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Research Article

Road Network Vulnerability Analysis Based on Improved Ant Colony Algorithm

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We present an improved ant colony algorithm-based approach to assess the vulnerability of a road network and identify the critical infrastructures. This approach improves computational efficiency and allows for its applications in large-scale road networks. This research involves defining the vulnerability conception, modeling the traffic utility index and the vulnerability of the road network, and identifying the critical infrastructures of the road network. We apply the approach to a simple test road network and a real road network to verify the methodology. The results show that vulnerability is directly related to traffic demand and increases significantly when the demand approaches capacity. The proposed approach reduces the computational burden and may be applied in large-scale road network analysis. It can be used as a decision-supporting tool for identifying critical infrastructures in transportation planning and management.

1. Introduction

As a primary infrastructure of the modern city, a robust transportation network is one of the preconditions of a flourishing economy and a high standard of living-class life. However, there are many events emergencies, such as traffic congestion, traffic accidents, road maintenance, bad weather, and terrorist activities, that can have a tremendous impact on the operational performance of the road network and can make some road segments impassible. These events will cause the traffic flow to be redistributed, which could cause congestion in other road segments to occur. In these cases, the vulnerabilities of the road network reveal themselves constantly [1–3]. It is uneconomical to solve these problems merely by constructing the road infrastructure to increase the capacity of the entire road network [4]. Instead, we should explore the characteristics and laws of the exposed problems, identify the vulnerable segments of the road network, and understand the operational performance variation of these segments in adverse conditions and the consequences are produced. Thus it is necessary and important to study the vulnerability of road networks.

1.1. State of the Art. The concept of vulnerability was first proposed by Timmerman in 1981 [5]. The research was focused in the field of geology. Since the 1990s, a multitude researches on vulnerability have emerged, where vulnerability was used in the field of disaster management, public safety, economics, sustainability, science, and so on. Vulnerability may be the most fundamental and essential problem in our daily life especially in emergency evacuation situations [6, 7]. Berdica defined the conception as the characteristic of the degenerating transportation system's accessibility in different cases and the characteristic that can be susceptible to unusual events [8]. Taylor and D'Este believed the vulnerability, reliability, and risk of the transportation network were the closely related concepts [9]. Murray-Tuite and Mahmassani established a bilevel programming model to excavate the vulnerable segments of the transportation network, in which traffic managers supervise the traffic to achieve optimization in the underlying programming model while the damage factors, such as traffic accidents, and bad weather, maximize the degradation of the transportation network [10]. Husdal considered the vulnerability of the transportation network as a prime, and the impact of vulnerability and reliability should be included in the cost-benefit analysis [11]. Chen et al. tried to connect vulnerability with probability and the consequence of risk [12]. Bell et al. analyzed vulnerability based on the probability of capacity degradation with game theory [13]. Erath et al. did research on the vulnerability of the transportation network in Switzerland, where vulnerability was defined as the product of the probability of capacity degradation and the combination of the direct and indirect results caused by interruption [14].

In short, the most current road network vulnerability researches focus on the consequence of some road network units' failure. Those researches can be separated into two kinds: one believes that vulnerability is only related to the consequence that some units' fail, while it has nothing to do with the probability of the failure; another believes that vulnerability is closely related to the risk, in other words, the product of the probability of the failure and its consequences. The shortcoming of this focus is that it cannot reflect the intrinsic quality of vulnerability, that is to say the sensitivity of the traffic state to the disturbance. In this paper, we will define the vulnerability based on the easiness of disruption to traffic operational performance.

Several studies have engaged vulnerability analysis for large-scale road networks (see, e.g., [2, 15–17]). A measure of road network vulnerability involves solving the traffic assignment problem repeatedly. As a result, computational burden has long been recognized as one of the most restrictive issues in this analysis. Therefore, many other algorithms are also proposed to conduct traffic assignment, such as the Frank-Wolfe algorithm, neural network algorithm, genetic algorithm, and fuzzy algorithm. However, it is impossible for these algorithms to simulate the process of how vehicles select routes, veritably and dynamically. A difference between the traffic assignment outcomes and reality also existents. To address this problem, the improved ant colony algorithm is introduced to conduct traffic assignment. The ant colony algorithm not only owns an ability of stochastic searching optimization, but also has the attribute of adaptive distributed computation. Moreover, its optimal path searching procedure is very similar to the process of how vehicles select routes; consequently, we will use the ant colony algorithm to solve the traffic assignment problem.

1.2. The Objectives and Organization of the Study. The assessment of road network vulnerability is a new hot spot and difficult in present research. Discriminating and supervising the vulnerability of the transportation network effectively is a significant study to help improve resilience in emergency events. Therefore, developing methods for the evaluation of road network vulnerability would be interesting and meaningful. This will constitute a more useful performance measure of a road network. This measure will be used for robust network planning and design. The objective of the proposed study is to develop methods for evaluating and determining the vulnerable road segments in a road network.

This paper is organized as follows. The next section presents the definition of road network vulnerability. Then, Section 3 builds up the vulnerability model. In Section 4, the improved ant colony algorithm is developed to solve the traffic assignment problem for vulnerability analysis. Section 5 provides two examples to demonstrate the applications of the proposed model and methodology. In Section 6, conclusions are presented.

2. Definition

Vulnerability was defined by many scholars from different angles. Timmerman took the vulnerability as a kind of sensitivity of road network system to disasters. The sensitivity depends on the flexibility of the system, which indicates the ability of the system to recover from the disaster [5]. Jenelius and Mattsson divided the concept of vulnerability into two kinds; one is the probability of dangerous incidents, while the other is the result of the events that occurred at a specified place [18]. Husdal defined the road network vulnerability as the function of the degradation of the road network in some certain circumstances [11].

The implication of vulnerability is that some part or portion of a system disturbed by internal and/or external causes will break down. The result is that some portion of the system, perhaps the whole system, would be affected directly or indirectly, and eventually the whole system will be destroyed. This characteristic is called the vulnerability of a complicated system. This paper defines vulnerability as the sensitivity of some part of the system disturbed by internal and/or external causes leading to a change in other parts of the system or the system in its entirety, which reflects the adaptation to the traffic environment. From another viewpoint, vulnerability shows the extent and ease of interference to the traffic condition.

2.1. Definition Demarcation

2.1.1. The Origins of Vulnerability. Vulnerability is caused by internal and external factors and is the result of interconnections between both causes under specified space-time conditions. The internal causes relate to the reasonability of the road network structure, while the external causes relate to the disturbances of the external environment such as traffic accidents, road maintenance, bad weather, terrorist activities, and many other emergency events.

2.1.2. Evaluation Criterion. According to the definition proposed in this paper, the core of the evaluation criterion is the degree of sensitivity to disturbances of the traffic conditions, that is to say the extent and ease of interference to the traffic conditions. Although most definitions focus on the result produced by a disturbance, we will pay more attention to the degree of sensitivity in this paper.

3. Establishment of the Vulnerability Model

3.1. Utility Index of Road Network Unit. Once a road network unit loses or decreases its efficacy, the traffic on it will be redistributed to other alternative routes [10]. This traffic redistribution will induce the loss or degradation of other units' efficacy, triggering the dominoes phenomenon. In other words, this will cause other units' or even the whole traffic system's operational performance to decrease rapidly. In this way, the vulnerability is spread throughout the system. The consequence of this phenomenon is the travel time of the units or even the whole transportation system would vastly increase to a point where on some roads paralysis could occur which would make some specific routes impassible. For this purpose, a utility index is introduced to measure the influence of the degraded unit on all of the other road network units [10]. Consider

$$e_a = \frac{\Delta C_a}{C_a} \cdot \frac{c_a^0}{c_a}, \tag{1}$$

where C_a is the capacity of the road network unit a, pcu/h; ΔC_a is the surplus capacity of the road network unit a, $\Delta C_a = C_a - x_a$, pcu/h; x_a is the traffic volume on the road network unit a, pcu/h; c_a^0 is the travel cost of the road network unit a in free flow; c_a is the travel cost of the road network unit a; and e_a is the utility index of the road network unit a. While e_a approaches zero traffic conditions are worsening. When the traffic volume x_a is equal to the capacity C_a, $\Delta C_a = C_a - x_a \to 0$, the utility index is zero. On the contrary, this value tends to one when the traffic conditions approach the free-flow condition.

Travel time is the dominant element of travel cost. Most other elements of travel cost are closely related to travel time. Thus, in this paper, travel time is selected to measure travel cost, and the following BPR (Bureau of Public Roads) function is used to calculate it:

$$T_a = t_a \left[1 + \beta\left(\frac{x_a}{C_a}\right)^n\right], \tag{2}$$

where T_a is the travel time of road segment a, s; t_a is the free-flow travel time on road segment a, s; x_a and C_a are, respectively, the traffic volume and capacity on road segment a, pcu/h; and β and n are parameters with recommended values of $\beta = 0.15$, $n = 4$.

3.2. Vulnerability Model. The utility index was introduced to characterize traffic conditions. Then the vulnerability was defined as the ratio of the variation of the utility index to the initial utility index to reflect the sensitivity of traffic conditions to disturbance. The formulation can be written as

$$V_a = \frac{e_a' - e_a}{e_a}, \tag{3}$$

where e_a' is the initial utility index of the road network unit a; e_a is the utility index of the disturbed road network unit a; and V_a is the vulnerability index of the road network unit a. It is obvious that a smaller V_a results in a lower vulnerability of this road unit or higher resilience. Otherwise when V_a is higher, this road unit is more vulnerable and is more likely to be disturbed.

4. Traffic Assignment Based on Improved Ant Colony Algorithm

A measure of road network vulnerability involves solving traffic assignment problems repeatedly. Traffic will be redistributed in the road network when the network is disturbed under conditions such as adverse weather, traffic accidents, and the failure of one road segment or a collection of several road segments. As a result, computational burden has long been recognized as one of the most restrictive issues in this type of analysis. It is well known that ants are good at finding food and that they leave behind a pheromone trail that other ants can follow to reach the food. The ant colony algorithm simulates the way that the ant releases pheromone on the route and that its behavior is influenced by other ants. The ant colony algorithm has been successfully used to improve traffic assignment by many scholars [19–23]. Concrete steps to determine the optimal path with the primary ant colony algorithm are as follows.

(1) Parameter initialization: set the iteration number as $n = 0$; $\tau_{ij}(t)$ is the pheromone density on connection nodes and roads at t, $\tau_{ij}(0) = C$ (constant). η_{ij} is the heuristic information of the road segment (i, j), in this problem; $\eta_{ij} = 1/d_{ij}$, where d_{ij} is the length of the road segment (i, j).

(2) Dropping m ants on original point and putting it in present disaggregation, for ant k, there is a possibility of $p_{ij}^k(t)$ to move to next vertex j and then put vertex j in present disaggregation as well. Consider

$$p_{ij}^k = \begin{cases} \dfrac{\left[\tau_{ij}(t)\right]^\alpha \left[\eta_{ij}\right]^\gamma}{\sum_{j\in \text{allowed}} \left[\tau_{ij}(t)\right]^\alpha \left[\eta_{ij}\right]^\gamma}, & j \in \text{allowed} \\ 0, & \text{otherwise}, \end{cases} \tag{4}$$

where α is the relative importance of the pheromone ($\alpha \geq 0$); γ is the relative importance of the heuristic information ($\gamma \geq 0$).

(3) Calculating the objective function of the minimum travel cost of every ant and recording the present optimal solution.

(4) Modifying the pheromone density on every road segment according to the pheromone renewal equation. The pheromone renewal equation of road segment (i, j) at t is as follows:

$$\tau_{ij} = \rho\tau_{ij}(t-1) + \sum_k \Delta\tau_{ij}^k(t-1), \tag{5}$$

where ρ is the retention rate of the pheromone on road segment (i, j); $\Delta\tau_{ij}^k(t-1)$ is the pheromone quantity that ant k left on segment (i, j) per unit length at $(t - 1)$. The ant colony algorithm can be divided into three forms: ant-cycle model, ant-density model, and ant-quantity model. Since the pheromone density released by ants is independent with the length d_{ij} of road segment (i, j) in ant-cycle model and ant-density model, in this paper, we adopt the following ant-quantity model to calculate the pheromone density released by ants on road segment (i, j). Consider

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} \dfrac{Q}{d_{ij}}, & (i, j) \text{ is on the optimal route} \\ 0, & \text{else}, \end{cases} \tag{6}$$

where Q is a constant of the pheromone density released by ants.

(5) Set $\Delta\tau_{ij}^{k}(t) = 0$, $n = n + 1$ for every road segment (i, j) in the road network.

(6) If n is less than the number of predetermined iterations, then return to step (2).

(7) Output the optimal path.

4.1. Improved Ant Colony Algorithm. Traffic volume on road segments will increase with each execution of traffic assignment. At the same time, the impedance of road segment (i, j) will be changed as well. As more traffic would be distributed to the shorter road segments, which may lead to an increase in travel time on these road segments. On the other hand, some road segments are longer, but due to low traffic volumes, the travel time might be less than that of shorter routes. Therefore, it is necessary to modify the primary ant colony algorithm in order to accommodate this case.

The modification of ant colony algorithm focuses on changing the $\Delta\tau_{ij}^{k}(t)$ in the pheromone renewal equation; the concrete steps remain unchanged. In route choice, travelers would pay more attention to travel time, but not the distance. So we should replace distance d_{ij} with travel time T_{ij}, which could be calculated with the BPR function. Then $\Delta\tau_{ij}^{k}(t)$ may be expressed as

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} \dfrac{Q}{T_{ij}}, & (i, j) \text{ is on the optimal route} \\ 0, & \text{else}. \end{cases} \tag{7}$$

Bringing the BPR function into (7), then

$$\Delta\tau_{ij}^{k}(t) = \begin{cases} \dfrac{Q}{t_{ij}^{0}\left(1 + \beta\left(q_{ij}/C_{ij}\right)^{n}\right)}, & (i, j) \text{ is on the optimal route} \\ 0, & \text{else}. \end{cases} \tag{8}$$

In the ant colony algorithm, the heuristic information $\eta_{ij} = 1/d_{ij}$ on the road segment (i, j) only reflects the distance between the present nodes and connected points without considering the distance between the next node and destination point. Therefore a new parameter d_{jE} is introduced which is the optimal route distance between node j and destination point (food source) E. Then, set $\eta_{ij} = 1/(d_{ij} + d_{jE})$ which will allow the optimal solution to be determined. This new heuristic information η_{ij} could strengthen the search directionality. Note that the distance used in the improved ant colony algorithm should be replaced by travel time, so $\eta_{ij} = 1/(d_{ij} + d_{jE})$ should be expressed as $\eta_{ij} = 1/(T_{ij} + T_{jE})$.

The optimal solution can be figured out from the fact that the new heuristic information η_{ij} could strengthen the directionality in searching.

4.2. Traffic Assignment Model Based on the Improved Ant Colony Algorithm. The estimated minimum travel cost is assumed as the route choice criterion for travelers. Due to the complexity of the practical road network and the randomness of the traffic condition, the route choice is always random. As a result, the route choice behavior can be described by SUE (stochastic user equilibrium). The improved ant colony algorithm is used to solve the traffic assignment problem. The concrete steps for the incremental traffic assignment algorithm are as follows.

Step 0. Initialization: divide the OD traffic volume into N shares, according to a certain distribution rate λ. Each share is $q_{rs}^{n} = q_{rs} \cdot \lambda$. At the same time, set $n = 1$ and $q_{ij}^{0} = 0$, $\forall(i, j)$, while every parameter in the primary ant colony algorithm should be initialized.

Step 1. Use the primary ant colony algorithm to identify the shortest path in every OD pair. Then load the traffic volume q_{rs}^{n} on the shortest path to conduct the first traffic assignment, and set $n = 2$.

Step 2. Renew the travel time of every road segment, $t_{ij}^{n} = t_{ij}(q_{ij}^{n-1})$, $\forall(i, j)$, then identify the shortest path in every OD pair with the improved ant colony algorithm.

Step 3. Assign the traffic volume q_{rs}^{n} to every road segment in the road network and the additional traffic volume e_{ij}^{n} can be calculated.

Step 4. Renew the traffic volume by letting $q_{ij}^{n} = q_{ij}^{n-1} + e_{ij}^{n}$, $\forall(i, j)$.

Step 5. Make a judgment about whether this calculation ended or not, according to the number of iterations. If $n = N$, then q_{ij}^{n} is the result; otherwise, $n < N$ and set $n = n+1$; return to Step 2.

5. Numerical Examples

5.1. Test Road Network. A simple test road network is used to demonstrate the performance of the proposed model and methodology. This numerical network consists of four nodes and five arcs, as shown in Figure 1, where traffic demand

Table 1: Property data of arcs.

Arc number	1	2	3	4	5
t_a (min)	1	2.0	1.1	1.2	1.1
C_a (veh/min)	17	13	13	19	12

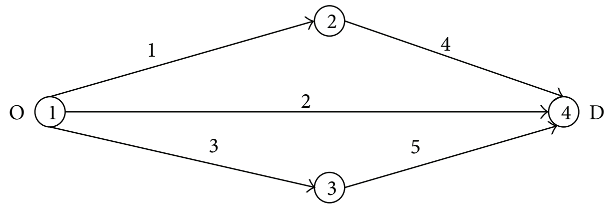

Figure 1: Test road network.

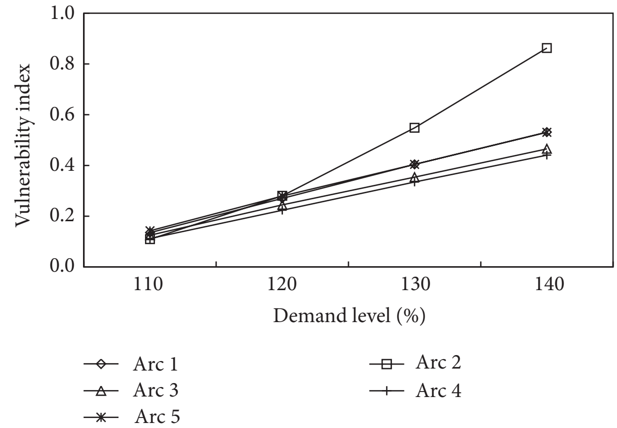

Figure 2: Curves of arcs vulnerability at different traffic demand.

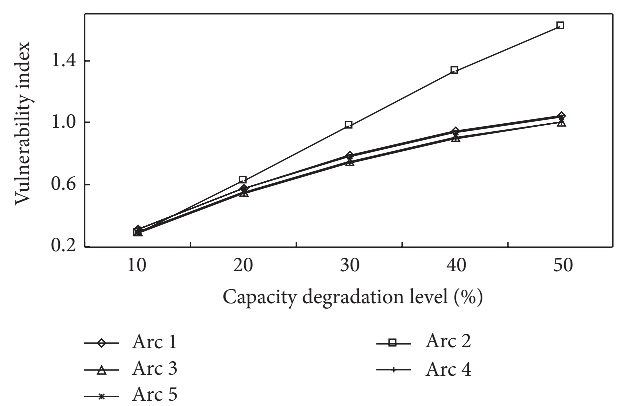

Figure 3: Vulnerability of arcs at different capacity degradation.

among OD(1,4) is 24 veh/min. $\beta = 0.15$ and $n = 4$ in the BPR. The free-flow travel time and capacity are shown in Table 1.

To illustrate the effect of traffic demand on vulnerability, we assume that the capacity of every arc is constant and traffic demand increases by 10%, 20%, 30%, and 40%, respectively. Traffic assignment was performed for the above scenarios with the improved ant colony algorithm. Firstly, according to formula (2), we can get the travel cost of all road segments with the results of traffic assignment. Then according to formula (1), the utility index may be calculated with the results of traffic assignment and travel cost. Finally, according to formula (3), we can get the vulnerability with the results of traffic utility index. The results are shown in Table 2 and Figure 2. The results show that (1) with increasing traffic demand, the vulnerability also increases and (2) due to the differences of every arc, the vulnerability is different for each of them under the same traffic demand disturbance. For example, the curve of arc 4 has the lowest vulnerability index and smallest slope, which means that both the vulnerability and the sensitivity to traffic demand increases are the lowest, followed by arc 3, arc 1, and arc 5. The curve of arc 2 has the highest vulnerability index and the steepest slope. This means that the vulnerability and the sensitivity to traffic demand increases in arc 2 are the highest. This is closely related to the fact that the capacity of arc 2 is the smallest. In general, a greater road capacity contributes to a stronger ability to handle growing traffic demand disturbances. In other words, a greater road capacity tends to an arc that is less sensitive to increasing traffic demand and has smaller vulnerability. The opposite is also true, which implies that a smaller capacity yields higher vulnerability.

To illustrate the effect of an arc's capacity degradation on vulnerability, assuming that the traffic demand of every arc is constant and capacity decreases by 10%, 20%, 30%, 40%, and 50%, respectively, the vulnerability of all arcs was studied. Traffic assignment was done for the above scenarios with the improved ant colony algorithm. The utility index and vulnerability, as shown in Table 3 and Figure 3, were calculated with the results of the traffic assignment. The results show that (1), with the degradation of capacity, arcs show increases in vulnerability at different levels and that (2) the vulnerability between every arc should be similar to the result of former traffic capacity analyses.

To study the influence of some arcs' failures on the others, we assume that arcs 3 and 5 are disconnected and all other conditions remain unchanged. Then the traffic volume on arc 3 and arc 5 would be redistributed to arcs 1, 2, and 4; therefore, the traffic volume would increase. As a result, the utility decreases to −0.003, −0.244, and 0.090, and the vulnerability increases to 1.011, 4.843, and 0.755, respectively. From the results it can be seen that the vulnerability of arc 2 is the highest. This is consistent with all former analyses. Arc 2 should, therefore, be considered priority in road reconstruction and maintenance.

In terms of efficiency, the improved ant colony algorithm adopted in this paper reduces the calculation time to 4/5 of the time required by the traditional traffic assignment method.

5.2. Medium-Sized Road Network. To demonstrate the applicability of the proposed method, a medium-sized road network, as shown in Figure 4, was used as a test. The road network consists of 106 directed arcs, 37 nodes, and 921 OD movements. The arc travel time model is set to $T_a = t_a[1 + 0.15(x_a/C_a)^4]$.

Table 2: Utility and vulnerability of arcs at different traffic demands.

Demand level		Arc 1	Arc 2	Arc 3	Arc 4	Arc 5
100%	x_a	7.152	12.072	4.776	7.152	4.776
	c_a	1.004	2.208	1.103	1.203	1.104
	e_a	0.577	0.065	0.631	0.622	0.600
110%	x_a	8.448	12.170	5.782	8.448	5.782
	c_a	1.009	2.215	1.106	1.207	1.108
	e_a	0.499	0.058	0.552	0.552	0.514
	V_a	0.135	0.109	0.125	0.112	0.143
120%	x_a	9.734	12.326	6.739	9.734	6.739
	c_a	1.015	2.226	1.111	1.212	1.115
	e_a	0.421	0.047	0.477	0.483	0.432
	V_a	0.270	0.280	0.244	0.223	0.279
130%	x_a	11.014	12.574	7.613	11.014	7.613
	c_a	1.025	2.245	1.118	1.219	1.125
	e_a	0.344	0.029	0.408	0.414	0.358
	V_a	0.404	0.548	0.354	0.335	0.404
140%	x_a	12.230	12.869	8.501	12.230	8.501
	c_a	1.038	2.269	1.128	1.229	1.139
	e_a	0.270	0.009	0.337	0.348	0.282
	V_a	0.531	0.862	0.465	0.440	0.530

Table 3: Utility and vulnerability of arcs at different capacity degradation.

Capacity degradation level		Arc 1	Arc 2	Arc 3	Arc 4	Arc 5
Normal	x_a	7.152	12.072	4.776	7.152	4.776
	c_a	1.004	2.208	1.103	1.203	1.104
	e_a	0.577	0.065	0.631	0.622	0.600
10%	x_a	7.752	10.968	5.280	7.752	5.280
	c_a	1.009	2.216	1.106	1.207	1.109
	e_a	0.396	0.046	0.442	0.440	0.411
	V_a	0.313	0.293	0.300	0.292	0.315
20%	x_a	8.328	9.960	5.712	8.328	5.712
	c_a	1.020	2.236	1.114	1.215	1.119
	e_a	0.243	0.024	0.285	0.286	0.255
	V_a	0.578	0.625	0.549	0.540	0.575
30%	x_a	8.832	9.072	6.096	8.832	6.096
	c_a	1.043	2.277	1.131	1.233	1.143
	e_a	0.121	0.001	0.157	0.160	0.129
	V_a	0.790	0.980	0.751	0.742	0.784
40%	x_a	9.264	8.352	6.384	9.264	6.384
	c_a	1.095	2.368	1.169	1.273	1.195
	e_a	0.030	−0.022	0.061	0.064	0.038
	V_a	0.948	1.333	0.903	0.898	0.937
50%	x_a	9.552	7.848	6.600	9.552	6.600
	c_a	1.223	2.595	1.264	1.372	1.326
	e_a	−0.025	−0.040	−0.003	−0.001	−0.021
	V_a	1.044	1.618	1.005	1.002	1.035

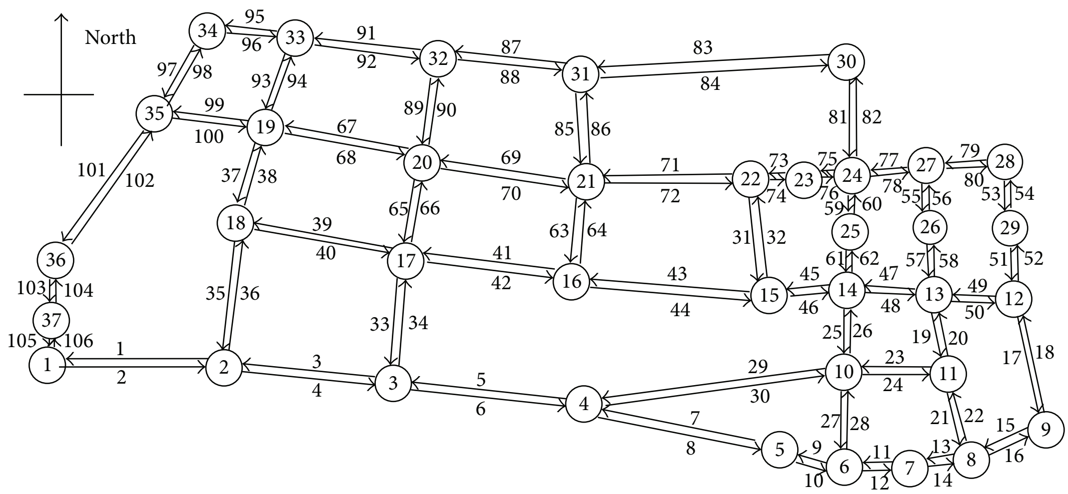

Figure 4: Partial road network.

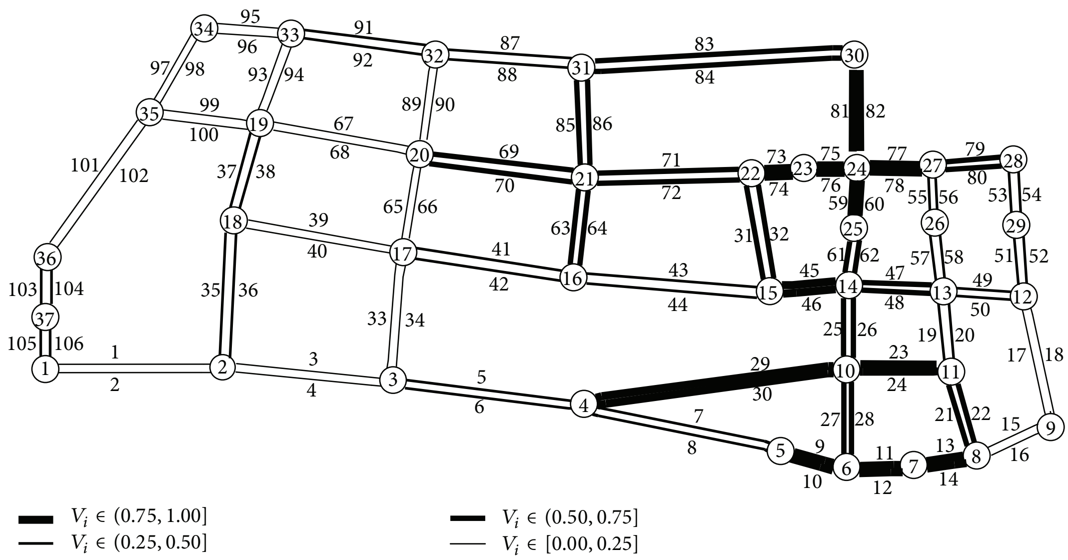

Figure 5: Vulnerability of arcs.

To illustrate the effect of different levels of capacity degradation and traffic demand increases on vulnerability, traffic assignment is conducted for the different scenarios with the improved ant colony algorithm. The utility index and vulnerability are calculated with the traffic assignment results. The vulnerability under capacity degradation and traffic demand increases has similar results; for the case with 20% capacity degradation the arcs' vulnerabilities are shown in Figure 5. It demonstrates that the analyzed road network has obvious vulnerable units. For instance, the vulnerability of arcs 9, 10, 11, 12, 13, 14, 23, 24, 29, 30, 45, 46, 59, 60, 73, 74, 75, 76, 81, and 82 is more than 0.75. It is consistent with the fact that the above arcs are bottlenecks in the road network, and congestion often occurs in the above arcs especially in the morning peak hours. Even with small fluctuations, the vulnerability will be magnified and the traffic conditions will get worse.

6. Conclusions

(1) With the increase of traffic demand or capacity degradation, the vulnerability would be magnified. When the traffic demand is especially close to capacity, the road segment will be very sensitive to an increase of traffic demand, and the vulnerability will be higher.

(2) There are two reasons why the vulnerability is magnified. One is the contradiction between traffic demand and the capacity supply or the imbalance of the traffic demand and capacity. There are two situations of this imbalance where either the traffic demand has increased too fast to be endured by normal capacity or the capacity has decreased so that it cannot meet the requirement of normal traffic demand. These two situations are both common in traffic congestion. The second reason vulnerability is magnified results from

traffic accidents, road maintenance, traffic control, or other reasons. Some units among the whole transportation network may even be suspended; therefore, the traffic demand would be redistributed to other routes and the traffic volume of these alternative routes would increase and possibly cause a vulnerability increase to emerge.

(3) The vulnerability of a road network unit is principally relevant to its ability to deal with disturbances. In general, a larger capacity is less sensitive to an increase of traffic demand and decrease of capacity, while the ability to deal with disturbances is greater and the vulnerability is lower. On the contrary, smaller traffic capacities are weaker dealing with disturbances.

(4) The proposed method based on the improved ant colony algorithm can be used as an effective tool to solve traffic assignments in vulnerability analysis. The vulnerability evaluation may provide the theoretical foundation for road network reforming, planning, and designing.

(5) This paper focused on the vulnerability of individual road network units, although knowing the vulnerability of the whole road network is important for the traffic manager. Future efforts will be put on determining the road network's vulnerability as a whole.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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References

[1] D. Watling and N. C. Balijepalli, "A method to assess demand growth vulnerability of travel times on road network links," *Transportation Research Part A: Policy and Practice*, vol. 46, no. 5, pp. 772–789, 2012.

[2] P. Luathep, A. Sumalee, H. W. Ho, and F. Kurauchi, "Large-scale road network vulnerability analysis: a sensitivity analysis based approach," *Transportation*, vol. 38, no. 5, pp. 799–817, 2011.

[3] B. F. Santos, A. P. Antunes, and E. J. Miller, "Interurban road network planning model with accessibility and robustness objectives," *Transportation Planning and Technology*, vol. 33, no. 3, pp. 297–313, 2010.

[4] K. Berdica, "An introduction to road vulnerability: what has been done, is done and should be done," *Transport Policy*, vol. 9, no. 2, pp. 117–127, 2002.

[5] P. Timmerman, "Vulnerability, resilience and the collapse of society," *Environmental Monograph—Institute for Environmental Studies, University of Toronto*, vol. 1, 1981.

[6] S. D. Clark and D. P. Watling, "Sensitivity analysis of the probit-based stochastic user equilibrium assignment model," *Transportation Research Part B: Methodological*, vol. 36, no. 7, pp. 617–635, 2002.

[7] R. D. Connors, A. Sumalee, and D. P. Watling, "Sensitivity analysis of the variable demand probit stochastic user equilibrium with multiple user-classes," *Transportation Research Part B: Methodological*, vol. 41, no. 6, pp. 593–615, 2007.

[8] E. S. Barber, *Calculation of Maximum Pavement Temperature from Weather Reports*, National Academy of Sciences National Research Council, Washington, DC, USA, 1995.

[9] M. A. P. Taylor and G. M. D'Este, *Transport Network Vulnerability: A Method for Diagnosis of Critical Locations in Trans-Port Infrastructure Systems, Critical Infrastructure: Reliability and Vulnerability*, edited by: A. T. Murray and T. H. Grubesic, Springer, New York, NY, USA, 2007.

[10] P. M. Murray-Tuite and H. S. Mahmassani, "Methodology for determining vulnerable links in a transportation network," *Transportation Research Record*, no. 1882, pp. 88–96, 2004.

[11] J. Husdal, "Reliability and vulnerability versus cost and benefits," in *Proceedings of the 2nd International Symposium on Transportation Network Reliability*, Queenstown, New Zealand, 2004.

[12] A. Chen, C. Yang, S. Kongsomsaksakul, and M. Lee, "Network-based acessibility measures for vulnerability analysis of degradable transportation networks," *Networks and Spatial Economics*, vol. 7, no. 3, pp. 241–256, 2007.

[13] M. G. H. Bell, U. Kanturska, J.-D. Schmöcker, and A. Fonzone, "Attacker-defender models and road network vulnerability," *Philosophical Transactions of the Royal Society of London. Series A. Mathematical, Physical and Engineering Sciences*, vol. 366, no. 1872, pp. 1893–1906, 2008.

[14] A. Erath, J. Birdsall, and K. W. Axhausen, "Vulnerability assessment of the Swiss road network," in *Proceedings of the 88th Transportation Research Board Annual Meeting*, Washington, DC, USA, 2009.

[15] K. Berdica and L. Mattsson, "Vulnerability: a model-based case study of the road network in Stockholm," in *Critical Infrastructure: Reliability and Vulnerability*, A. T. Murray and T. H. Grubesic, Eds., pp. 81–106, Springer, Heidelberg, Germany, 2007.

[16] E. Jenelius, "Network structure and travel patterns: explaining the geographical disparities of road network vulnerability," *Journal of Transport Geography*, vol. 17, no. 3, pp. 234–244, 2009.

[17] M. A. P. Taylor, "Critical transport infrastructure in urban areas: impacts of traffic incidents assessed using accessibility-based network vulnerability analysis," *Growth and Change*, vol. 39, no. 4, pp. 593–616, 2008.

[18] E. Jenelius and L.-G. Mattsson, "Developing a methodology for road network vulnerability analysis," in *Nectar Cluster Seminar*, Molde University College, Molde, Norway, May 2006.

[19] Z. Su, P. Wen, and R. Zhai, "Research on traffic assignment model based on multi-objective and ant colony algorithm," in *Proceedings of the 8th International Conference of Chinese Logistics and Transportation Professionals—Logistics: The Emerging Frontiers of Transportation and Development in China*, pp. 2926–2931, August 2008.

[20] R. Qiao, X. Zhu, and Y. Liu, "An improved ant colony algorithm for UE traffic assignment problem," in *Proceedings of the 7th*

International Conference of Chinese Transportation Professionals Congress 2007: Plan, Build, and Manage Transportation Infrastructures in China, pp. 542–548, May 2007.

[21] L. D'Acierno, B. Montella, and F. De Lucia, "A stochastic traffic assignment algorithm based on ant colony optimization," in *Proceedings of the 5th International Workshop Ant Colony Optimization and Swarm Intelligence (ANTS '06)*, pp. 25–36, 2006.

[22] L. D'Acierno, M. Gallo, and B. Montella, "Ant Colony Optimisation approaches for the transportation assignment problem," in *Proceedings of the 16th International Conference on Urban Transport and the Environment, Urban Transport*, pp. 37–48, May 2010.

[23] Z. Zhou, G. Ren, F. Yi, and C. Xu, "Optimal routing search method based on improved ant colony algorithm," in *Proceedings of the 2nd International Conference on Transportation Engineering (ICTE '09)*, pp. 1530–1535, July 2009.