road network and the road grade. That is, the higher the road grade, the greater the importance value of the road network unit. In other words, main roads and secondary trunk roads bear most of the traffic in some areas of the city, which plays an important role in the distribution of urban traffic. The comprehensive vulnerability of the road network will be calculated according to the selected key elements of the road network.

Table 2: Key segments and their failure probability

Serial number	Segments number	Road grade	Importance degree l	Failure probability
1	6	Arterial road	3817.6	0.406
2	9	Arterial road	3755.8	0.348
3	4	Arterial road	3680.6	0.239
4	17	Express road	3446.4	0.236
5	132	Arterial road	3411.0	0.219
6	89	Sub-arterial road	3201.6	0.244
7	41	Arterial road	3141.0	0.241
8	22	Arterial road	3020.6	0.236
9	69	Arterial road	2911.0	0.236
10	1	Express road	2795.4	0.184
11	13	Arterial road	2793.5	0.174
12	34	Arterial road	2750.4	0.089
13	60	Express road	2636.0	0.088
14	77	Sub-arterial road	2483.8	0.352
15	56	Arterial road	2471.2	0.342
16	167	Arterial road	2454.4	0.296
17	10	Sub-arterial road	2347.8	0.219
18	123	Sub-arterial road	2171.8	0.108
19	50	Arterial road	2167.0	0.210
20	166	Arterial road	2083.6	0.104
21	102	Sub-arterial road	2072.2	0.101
22	84	Sub-arterial road	2071.6	0.091
23	11	Sub-arterial road	2021.2	0.090
24	63	Sub-arterial road	2008.1	0.083
25	24	Arterial road	1944.4	0.082
26	99	Sub-arterial road	1937.8	0.130
27	153	Arterial road	1880.8	0.115

28	19	Sub-arterial road	1877.8	0.109
29	174	Slip road	1869.5	0.125
30	59	Arterial road	1810.7	0.103
31	88	Arterial road	1807.4	0.183
32	133	Sub-arterial road	1805.6	0.072
33	18	Slip road	1785.2	0.062
34	147	Express road	1772.8	0.055
35	91	Slip road	1761.2	0.054

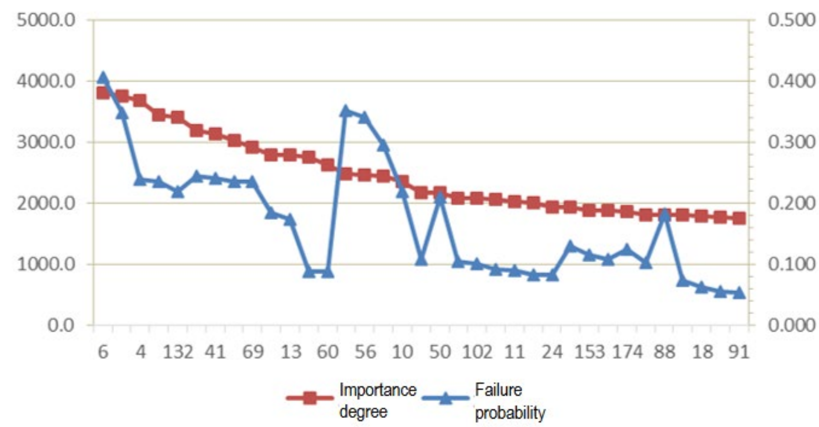

Figure 4: Failure probability of road segments

It can be known from the above Fig. 4 that the probability of failure tends to decrease as the road segment becomes less important. However, there is no strict monotonically decreasing function relationship between the failure probability and the importance of road segment. The road segments with more importance are not necessarily more likely to fail than those with less importance.

3.3 Calculation of key segment failure consequences

In this paper, the de-edge method (removing the node means the resistance of directly connected road sections is changed to ∞) is used to calculate the failure consequences of key segments in the road network. The congestion of the urban road network is simulated according to the above-mentioned cascading failure assessment method.

Removing the road segment 6 is taken as an example to analyze the road network topology and traffic volume distribution results. As shown in Fig. 5, after the road segment 6 is removed, the flow between the OD pairs through this road segment is transferred to other roads, causing the successive failure of three surrounding roads, which simulates the traffic flow state accurately.

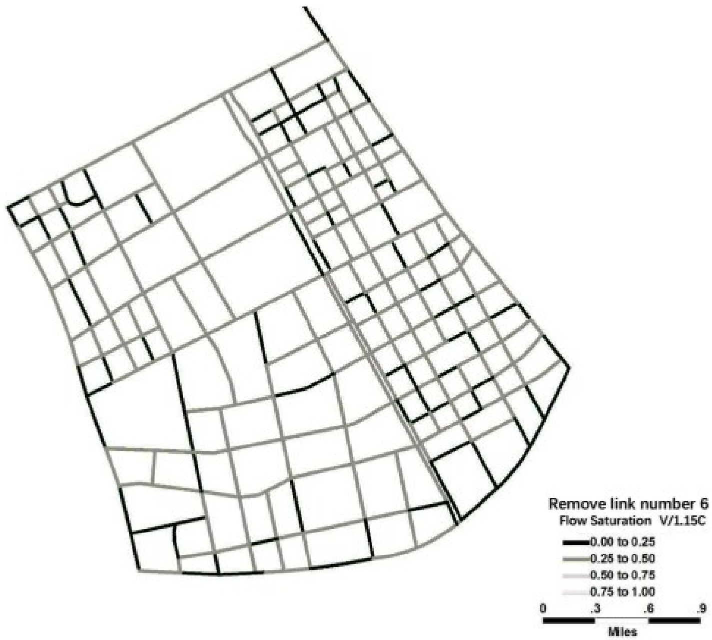

Figure 5: Flow Saturation after the road segment 6 is removed

Table 3: Key segments and their failure probability

Serial number	Segments number	Network efficiency (%)	Travel efficiency (%)	N-Q index (%)	Generalized travel cost (%)
1	6	9.95	3.61	3.64	7.95
2	9	10.81	3.45	3.70	8.22
3	4	17.89	4.31	3.70	8.89
4	17	16.66	4.80	6.95	8.19
5	132	13.03	4.12	1.90	8.39
6	89	3.44	1.70	1.96	6.76
7	41	4.01	3.22	1.45	6.88
8	22	4.07	2.62	1.63	6.62
9	69	4.19	3.63	3.02	8.26
10	1	6.49	2.52	1.44	5.52
11	13	4.66	1.98	2.53	8.64
12	34	9.61	2.69	3.24	8.94
13	60	3.96	2.77	1.76	7.51
14	77	4.63	0.44	2.73	7.76
15	56	5.79	0.50	1.87	7.83
16	167	6.23	0.87	1.68	5.03

17	10	5.65	1.51	2.43	4.70
18	123	5.94	0.06	1.88	4.85
19	50	6.23	6.36	2.13	4.78
20	166	5.89	-1.19	1.90	7.92
21	102	6.46	3.38	2.00	5.51
22	84	6.46	-0.54	4.64	5.21
23	11	5.24	-2.29	1.94	4.08
24	63	7.12	0.38	1.33	4.82
25	24	5.46	1.05	0.89	4.89
26	99	5.69	1.44	0.90	2.09
27	153	9.86	3.64	0.91	5.00
28	19	5.34	0.76	0.91	5.68
29	174	5.75	-0.11	0.87	5.38
30	59	5.59	3.56	0.86	4.25
31	88	5.78	5.91	1.15	4.99
32	133	5.12	-3.84	0.91	8.15
33	18	6.09	-0.71	0.98	5.35
34	147	5.74	-2.72	1.13	5.02
35	91	5.11	0.69	0.59	5.17

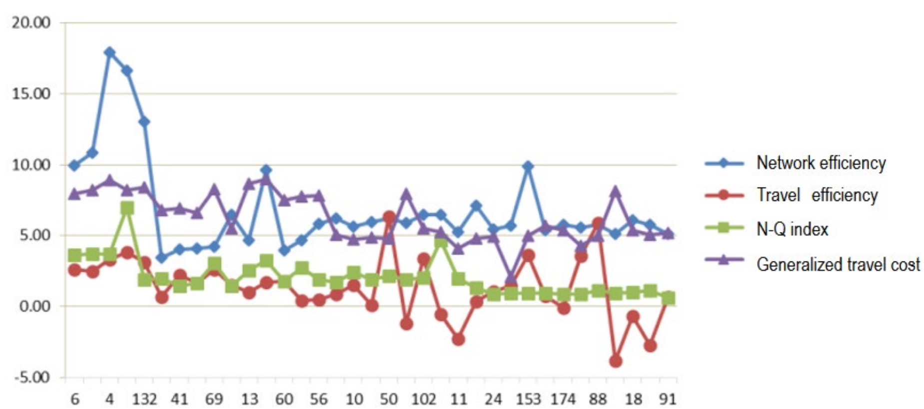

Figure 6: Four failure consequence indexes

The impedance value of the key road segment is set to ∞ (equivalent to the removal of the key road segment) using the de-edge method, and the traffic flow of the road network is distributed. Considering the cascading failure effect of the road network, the physical topology of the road network is changed substantially. According to Tab. 3. and Fig. 6, the network operation efficiency and the generalized travel cost index are larger than those of the other two indicators. The average change ranges are 6.86% and 6.26%, respectively, while the change magnitude of travel efficiency and N-Q index is 1.36% and 2.04%. Meanwhile, the order of the failure consequence indicators is also inconsistent. Therefore, judging the failure consequences of the road network based on a single indicator is not comprehensive.

3.4 Key segment failure consequence calculation

The weight values of different failure consequence indicators are calculated according to the analytic hierarchy process. Different levels of judgment matrix are constructed using the 9-level scale method and the expert scoring method. The calculation results and the consistency test results are shown in the following table.

Table 4: Judgment matrix of A

A	S1	S2	w_A
S1	1	1/2	0.3333
S2	2	1	0.6667
Consistency test	λmax=2, CI=0, CR=0<0.1		

Table 5: Judgment matrix of S_2

S2	F2	F3	F4	w_{S2}
F2	1	3	1	0.4434
F3	1/3	1	1/2	0.1692
F4	1	2	1	0.3874
Consistency test	λmax=3.0183, CI=0, CR=0.0176<0.1			

From the above calculation results, the weight values of each evaluation index are listed in the following table.

Table 6: The weight values of each evaluation index

	t1	t 2	t 3	t 4
weight value	0.3333	0.2956	0.1128	0.2582

According to the above selected key sections, the failure probability of the nodes and the failure consequence indicators, the composite vulnerability values are calculated as shown in the following table.

Table 7: Composite vulnerability values of the selected segments

Serial number	Segments number	Failure Probability (%)	Comprehensive index (%)	Comprehensive vulnerability/10^{-4}
1	6	0.406	6.551	2.662
2	9	0.348	6.867	2.388
3	4	0.239	9.654	2.302
4	17	0.236	9.575	2.262
5	132	0.219	7.646	1.673
6	89	0.244	3.320	0.809
7	41	0.241	3.933	0.946
8	22	0.236	3.729	0.881
9	69	0.236	4.647	1.094
10	1	0.184	4.200	0.772
11	13	0.174	4.359	0.758
12	34	0.089	6.376	0.565
13	60	0.088	3.981	0.351
14	77	0.352	3.985	1.403
15	56	0.342	4.310	1.472
16	167	0.296	3.822	1.129
17	10	0.219	3.817	0.836
18	123	0.108	3.462	0.375
19	50	0.210	5.431	1.140
20	166	0.104	3.871	0.403
21	102	0.101	4.801	0.484
22	84	0.091	3.862	0.352
23	11	0.090	2.342	0.211
24	63	0.083	3.880	0.321
25	24	0.082	3.493	0.286
26	99	0.130	2.963	0.386
27	153	0.115	5.756	0.663
28	19	0.109	3.574	0.389
29	174	0.125	3.371	0.422
30	59	0.103	4.110	0.424
31	88	0.183	5.092	0.932
32	133	0.072	2.778	0.201
33	18	0.062	3.312	0.205
34	147	0.055	2.533	0.139
35	91	0.054	3.309	0.177

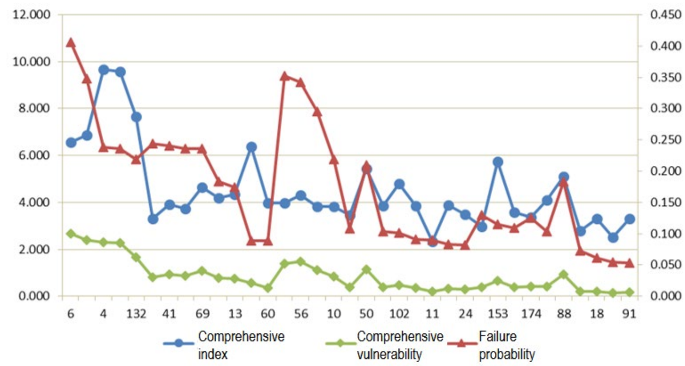

Figure 7: Comparison chart of the 3 vulnerability values

As shown in Fig. 7, there is no specific functional relationship between the failure consequence and the failure probability, and the failure consequence does not increase with the increase of the failure. In other words, the road segment with large failure probability may have low failure effect. For example, the secondary road numbered 77 has a failure probability of 35.2%, and its comprehensive failure consequence index is 3.985%, which is smaller than the average failure consequence index of all road sections of 4.535%. Another example is the main road with the number 34, which has a combined failure index of 6.376% and a failure probability of only 8.9%. To some extent, this reflects the narrowness of defining the road network vulnerability only from the failure consequences. It can also be seen from the above figure that when the importance of the road section decreases, the composite fragility value of the road network shows an overall downward trend. However, there is no strict monotonically decreasing function relationship. When the probability of failure is large, the road network is more vulnerable.

Based on the above analysis, the road network vulnerability with two levels of failure probability and failure consequence can better identify the accuracy of the weak link of the road network. The failure comprehensive result index can make up for the failure consequence of a single failure consequence indicator. The inadequacies, so that the accuracy and practicability of the evaluation results are better, can help the planning department and traffic management department to scientifically prevent and manage the weaknesses in the road network.

4 Conclusions

This paper put forward the cascade aging condition based on the impact of traffic congestion propagation. Considering the influence of traffic congestion, this study proposed the cascading failure of road network units by IoT monitoring system which can collect data from a wireless sensor network in the transport environment. Meanwhile, on the basis of previous research on the vulnerability of road network, a vulnerability evaluation model based on trip delay was established, which is based on trip time cost, energy cost and environmental cost. The vulnerability was measured by the failure of the network unit in the road network. The evaluation method can better simulate the real situation of urban road network traffic congestion. The travel cost and environmental cost of travelers are fully taken into account from the perspective of travel cost in the broad sense, which greatly improves the accuracy of vulnerability assessment and helps the government planning department and the traffic management department to effectively identify vulnerable units in the road network. Effective measures will be taken to reduce the vulnerability of vulnerable units in road network planning and traffic management. From the evaluation results of examples, the proposed evaluation method can identify the road network units whose failure will cause serious damage. By analyzing the relationship between vulnerability and OD demand and road capacity, the results show that the increase of OD demand will intensify the vulnerability of road network units, while improving road capacity will reduce the vulnerability of road network units.

Acknowledgments: This work was supported by the Shanghai philosophy and social science planning project (2017ECK004). The author of the grant is Weiwei Liu, and the URL of the sponsor's website is "http://www.sh-popss.gov.cn/". We would also like to thank Jieshuang Dong and Weigang Jing for their contributions to this article. Prof. Gwang-jun Kim is the corresponding author.

Funding Statement: The author(s) received no specific funding for this study.

Conflicts of Interest: We declare that we have no conflicts of interest to report regarding the present study.

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