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Research Article

Resilience of Urban Road Network to Malignant Traffic Accidents

Yiding Lu,[1] **Zhan Zhang**,[2] **Xinyi Fang**,[1] **Linjie Gao**,[1] **and Linjun Lu**[1]

[1]*Department of Traffic Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China*
[2]*School of Design, Shanghai Jiao Tong University, Shanghai 200240, China*

Correspondence should be addressed to Zhan Zhang; zhanzhang@sjtu.edu.cn

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Malignant traffic accidents are typical devastating events suffered by the urban road network. They cause severe functional loss when loading on the urban road network is high, exerting a significant impact on the operation of the city. The resilience of a road network refers to its ability to maintain a certain level of capacity and service when disturbed by external factors and to recover after a disturbance event, which is a crucial factor in the construction of transportation infrastructure systems. A comprehensive understanding of the adverse effects of malignant traffic accidents on the urban road network is imperative, and resilience is a concept employed to systematically explain this. This study investigates the impact of malignant traffic accidents on the resilience of the urban road network. A simulation is carried out focusing on an ideal urban road network, describing the temporal and spatial distribution of the average speed of road sections in the network. Inspired by the simulation experiment results, the ideal resilience curve is summarized, and the theory of resilience concept portrayal is innovatively developed into "6R" (redundancy, reduction, robustness, recovery, reinforcement, and rapidity). Combining the topological and "6R" resilience attributes of the urban road network, the urban road network resilience evaluation system is constructed, which yields an all-round and full-process evaluation for the urban road network with malignant traffic accidents. Results show that under malignant traffic accidents, the resilience of high-class surface roads, such as primary roads, is the poorest, suggesting that more attention and resources must be devoted to high-class surface roads. This study on the urban road network deepens the understanding and portrayal of its resilience and proposes an evaluation method to analyze its performance under disruption events.

1. Introduction

The continuous development of the urban road network has significantly boosted the construction of transportation infrastructure systems, and at the same time, it has inevitably caused numerous traffic problems. The occurrence of unanticipated disruptive events often has serious consequences [1, 2]. Malignant traffic accidents are typical devastating events, which often cause loss of life and property. Although malignant traffic accidents are not very common, once they occur, they provoke considerable adverse impacts. For example, on January 16, 2014, a large traffic accident occurred on China's Beijing-Shenyang Expressway. More than one hundred vehicles collided, and a flour truck exploded into flames, killing two people, injuring five others, and damaging forty-five vehicles. With the growing development of the urban road network, the impact of malignant traffic accidents on it is attracting increasing interest.

Resilience originally refers to the ability of a material to absorb energy during plastic deformation and rupture. Holling [3] introduced the concept of resilience to the field of ecology in 1973. Since, the concept has been gradually extended to various fields, such as socio-economy and engineering [4, 5]. Hansen and Sutter's [6] study of the effects of road closures caused by the Loma Prieta earthquake initiated the research field of road traffic system resilience. In recent years in the field of transportation, resilience has become a hot research topic. The urban road network forms the basic network for urban transportation activities. The resilience of the urban road network refers to the ability to maintain a certain level of capacity and service when disturbed by external factors and to recover after a disturbance event. Research on the resilience of the urban road network helps us better manage the operation of urban road traffic.

The urban road network with better resilience has a stronger ability to resist the adverse impacts of malignant traffic accidents and quickly recover from them. Improving the ability to respond to and handle malignant traffic accidents enhances the resilience of the urban road network, and in turn, developing the portrayal of the resilience concept helps us better understand the mechanism of malignant traffic accidents. The impact of malignant traffic accidents on the resilience of the urban road network is a problem that involves both temporal and spatial dimensions. Its propagation mechanism is difficult to capture, and the spatiotemporal mechanism is difficult to portray, which reveals the lack of research about the impact of malignant traffic accidents on the urban road network. Furthermore, it is difficult to make an all-round and full-process evaluation of the resilience of the urban road network with malignant traffic accidents. Therefore, the study of the impact of malignant traffic accidents on the resilience of the urban road network is extremely necessary.

This study combines traffic simulation technology with the study of the resilience of the urban road network. Focusing on an ideal urban road network, the entire process is simulated from before the occurrence of malignant traffic accidents to after the implemented recovery measures, obtaining temporal and spatial distributions of the average speed of road sections in the network. Inspired by the results of simulation experiments, the ideal resilience curve is obtained, and the theory of resilience concept portrayal is innovatively developed. Based on the topological and resilience attributes of the urban road network, the resilience evaluation system is established, yielding a full-process evaluation of the resilience under malignant traffic accidents. From the perspective of the government, based on the spreading characteristics of the congestion phenomenon, corresponding policy suggestions are made to improve the resilience of the urban road network when facing malignant traffic accidents.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and highlights the identified research gaps. The parameters and flow of the simulation experiments are described in detail in Section 3. Section 4 shows and analyses the results of the simulation experiment and proposes the ideal resilience curve. Section 5 innovatively discusses the resilience evaluation system and provides corresponding policy suggestions for the urban road network from the perspective of the government. Finally, conclusions are presented in Section 6. The structure of the paper is shown in Figure 1.

2. Literature Review

2.1. Impact of Emergency Events on Traffic Networks. Research on the impact of emergencies on urban road networks have attracted the interest and attention of researchers in the past decade. The day-long traffic jams in New York City after 9/11 caused massive disruptions in the city's transportation network, demonstrating its vulnerabilities and their negative consequences and prompting research on this topic.

Berdica [7] was the first to define the degree of impact on the traffic network of such sudden events that lead to a significant reduction in the network service capacity as the vulnerability of the traffic network. Vulnerability focuses on the weaknesses of the network and the consequences of failure. According to [8–10], the vulnerability of urban road networks could be viewed in a similar manner to measure the risk. The concept of vulnerability can be separated into two parts, using both the product of the probability of an event occurring and the outcome. Murray et al. [11] classified the current methods for assessing disturbance events on road networks into four broad categories: the scenario-specific, attack strategy-specific, simulation, and mathematical model.

The scenario-specific assessment method examines the impact on the road network in the case of a specific edge or node disruption and evaluates its possible consequences [12–15]. The attack strategy-specific assessment method involves the study of the sensitivity of different network structures to external stimuli and attacks. The method sets up an attack strategy and then applies statistical methods to study the vulnerability of the infrastructure network [16, 17]. The simulation assessment method analyses the factors affecting network performance using simulation software to simulate macro or micro road networks, such that the consequences of the impact can be evaluated [7, 18]. The mathematical model assessment method focuses on the methodology and model and uses mathematical expressions or models to determine the consequences of network unit failure [19].

The above four methods do not conflict with each other and can be used to study the impact of unexpected events on the road network, identify critical points and key locations, and assess the vulnerability of the network. In practice, several of these methods can be used in combination.

The emergency event that is the focus of current studies is a broad and abstract concept. It has not been refined to specific events. Furthermore, because the consequences of malignant traffic accidents are generally measured in terms of human or property damage, there are little data about the impact of malignant traffic accidents on the urban road network. Moreover, few studies have been conducted on the impact of malignant traffic accidents on the urban road network.

2.2. Resilience of Road Traffic System. The resilience of the road traffic system refers to the ability of the road traffic system to maintain a certain capacity and level of service when disturbed by external factors and to recover after a disturbance event. Research related to road traffic system resilience began in 1990 with Hansen and Sutter's [6] study of the effects of road closures caused by the Loma Prieta earthquake. This study inaugurated the field of road traffic system resilience research. Research on traffic system resilience has gone through three main stages: the stage of conceptual framework research, the stage of metrics, and the stage of quantitative evaluation.

In the stage of conceptual framework research, Bruneau and Chang [20] proposed the classical conceptual

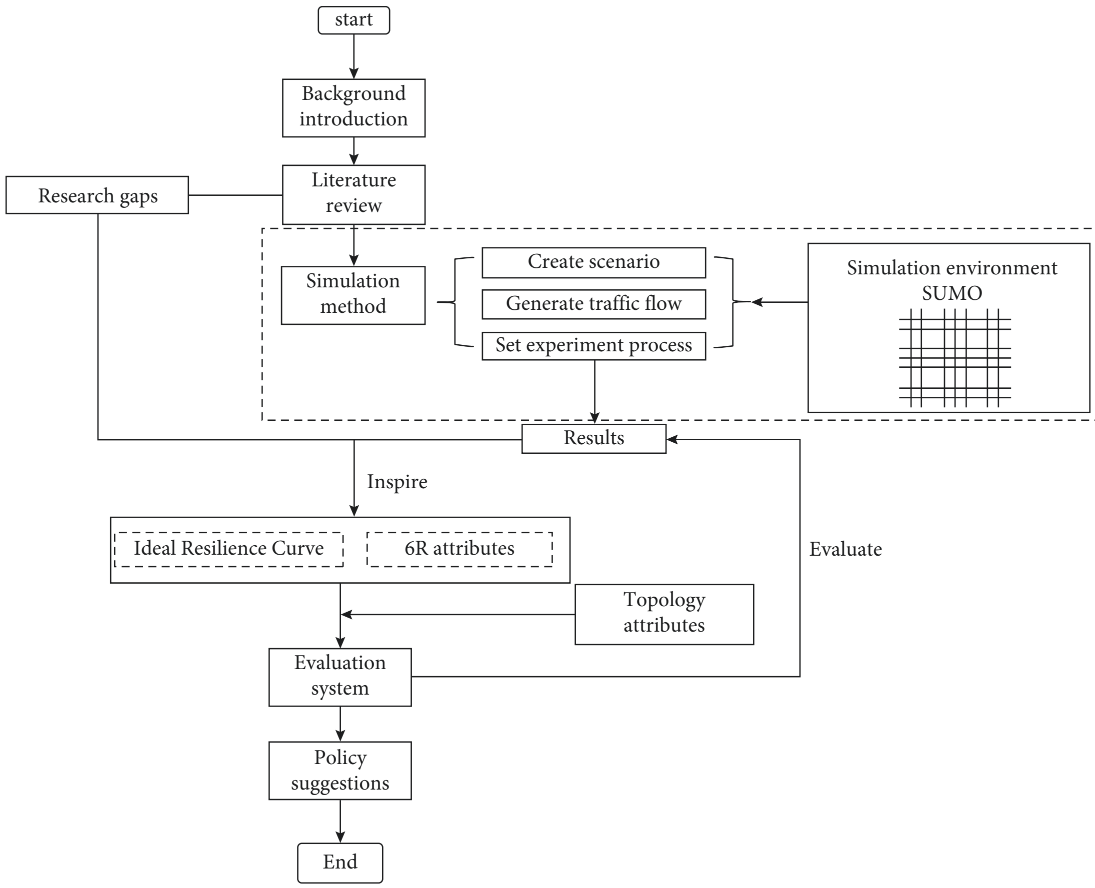

Figure 1: Structure of the paper.

framework of resilience, which is defined as the ability of a system to mitigate the effects of a disaster and maintain its own function. This was measured by a resilience triangle consisting of robustness, rapidity, redundancy, and resourcefulness. Cutter and Barnes [21] defined resilience as the ability of a system to cope with and recover from a disaster, including the ability of the system to absorb and resist its adverse effects. Mattsson and Jenelius [22] argued that the concept of resilience aimed to capture the ability to maintain its functionality and the speed to return to a normal state after a large-scale disruption or disaster. According to Qiliang et al. [23], resilient city construction requires that cities not only have the ability to absorb disaster disturbances by engineering measures but also have the ability of self-adaptation and rapid recovery. Based on the existing research results, three consensus points of the concept of road traffic system resilience are summarized. First, resilience refers to the ability of the system to withstand, respond to, and recover from disasters, rather than a state or outcome of the system. Second, resilience emphasizes the adaptability of the system in the face of disasters rather than stability. Third, resilience emphasizes the capacity of the system throughout the process of disaster occurrence and encompasses numerous aspects, rather than one attribute.

In the stage of metrics, there has been significant growth in the metric study of road traffic system resilience in recent years. Faturechi and Miller-Hooks [24] provided a comprehensive overview of the performance of transportation infrastructure systems in disasters and found that resilience was often measured by characteristics such as risk, vulnerability, reliability, robustness, mobility, and survivability. Murray-Tuite [25] classified traffic resilience into ten metrics: cooperation, redundancy, diversity, efficiency, safety, self-organization, strength, adaptability, mobility, and ability to recover quickly. In the stage of quantitative evaluation, Bruneau and Chang's research [20] on resilience provided a solid basis for quantitative evaluation of the resilience of urban road traffic systems. Ip and Wang [26] defined the independent paths between every two nodes of an urban road traffic network and measured the resilience of the road network in terms of the number of independent paths across the whole network. Wang et al. [27] introduced the degree of nodes as a measure of node resilience with the help of the entropy method in physics. Furthermore, some researchers use mathematic models to perform the evaluation and optimization work in transportation systems from the perspective of resilience [28, 29].

Notably, most current research on resilience involves static evaluation studies, focusing on proposing a metric system and conducting a static evaluation for an urban road system under a certain state. Few studies have been performed on the whole dynamic process of perturbation events.

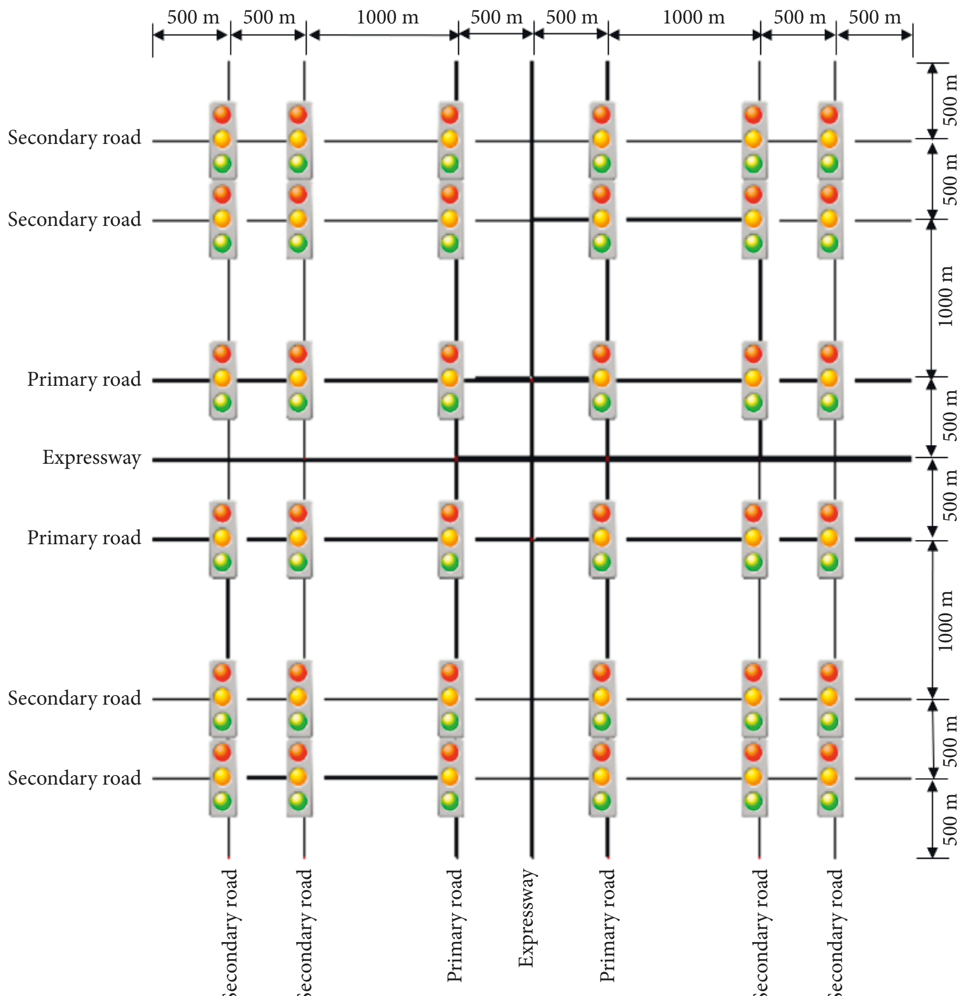

Figure 2: Ideal urban road network in SUMO.

To solve the research gaps mentioned above, this study specifies the unexpected event as malignant traffic accidents and uses traffic simulation technology to obtain data about the impact of malignant traffic accidents on the road network. The dynamic impact on the urban road network resilience of the whole process from before the occurrence of malignant traffic accidents to after the recovery measures have been implemented is explored. Based on the topological attributes and resilience attributes of the urban road network, the urban road network resilience evaluation system is established, which renders a full-process evaluation of the resilience of the urban road network under malignant traffic accidents conditions.

3. Simulation Method

In this study, SUMO (Simulation of Urban MObility), a microscopic traffic simulation software, was used to conduct simulation experiments. SUMO is an open-source traffic simulation software that enables the control of traffic flow.

In SUMO, we draw an ideal urban road network with a scale of 5×5 km, including three types of urban roads, namely secondary roads, primary roads, and expressways. The three types of urban roads have a regular distribution, as shown in Figure 2. Each intersection on secondary and primary roads is a level intersection with traffic signals within it. The expressways intersection is treated as a separate grade to simulate three-dimensional crossings in real scenarios. Connections are set between primary roads and expressways to simulate ramps.

As shown in Figure 2, there are eight secondary roads, four primary roads, and two expressways in the ideal urban road network. An ideal traffic flow with a uniform and symmetrical distribution of vehicles was added to these fourteen roads to make them operate in the network. The specific traffic flow setting is as follows. Each of the twenty-eight endpoints of the fourteen roads is used as the origin of the traffic flow. Each origin corresponds to all twenty-eight endpoints, that is, the twenty-eight endpoints are the destinations of this origin. The interval of traffic generation and traffic flow volume is well designed and adjusted according to pre-repeated experiments such that the traffic generated in the network and the arriving traffic are basically in a level state, making it possible for the traffic to be evenly and symmetrically distributed in the network in a stable manner. We set the volume based on this principle: the traffic runs

Table 1: Parameters and model settings of simulation experiment.

Parameter/model	Scenario	Description
Number of lanes	Secondary roads Primary roads Expressways	Two lanes in both directions Four lanes in both directions Six lanes in both directions
Speed limit	Secondary roads Primary roads Expressways	60 km/h 60 km/h 100 km/h
Traffic volume between each OD (origin-destination) pair	All	24 vehicles
Car-following model	All	Krauss
Lane-changing model	All	LC2013

smoothly in normal conditions, and when malignant traffic accidents happen, there will occur congestion.

Some specific parameters and model settings of the simulation experiment are shown in Table 1.

In the simulation experiment, there are three scenarios where malignant traffic accidents occur: at secondary and primary roads intersections and at the expressways intersection. The process of the simulation experiment is described as follows.

During the first 30 min, the traffic flow is gradually distributed to the whole network, reaching a balanced and stable state. According to our repeated tests, it takes more than 20 minutes for the traffic flow to spread throughout the network and reach a stable running state. In order not to interfere with the later experiments, the traffic flow runs freely for the first 30 minutes of the simulation. At 30 min, malignant traffic accidents occur at an intersection, causing damage to the intersection and making it impassable. Vehicles are stalled on the roads connected to the intersection, but other road users in the network are unaware of the malignant traffic accidents and continue to follow the originally planned path, resulting in gradual congestion on the roads connected to the intersection where the accidents occur. According to daily experience, the road repair department needs some time to arrive at the scene of the accident, and it also takes some time to notify other road users of the accident through the news and radio broadcast. Here, we set the time interval as 15 minutes. So, at 45 min, the roads connected with the intersection are closed for road repair. At the same time, initial recovery measures are taken. There are two initial recovery measures. First, when the road is closed, the original signalized intersection becomes a T-intersection. The capacity of the intersection can be optimized by extending the green signal ratio on the long side of the T-intersection and shortening the green signal ratio on the short side. Second, repairing or opening emergency lanes on roads around the disrupted intersection improves the capacity. In the simulation, each vehicle in the network chooses the path with the shortest total travel time at every iteration. After the roads connected to the intersection are closed, each vehicle will reroute between the OD and choose the route with the shortest travel time among all the remaining alternative routes according to the calculation results at every iteration. Statistics show that the average time to deal with a traffic accident in the city is about 30 minutes. Therefore, we set the time for the roads closed for emergency repairs as 30 minutes. At 75 min, the accidents are handled, the road repair is completed; the intersection damaged by the accident resumes traffic; and the traffic light phase returns to normal. To relieve the congestion on the surrounding roads due to the malignant traffic accident, the emergency lane remains open. After the accidents are handled, it takes another 30 minutes for the traffic flow to reach a new stable state, so the simulation is allowed to run for another 30 min to reach a new equilibrium stable state, after which it ends. The flow of the whole simulation experiment is shown in Figure 3.

4. Results and Analysis

From the SUMO data output, we select the average speed of each road section in the network during each one-minute period as a measure of its function. The ideal road network in SUMO is a directed graph. To facilitate data visualization, we process it to be an undirected graph. The average speed of road sections closed due to malignant traffic accidents is set to zero, and the average of the road sections' speed in two directions is calculated. Then, we obtain the average speed of each road section in the road network per minute (undirected graph).

4.1. Time Distribution. With the horizontal axis depicting time and the vertical axis depicting the network average speed, we plot a graph of network average speed changing with time. Then, we use a polynomial to fit the curve and obtain the time distribution of network average speed for the whole process under the three accident scenarios.

The temporal distribution of the network average speed under three accident scenarios is shown in Figure 4. Figure 4(a) represents the temporal distribution of the network average speed when malignant traffic accidents occur at the secondary roads intersection. Figure 4(b) shows the temporal distribution of the network average speed when malignant traffic accidents occur at the primary roads intersection. Figure 4(c) shows the temporal distribution of the network average speed when malignant traffic accidents occur at the expressways intersection. The blue line in Figure 4 depicts the processed simulation experiment data, and the red dashed line depicts the polynomial fitted curve.

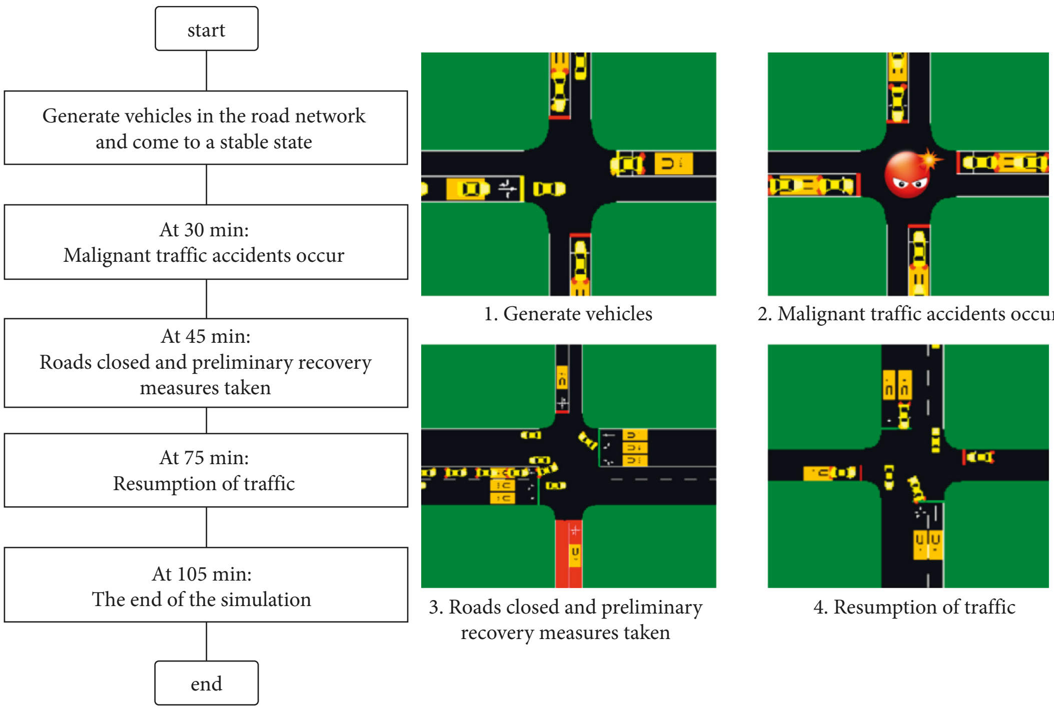

Figure 3: Flow of simulation experiment.

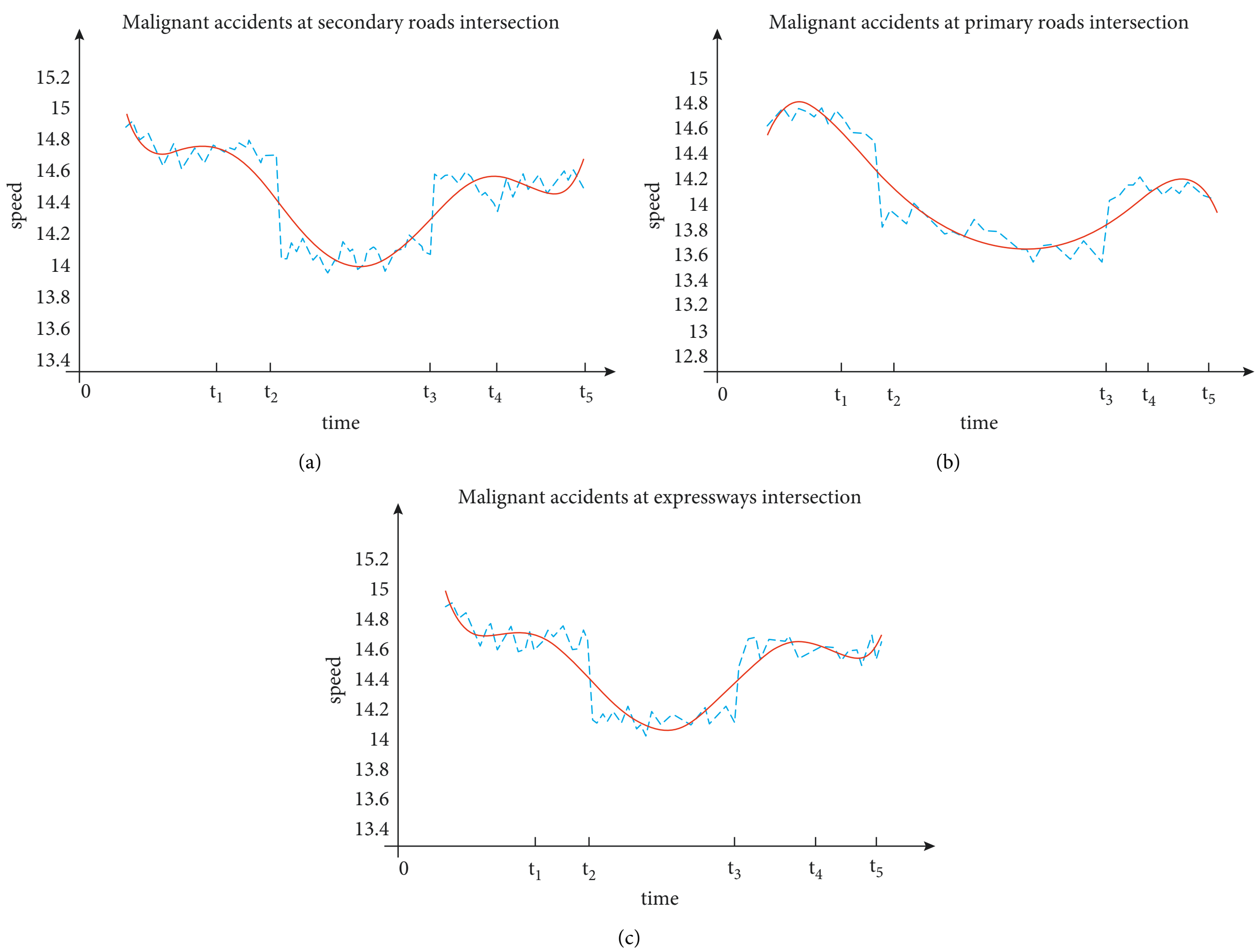

Figure 4: Time distribution of network average speed with malignant accidents at (a) secondary roads intersection, (b) primary roads intersection, and (c) expressways intersection.

Figure 4 shows that the time distribution of the network average speed can be divided into five periods: the initial stable period (0–t_1), disruption period (t_1–t_2), stable period after disruption (t_2–t_3), recovery period (t_3–t_4), and stable period after recovery (t_4–t_5). Before the accidents (initial stable period), the entire network is in a normal operating state, and the network average speed is generally stable with slight fluctuations. After malignant traffic accidents occur (disruption period), the network average speed gradually decreases. Dropping to the lowest value (stable period after a disruption), it reaches a stable period with a low service level, and the network average speed is at a low, slightly fluctuating stable period. After implementing the recovery measures (recover period), the network average speed gradually increases. A new stable period (stable period after recovery) is reached after the network average speed rises to a certain value. Because we simulate a short-term recovery, the network average speed in the stable period after recovery is lower than that in the initial stable stage.

4.2. Spatial Distribution. Each road section is assigned a color according to its average speed, such that the spatial distribution of the average speed of the whole network can be plotted.

We select the spatial distribution graphs of the average speed of each road section at a representative moment of each period and plot them on the time axis. Thus, the spatial distribution pattern of road sections' average speed over time is revealed, as shown in Figure 5.

Figures 5(a)–5(c) show the spatial distribution of the average speed of road sections over time under the scenarios of malignant traffic accidents occurring at the secondary roads, primary roads, and expressways intersections, respectively. t_1 denotes a certain moment in the initial stable period. The traffic runs smoothly throughout the network, and the speed of the expressways is higher than that of the surface roads. Due to the phase of the traffic lights, the average speed on the road sections near the signalized intersection is slightly lower. t_2 is a certain moment in the disruption period. Malignant traffic accidents occur at a certain intersection (circled part in Figures 5(a)–5(c)). Herein, we define the road sections whose average speed is lower than 80% of the speed limit, that is, 13 m/s, as congested road sections. At this time, traffic on the four road sections connected to the intersection generates congestion, whereas the rest of the network is not affected. t_3 denotes a certain moment in the stable period after a disruption. When malignant traffic accidents occur at the secondary roads intersection, the roads connected to the intersection close. Because traffic volume is not very high on secondary roads, the traffic congestion only gradually spreads to several roads around this intersection. When malignant traffic accidents occur at the primary roads intersection, the roads connected to the intersection are closed, and the traffic congestion gradually spreads along with the horizontal and vertical directions northwest and southeast of the network. The entire network is at a low level of service. When malignant traffic accidents occur at the expressways intersection, the roads connected to the intersection close. However, because expressways are equipped with ramps, their good connectivity with primary roads stops the traffic congestion phenomenon from spreading, making the congestion only generates on the roads connected to the intersection. t_4 denotes a certain moment in the recovery period. Owing to the completion of road repair, the intersection suffering malignant traffic accidents resumes traffic, and the congestion on the connected and impacted roads is eased. However, some impact on the network remains. t_5 marks a certain moment in the stable period after recovery. The entire network enters a new state of stable operation, but the overall level of service is slightly lower than that in the initial stable stage.

4.3. Ideal Resilience Curve. Using the network average speed per minute as a functional measure of the road network resilience, we obtain the time distribution of road network resilience in the whole process of malignant traffic accidents. The ideal resilience curve of the road network is proposed according to the time distribution of network average speed, which is shown above. Based on the classical "4R" resilience theory [20], the conceptual portrayal of resilience is further extended to "6R."

The ideal curve of road network function with respect to time is shown in Figure 6. The horizontal axis represents time, and the vertical axis represents the functional attributes that can characterize the resilience of the road network. The ideal resilience curve can be divided into five periods: initial stable period, disruption period, stable period after disruption, recovery period, and stable period after recovery. Before the malignant traffic accidents, the road network is in a stable state with slight fluctuations. After the malignant traffic accidents, the functional level of the road network gradually decreases and then enters a lower functional level with slight fluctuations. After the recovery measures are taken, the functional level of the road network gradually rises and then enters a new stable state with slight fluctuations. Notably, the duration of the three stable periods can be extended or shortened, mainly depending on when malignant traffic accidents happen and when recovery measures are taken.

Compared with the resilience curve proposed by Bruneau and Chang [20], the ideal resilience curve presented here has several differences. First, we believe that the three stable periods are not completely stable states but stable states with slight fluctuations. Second, we suggest that the damage caused by malignant traffic accidents to the function of the road network is not instantaneous but takes some time to gradually impose on the road network. Therefore, the road network function does not decline instantaneously when the damage occurs but experiences a gradual decline process. Third, we suggest that the road network function does not recover immediately after the disruption but enters a stable state with a low level of service. It gradually recovers only after the intervention of recovery measures. Fourth, in the ideal resilience curve, we describe a short-term recovery such that the functional level of the road network after recovery is lower than that in the initial stable period.

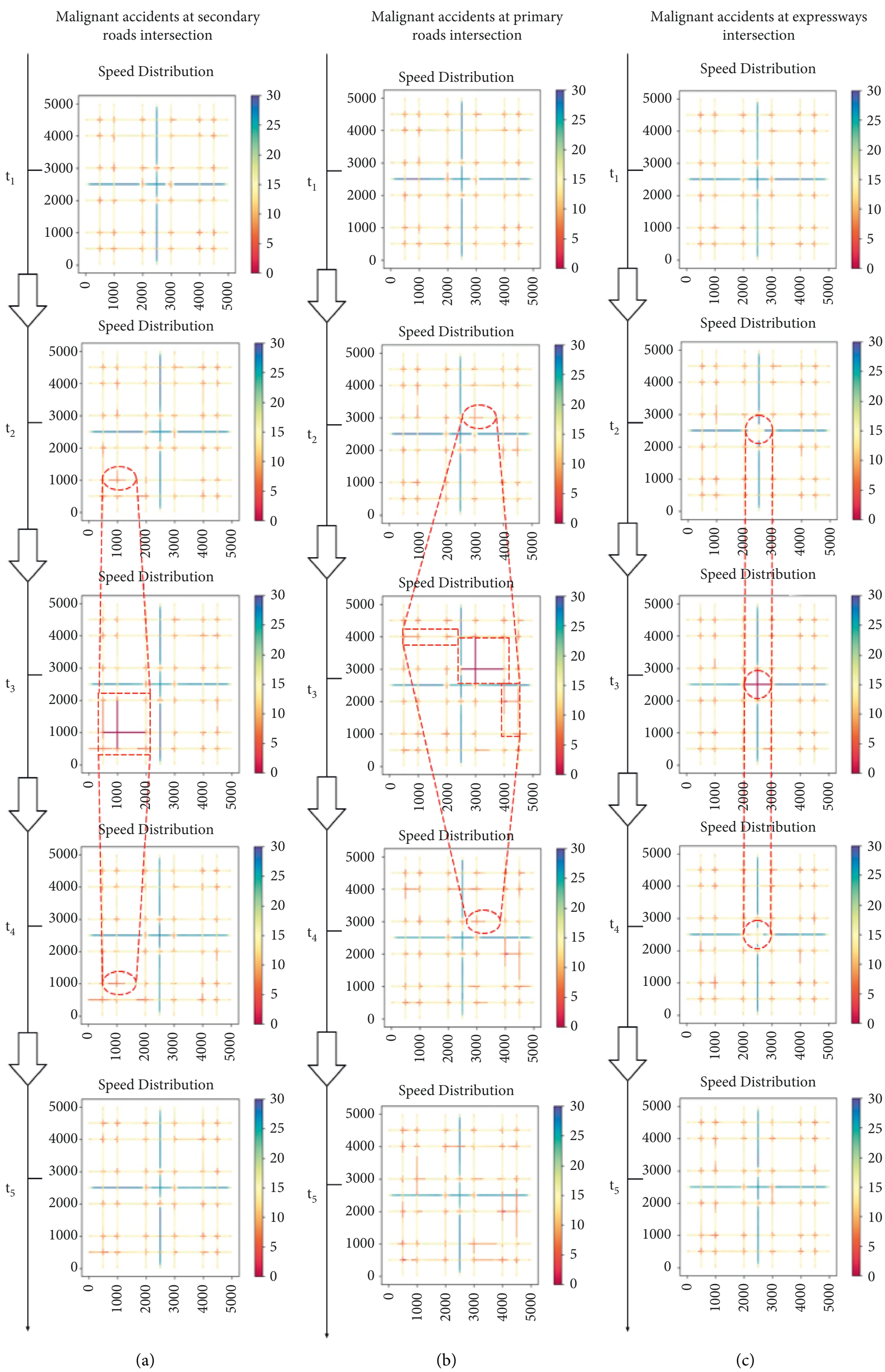

Figure 5: Spatial distribution of average speed with malignant accidents at (a) secondary roads intersection, (b) primary roads intersection, and (c) expressways intersection.

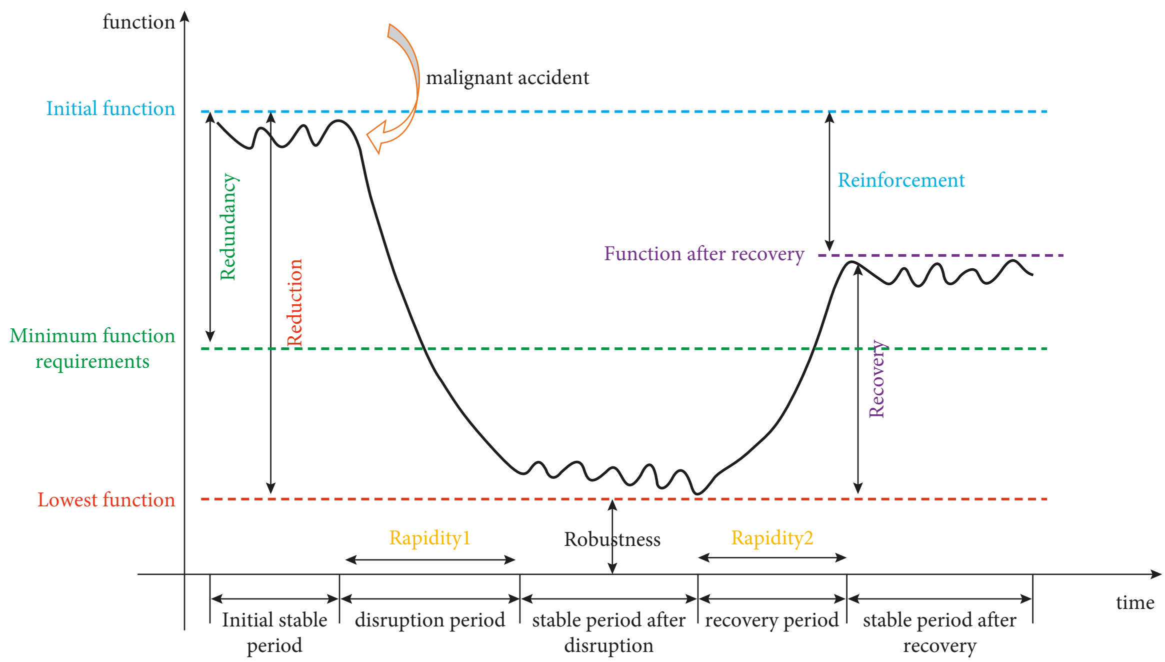

Figure 6: Ideal resilience curve.

After deriving the ideal resilience curve, we can define relevant "6R" resilience attributes. There are four baselines in Figure 6. The blue dashed line indicates the initial function; the green dashed line indicates the minimum functional requirements; the red dashed line indicates the lowest function, and the purple dashed line indicates the function after recovery. Redundancy refers to the difference between the initial function and the minimum function requirements, reflecting the part of the initial function that is higher than the requirement. Reduction refers to the difference between the initial f-function and the lowest function, indicating the loss of the road network's function due to the damage. Robustness refers to the lowest function, indicating the remaining function of the road network after the damage. Recovery refers to the difference between the function after recovery and the lowest function, indicating the degree of road network recovery. Reinforcement refers to the difference between the initial function and the function after recovery, indicating the lack of function in the stable period after recovery compared to the initial stable period. Rapidity refers to the rate at which the function level of the road network decreases and increases. To facilitate the calculation and subsequent use, we conduct normalization for the "6R" resilience attributes. The calculation of the "6R" resilience attributes is shown in the following equations:

$$\text{Redundancy} = \frac{\text{IF} - MFR}{\text{IF}}, \tag{1}$$

$$\text{Reduction} = \frac{IF - LF}{IF}, \tag{2}$$

$$\text{Robustness} = \frac{LF}{IF}, \tag{3}$$

$$\text{Recovery} = \frac{FAR - LF}{IF}, \tag{4}$$

$$\text{Reinforcement} = \frac{IF - FAR}{IF}, \tag{5}$$

$$\text{Rapidity1} = \frac{To\ D}{TT}, \tag{6}$$

$$\text{Rapidity2} = \frac{ToR}{TT}, \tag{7}$$

where IF denotes the initial function, depicted by the blue dashed line in Figure 6; MFR denotes the minimum function requirements, depicted by the green dashed line; LF denotes the lowest function, depicted by the red dashed line; FAR denotes the function after recovery, depicted by the purple dashed line; ToD denotes the time of disruption period; ToR denotes the time of recovery period; and TT denotes the total time of the whole process of malignant traffic accidents.

Among the "6R" attributes, redundancy, robustness, recovery, and rapidity1 are positively correlated with resilience, that is, the larger the Rs the better the resilience. Reduction, reinforcement, and rapidity2 are negatively correlated with resilience, that is, smaller Rs indicate better resilience. The "6R" attributes together reflect the resilience of the road network under the scenarios of malignant traffic accidents.

Based on the results obtained from the simulation experiments, we can calculate the values of "6R" under three scenarios of malignant traffic accidents, as shown in Table 2.

The three classes of roads have their own advantages and disadvantages in terms of "6R" attributes under the scenario of malignant traffic accidents. According to the correlation between "6R" and resilience, three classes of roads intersections

Table 2: Values of "6R" under three scenarios of malignant traffic accidents.

	Secondary roads intersection (%)	Primary roads intersection (%)	Expressways intersection (%)
Redundancy	6.10	5.18	6.10
Reduction	6.41	8.32	5.98
Robustness	93.59	91.68	94.02
Recovery	4.37	4.60	4.47
Reinforcement	2.04	3.72	1.51
Rapidity1	7.77	6.67	4.44
Rapidity2	7.77	8.33	11.11

under the condition of malignant traffic accidents are ranked based on the simulation experiment data. The higher the ranking, the higher the score, indicating better resilience performance under a certain R attribute. The radar diagram shows the resilience performance of three classes of roads intersections under the "6R" attribute in the event of malignant traffic accidents, as shown in Figure 7. The secondary roads intersection performs best in terms of redundancy and rapidity and worst in terms of recovery. The primary roads intersection performs best in recovery and worst in redundancy, reduction, robustness, and reinforcement. The expressways intersection performs best in redundancy, reduction, robustness, and reinforcement and worst in rapidity.

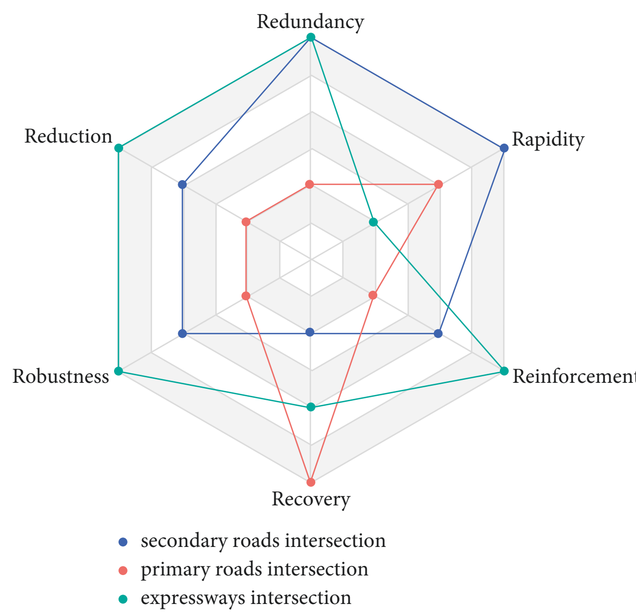

Figure 7: Radar diagram of "6R" resilience performance for three classes of roads.

5. Discussion

In this section, by combining the topological and resilience attributes of the urban road network, the evaluation system of urban road network resilience is constructed. Based on the spreading characteristics of the congestion phenomenon, from the perspective of government management, we propose relevant policy suggestions about how the urban road network resists and responds to malignant traffic accidents.

5.1. Evaluation System. Combining the topological and "6R" resilience attributes of the urban road network, its resilience evaluation system can be established.

Among the topological attributes, degree centrality, closeness centrality, and betweenness centrality, which characterize the importance of node locations, are selected as the topological evaluation metrics of the network. Degree centrality is the most direct metric to portray the centrality of a node. A large degree of a node indicates a higher centrality. In the ideal urban road network, the degree centrality of a node is characterized by the number of lanes of one road connected to it. Closeness centrality indicates the closeness between a node and other nodes in the network. The inverse of the sum of the shortest path distance from a node to all other nodes indicates closeness centrality. Betweenness centrality is the sum of the ratio of the number of times a node lies on the shortest path between any two other nodes to the number of all paths between the two nodes. The calculations of the three topological attributes are shown in the following equations:

$$C_d(i) = \frac{d(i)}{n-1} * nl, \tag{8}$$

$$C_c(i) = \frac{n-1}{\sum_j d_{ij}}, \tag{9}$$

$$C_b(i) = \frac{2\sum_{j<k} g_{jk}(i)/g_{jk}}{(n-1)(n-2)}, \tag{10}$$

where n is the number of nodes, $C_d(i)$ is the degree centrality of node i, $d(i)$ is the degree of node I, nl is the number of lanes on one road connected to node i, $C_c(i)$ is the closeness centrality of node i, d_{ij} is the shortest path distance between node i and j, $C_b(i)$ is the betweenness centrality, g_{jk} is the number of shortest paths between node j and k, and $g_{jk}(i)$ is the number of shortest paths between node j and k through node i.

Among "6R" resilience attributes, since the reduction is negatively correlated with robustness and reinforcement is negatively correlated with recovery, four attributes that are independent of each other are selected. Redundancy, robustness, recovery, and rapidity1, which are positively correlated with resilience, and rapidity2, which is negatively correlated with resilience, are selected as the resilient

Table 3: Resilience score for three scenarios of malignant traffic accidents.

		Secondary roads intersection	Primary roads intersection	Expressways intersection
Topology attributes	Degree centrality	0.006	0.012	0.018
	Closeness centrality	0.029	0.0398	0.0403
	Betweenness centrality	0.0968	0.207	0.0087
Resilience index		0.958	0.936	0.96
Resilience attributes	Redundancy	0.061	0.052	0.061
	Robustness	0.936	0.9168	0.9402
	Recovery	0.0437	0.046	0.0447
	Rapidity1	0.0777	0.0667	0.0444
	Rapidity2	−0.0777	−0.833	−0.1111
Resilience score		2.54974282	1.027532398	2.685798309

evaluation metrics. The calculation of redundancy, robustness, recovery, rapidity1, and rapidity2 is depicted as equations (1), (3), (4), (6), and (7).

The resilience index refers to the integral of the resilience function curve over time during the whole process of malignant traffic accidents, reflecting the overall resilience performance of the urban road network under a certain damage scenario. The calculation of the resilience index is improved from the calculation of resilience loss in the literature [20]. The resilience index is positively related to resilience, as shown in the following equation:

$$RI = \frac{\int_0^T F(t)\mathrm{d}t}{T * F_0}, \tag{11}$$

where RI is the resilience index, T is the duration of the whole process of malignant traffic accidents, $F(t)$ is the resilience function curve with respect to time, and F_0 is the initial function of the road network.

The resilience evaluation system includes the above-mentioned topological attributes, resilience attributes, and the resilience index. The resilience evaluation system is given in the form of a resilience score of the road network under a certain damage scenario, which is shown in the following equation:

$$RS = RI * e^{C_d(i)+C_c(i)-C_b(i)} *, \quad e^{\text{Redundancy}+\text{Robustness}+\text{Recovery}+\text{Rapidity1}-\text{Rapidity2}}, \tag{12}$$

where RS denotes the resilience score.

Equation (12) indicates that the road network resilience score is approximately between the interval $(0, e^2)$. A higher resilience score indicates better resilience performance of the road network. Theoretically, equation (12) can be used to evaluate the resilience of any road network under the occurrence of any event.

Based on the data obtained from simulation experiments, the resilience scores under three scenarios of malignant traffic accidents can be calculated, as shown in Table 3.

Table 3 indicates that under this evaluation system, the road network resilience is optimal when malignant traffic accidents occur at an expressways intersection, and the road network resilience is poorest when malignant traffic accidents occur at the intersection of the primary roads. The main reason is that in this ideal urban road network, the betweenness centrality of primary roads intersection is relatively high, resulting in more vehicles passing through this intersection. Furthermore, this has a low resilience index and relatively poor resilience attributes, thus resulting in the lowest resilience score.

5.2. Policy Suggestions. According to “6R” resilience attributes and the resilience evaluation system, based on the spreading characteristics of the congestion phenomenon, we propose policy suggestions for the urban road network to resist and cope with malignant traffic accidents from the perspective of government managers.

First, the resilience performance of low-class surface roads, such as secondary roads, is good under the conditions of malignant traffic accidents. The congestion on low-class surface roads has a tendency to spread to surrounding roads in the event of malignant traffic accidents. Small-scale spreading must be prevented, and traffic control and congestion dispersal on surrounding roads must be strengthened. Consistently, the current level of service on low-class surface roads must be maintained and steadily improved.

Second, the resilience performance of high-class surface roads, such as primary roads, is poor under the conditions of malignant traffic accidents. The congestion on high-class surface roads has a tendency to spread to the entire network. Large-scale spreading must be prevented, and the traffic control and congestion dispersal on roads in horizontal and vertical directions, where the accidents occur, must be strengthened to prevent the proliferation of congestion. The investment of human and material resources for high-class surface roads must be increased; the traffic control must be strengthened; and the resistance and recovery ability of high-class surface roads against damage caused by malignant traffic accidents must be improved.

Finally, expressways, urban interchanges, elevated roads, and other high-class roads are more resilient under the conditions of malignant traffic accidents owing to good connectivity. There is no tendency for congestion on high-class roads to spread. However, the speed at which the high-class roads recover from malignant traffic accidents is relatively low. The efficiency of the handling of traffic accidents must be improved to accelerate the speed of recovery from malignant traffic accidents. The capacity construction must be strengthened, enabling high-class roads to better withstand the impact of reduced capacity due to the occurrence of malignant traffic accidents. The current management efforts must be maintained without slackening, and the maintenance of high-class roads must be strengthened to ensure their connectivity and smoothness.

6. Conclusion

Focusing on an ideal urban road network, we conducted traffic simulations to evaluate the impact of malignant traffic accidents on the resilience of the urban road network. The simulation experiments simulate the whole process from before the occurrence of malignant traffic accidents to after the recovery and obtain the temporal and spatial distributions of the average speed of road sections in the road network. The results show that in terms of temporal distribution, the network average speed under the scenario of malignant traffic accidents goes through five periods: initial stable period, disruption period, stable period after disruption, recovery period, and stable period after recovery. In terms of spatial distribution, with the passage of time in five periods, congestion due to malignant traffic accidents first becomes aggravating, then gradually eases, and finally returns to normal. It has the tendency to spread outward during the disruption period.

Inspired by simulation experiments, the ideal resilience curve is summarized as follows. It can be divided into five periods: initial stable period, disruption period, stable period after disruption, recovery period, and stable period after recovery. Based on the classical "4R" resilience theory [20], we further refine it into the "6R" resilience theory, including redundancy, reduction, robustness, recovery, reinforcement, and rapidity, improving the portrayal of the resilience concept. The "6R" resilience attributes together reflect the resilience of the road network under malignant traffic accidents. Combining the topological attributes and resilience attributes of the urban road network, we establish an urban road network resilience evaluation system to obtain an all-round evaluation of the urban road network under malignant traffic accidents. Results show that when malignant traffic accidents occur at expressways intersection, the road network's resilience performance is optimal, and when malignant traffic accidents occur at primary roads intersection, the road network's resilience performance is the poorest. Therefore, more resources and attention must be devoted to high-class surface roads to help improve the resilience in dealing with malignant traffic accidents. Finally, from the perspective of government management, based on the spreading characteristics of the congestion phenomenon, we propose relevant policy suggestions for urban road networks to resist and respond to malignant traffic accidents.

The major contributions of this work are as follows. First, we propose the ideal resilience curve for the urban road network under the scenario of malignant traffic accidents to describe the time distribution of the road network resilience, which is more detailed compared with previous studies. We plot the spatial distribution of the average speed of the whole network and find the propagation characteristics of congestion when malignant traffic accidents occur at different classes of intersections. Second, we develop the classical resilience theory into "6R" (redundancy, reduction, robustness, recovery, reinforcement, and rapidity), improving the theory of resilience concept portrayal. Third, we establish an evaluation system based on the topological and resilience attributes of the urban road network, which can make an all-round and full-process resilience evaluation under the scenario of malignant traffic accidents.

Several limitations persist in this work. We use an ideal urban road network and set ideal traffic flow in the simulation, which differs from actual situations. Furthermore, we only qualitatively describe the spreading characteristics of the congestion phenomenon without any quantitative expression. Subsequent research will focus on the real road network in cities and quantify the propagation of the congestion phenomenon.

Data Availability

The data generated by the simulation experiment are used in the paper. The data can be obtained from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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