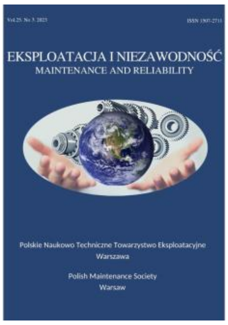

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Cascading failures and maintenance optimization of urban transportation networks

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Highlights

- Cascading failure process of a traffic distribution system is studied.
- The maintenance optimization is analyzed with minimizing maintenance time.
- The intra-area and inter-area maintenance models are analyzed.
- A city transportation network is used to illuminate the proposed models.

Abstract

A convenient urban transportation network facilitates a high-quality life and a high-growth economy. Due to cascading failures being a ticklish question triggering continuous road congestion, the maintenance plan is momentous to restore the urban transportation network. Considering fault edges are removed and cars slowly drive out of these edges to ease traffic congestion, a traffic distribution model is proposed to analyze the cascading failures process. To resume the transportation network, this paper proposes a maintenance optimization with minimizing maintenance time. It recovers the cascading failures from two perspectives: the intra-area maintenance model and the inter-area maintenance model. At last, a transportation network of a city in China is regarded as a case study to illuminate the feasibility of the proposed models. The results show that on the premise of dividing traffic areas, it is reasonable to adopt the intra-area maintenance plan for cascading failures. Compared with the previous travel data, the inter-area maintenance plan saves more time.

Keywords
reliability, maintenance optimization, cascading failures, transportation networks.

1. Introduction

In recent years, with the increase in residents-travel demand and the development of transportation networks, urban transportation networks are becoming more important to a high-quality life and a high-growth economy. Cascading failures cause congestion which damages urban transportation networks [24]. Ignoring the cascading failures is not only detrimental to the recovery of transportation networks but also may lead to worse congestion [8]. Timely and effective maintenance plans help to maximize the recovery of transportation networks and ensure smooth travel of residents.

Many scholars have studied the cascading failures of networks [2, 9, 10], but few researchers focus on the area maintenance of urban transportation networks due to their network complexity. An urban transportation network plays an important role in ensuring smooth travel for residents. A cascading failure is a failure in a network that causes other edges to fail due to the coupling relationship between the edges. Because maintenance resources are limited, maintenance scheduling is widely used as a time-centered maintenance strategy. Dui et al [11] gave the maintenance analysis of

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transportation networks by the traffic transfer principle considering node idle capacity. Shi et al [20] developed joint optimization maintenance planning of multi-facility transportation infrastructure systems. Shen et al [21] analyzed the cascading congestion in traffic networks. Barahimi et al [3] analyzed multi-modal urban transit network maintenance considering reliability. Saeedmanesh and Geroliminisa [22] studied the congestion propagation in urban traffic networks. Yin et al [23] analyzed the cascade failure model in scale-free networks and random networks by introducing the average distance and the state change time of road junction. Jia et al [13] studied the dynamic cascading failure analysis in congested urban road networks with self-organization.

Matching skills that require by fault edges is a key problem in maintenance. Identifying the reasons resulting in cascading failures is most important [25]. Maintenance optimization is widely used in systems, which can be used to reduce maintenance costs and time. At present, maintenance optimization is not considered in urban transportation networks. Chen et al [6] developed policies for preventative and corrective maintenance actions and built optimized routes for maintenance vehicles.

Due to the transportation network complexity, some methods can be used to find the approximate solution for maintenance optimization. For example, Behiri et al [4] proposed a robust ant colony metaheuristic for urban transport scheduling using a passenger rail network. Aksoy et al [1] introduced the urban road network maintenance optimization model using ant colony optimization. Peng et al [19] investigated route planning in stochastic common-lines multi-modal transportation networks by integrating genetic algorithm and monte Carlo simulation. Chen et al [7] suggested modeling emergency supply maintenance problems based on reliability and its solution algorithm under variable road networks. Nguyen et al [18] suggested an algorithm employing the boundary points and recursive sum of disjoint products technique to maintain the transportation network.

However, the following problems exist in cascading failures of a transportation network: choosing how to identify fault edges in the network during cascading failure propagation and choosing how to perform maintenance optimization on these fault edges under different skill constraints to recover the transportation network. This paper studies the maintenance optimization of fault edges in the transportation network under skill constraints. Firstly, a traffic distribution model is used to search for the fault edges in the network so that maintenance plans can be performed on congested roads. Secondly, intra-area and inter-area maintenance models are proposed to match skills that require by fault edges under different skill constraints.

The rest of the paper is organized as follows. Section 2 introduces the problem description and assumptions. Section 3 gives a traffic distribution model to illustrate cascading failure propagation. Section 4 proposes maintenance optimization models to recover the congested transportation network. Section 5 proves the effectiveness of methods by taking the transportation network of a city as an example. Section 6 concludes the paper and proposes future work.

2. Problem description and assumptions

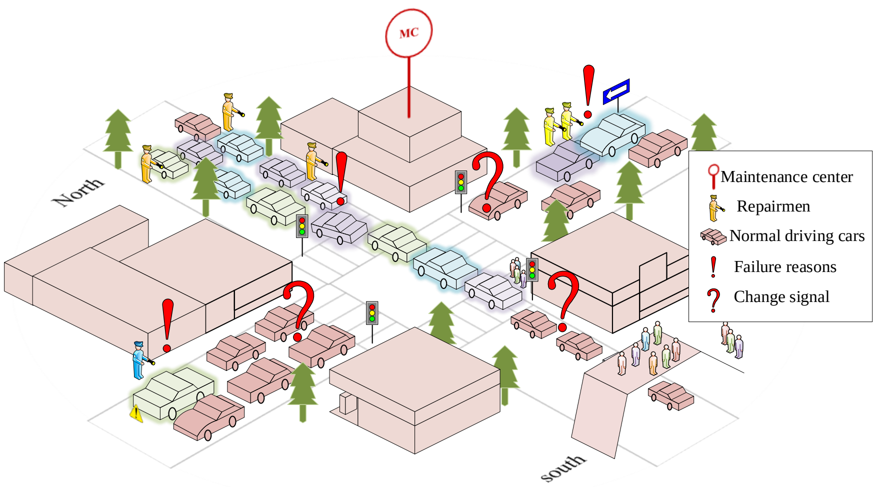

Fig. 1. The cascading failures in an area.

An urban transportation network is divided into several areas. Fig. 1 shows the cascading failures in an area. Each area has a maintenance center (MC) to formulate maintenance plans to ease traffic congestion. A faulty edge is treated as a subtask, which is done by skilled repairmen. All subtasks are complete, then the maintenance plan is complete. The reasons for cascading failures are cars breaking down, collisions between cars, and insufficient road capacity [25]. They correspond to the three maintenance skills mastered by repairmen.

Fig. 2 shows the dynamic maintenance optimization in detail. R2 indicates a kind of maintenance resource. Its color indicates a kind of skill needed for the edge. The shade of the color indicates the time spent maintaining the faulted edge. The congested roads have different degrees and types of failure. The same is true for R1 and R3. Lines with arrows indicate the maintenance order of the failed edges.

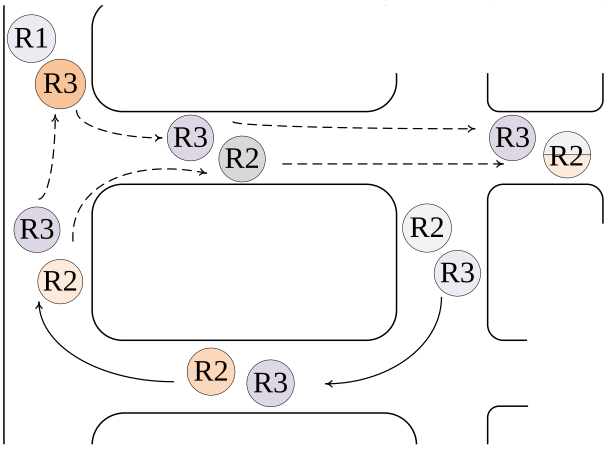

Fig. 2. Dynamic maintenance optimization in detail.

The maintenance plan is divided into the intra-area maintenance model and the inter-area maintenance model. The intra-area maintenance is where an MC modeling cascading failures within its area. The inter-area maintenance is where the MCs model the cascading failures in areas. The two models formulate optimal maintenance strategies with minimizing maintenance time as the objective function.

Based on the above content, the following assumptions are proposed.

- Once a failed edge is removed from the network, it is no longer considered an edge to which traffic can be distributed.
- When repairmen are repairing a failed edge, it can't be interrupted and the repairmen can't be replaced.
- Repairmen use mastered skills to provide maintenance services. The use of skills will not affect each other.

3. Cascading failure model

An urban transportation network is denoted as $G = (V, E)$. V is the set of nodes. E is the set of edges. $e(i,j)$ is the edge from node i to node j. $v(i,j)$ is the weight of the edge, and describes the time from node i to node j. $K_i = \sum_{j \in V} \eta_{ij}$ is the degree of node i. $\eta_{ij} = 1$, if i is connected to j. Otherwise, $\eta_{ij} = 0$. $A_i = 2E_i/[K_i(K_i - 1)]$ is the local clustering coefficient of node i. E_i is the actual number of edges between neighbors of node i.

The relationship between the initial flow of an edge and the degree value of its connected nodes [11] is represented as

$$L(t)_{e(i,j)} = a(K_i K_j)^b, i\, j \in V. \quad (1)$$

In Equation (1), $L(t)$ represents the initial flow of $e(i,j)$. a and b denote the zoom factors. a is a positive integer. The scope of b is [0,1].

According to the on-demand capacity principle proposed by Motter and Lai [17], it can be determined that the capacity of a node is proportional to the flow rate. The capacity of an edge is represented as follows

$$P_{e(i,j)} = L(t)_{e(i,j)} \cdot (1 + \sigma), i\, j \in V, \quad (2)$$

$$\Delta L_{e(*,m)}(t) = K_{e(i,j)} \cdot \frac{L(t)_{e(*,m)}}{\sum_{* \in \{i,j\}} L(t)_{e(*,m)}}, \quad (3)$$

where $* \in \{i,j\}$. In Equation (2), P represents the capacity of an edge. In Equation (3), ΔL represents the flow of $e(i,j)$ transferring to its adjacent edges $e(*,m)$. $K_{e(i,j)}$ is a flow to be allocated, equal to the value of flow minus capacity. $L(t)_{e(*,m)}/\sum_{* \in \{i,j\}} L(t)_{e(*,m)}$ is a distribution proportion of adjacent edges $e(*,m)$.

Fig. 3 shows the restoration of urban transportation networks by the proposed traffic distribution model. In Fig. 3 (a), the initial faulted edge is e (7,11), because its flow value 37 exceeds its capacity value 20. The excess value 17 flows into adjacent edges. If the excess value 17 can be accommodated by the flow allocated to adjacent edges, the failed edge is restored. Otherwise, e (7,11) and its adjacent edges fail. In Fig. 3 (b), the sum of the flow value 2 allocated to e (11,16) and its flow value 29 exceeds its capacity value 28 and causes failure. The same occurs in e (16,6). In Fig. 3 (c), the capacity value of e (6,1), e (6,5), and e (6,10) can accommodate the excess value 3. Considering the closed-loop of flow interferes with network recovery, the flow cannot move from e (16,6) to e (6,11) and e (6,7). In Fig. 3 (d), when the excess flow is allocated completely, the congestion of edges e (16,6), e (11,16), and e (7,11) are solved. The urban transportation network is restored.

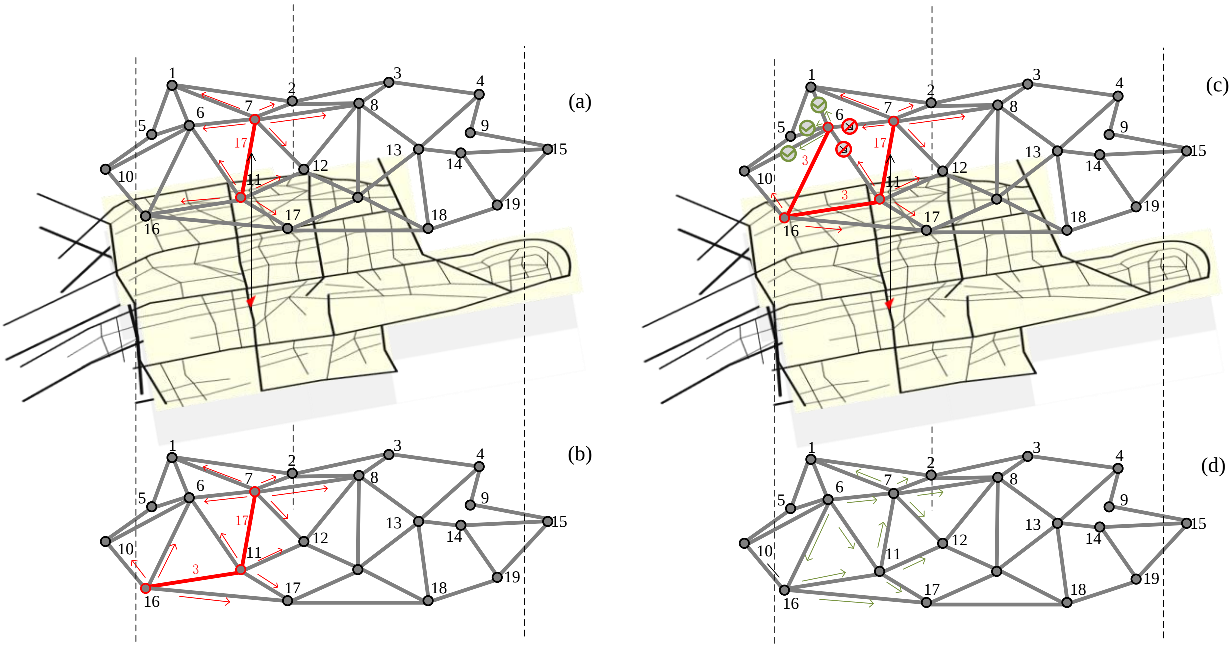

Fig. 3. The process of the cascading failures on urban transportation network.

4. Maintenance optimization

Fig. 4 shows the flowchart for solving the cascading failures subject to skill constraints and time constraints.

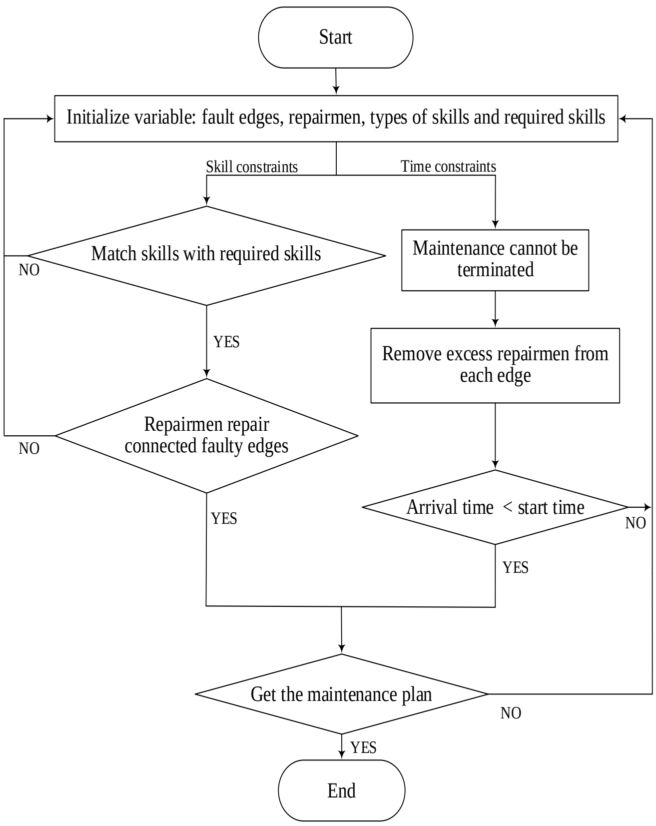

Fig. 4. Flow chart of maintenance optimization subject to skill constraints and time constraints.

It corresponds to the intra-area maintenance model in Section 4.1 and the inter-area maintenance model in Section 4.2. The maintenance optimization algorithm is given in Section 4.3.

Skill constraints are: 1) Ensure that the skills mastered by repairmen match the skills required for congested roads. 2) The second congested road that a repairman needs to restore must be the adjacent road of the first. This shortens the travel time of repairmen. If a repairman matches a failed edge that is not adjacent, he would end the work.

Time constraints are: 1) In a certain maintenance time, maintenance behaviors cannot be interrupted. 2) A failed edge may require multiple repairmen. Their start time is the same, but the end time is not necessarily the same. Once finished, immediately go to the next failed edge. 3) A failed edge starts being repaired after its repairmen arrive.

4.1. Intra-area maintenance

An urban transportation network is divided into n areas. The collection of MCs is $M=\{M_1, M_2 \dots M_\varphi \dots M_n\}$. S_φ is the collection of repairmen in the area φ. Q_φ is the collection of failed edges in area φ. $a=\{a^1, a^2 \dots a^\xi \dots a^Z\}$ is the collection of the kind of skills. Intra-area maintenance is the scheduling process controlled by an MC in its area. For $w \in S_\varphi$, the decision matrix of maintenance time is specifically described as

$$T = \begin{bmatrix} t_1^{11} & t_1^{12} & & t_1^{1w} & & t_1^{1W} \\ t_1^{21} & t_1^{22} & \cdots & t_1^{2w} & \cdots & t_1^{2W} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ t_1^{F1} & t_1^{F2} & \ddots & t_1^{Fw} & \ddots & t_1^{FW} \\ t_2^{11} & t_2^{12} & \cdots & t_2^{1w} & \cdots & t_2^{1W} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ t_\xi^{f1} & t_\xi^{f2} & \ddots & t_\xi^{fw} & \ddots & t_\xi^{fW} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots \\ t_Z^{F1} & t_Z^{F2} & & t_Z^{Fw} & & t_Z^{FW} \end{bmatrix}. \quad (4)$$

In Equation (4), t_ξ^{fw} denotes the time that the repairman w used skill ξ to repair the failed edge f. The length of maintenance time relates to the degree of failure which is quantified by the number of required skills. The maintenance time matrix depending on the degree of failure is expressed as follows.

$$T_{aJ}^{Q^\varphi S^\varphi} = \begin{bmatrix} t_{a^1J^1}^{11} & t_{a^1J^2}^{11} & \cdots & t_{a^1J^\theta}^{11} & t_{a^2J^1}^{11} & \cdots & t_{a^ZJ^\theta}^{11} \\ t_{a^1J^1}^{21} & t_{a^1J^2}^{21} & \cdots & t_{a^1J^\theta}^{21} & t_{a^2J^1}^{21} & \cdots & t_{a^ZJ^\theta}^{21} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ t_{a^1J^1}^{F1} & t_{a^1J^2}^{F1} & \cdots & t_{a^1J^\theta}^{F1} & t_{a^2J^1}^{F1} & \cdots & t_{a^ZJ^\theta}^{F1} \\ t_{a^1J^1}^{12} & t_{a^1J^2}^{12} & \cdots & t_{a^1J^\theta}^{12} & t_{a^2J^1}^{12} & \cdots & t_{a^ZJ^\theta}^{12} \\ \vdots & \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ t_{a^1J^1}^{FW} & t_{a^1J^2}^{FW} & \cdots & t_{a^1J^\theta}^{FW} & t_{a^2J^1}^{FW} & \cdots & t_{a^ZJ^\theta}^{FW} \end{bmatrix} \quad (5)$$

$t_{a^\xi J^\theta}^{fw}$ represents the time repairmen has to work at an edge depending on the degree of failure. The transfer time matrix is specifically described as

$$T^{jf} = \begin{bmatrix} t^{11} & t^{21} & \cdots & t^{J1} \\ t^{12} & t^{22} & \cdots & t^{J2} \\ \vdots & \vdots & \ddots & \vdots \\ t^{1F} & t^{2F} & \cdots & t^{JF} \end{bmatrix}. \quad (6)$$

t^{jf} represents the time required to a repairman from edge j to edge f.

Equations (7)-(11) are maintenance skill constraints. B represents the degree of skills used by the repairman, which is obtained by

$$\mathrm{B}_{t\xi}^{w} = \begin{cases} 1, \text{if the repairman } w \text{ uses the skill } \xi \text{ at time } t \\ 0, \text{otherwise} \end{cases}. \quad (7)$$

ψ represents the skills that the repairman has mastered. It is gotten by

$$\psi_\xi^w = \begin{cases} 1, \text{if the repairman } w \text{ has mastered the skill of } \xi \\ 0, \text{otherwise} \end{cases}. \quad (8)$$

Z represents fault edges that the repairman maintains.

$$\mathrm{Z}_t^{fw} = \begin{cases} 1, \text{if the repairman } w \text{ is at the fault edge } f \text{ at time t} \\ 0, \text{otherwise} \end{cases} \quad (9)$$

Y represents the skills used by the repairman in the failed nodes. R represents the skills needed by a failed edge. The congestion causes the total number of skills R^f required by the failed edge f to differ.

$$\mathrm{Y}_\xi^{fw} = \begin{cases} 1, \text{if the repairman } w \text{ uses the skill } \xi \text{ in the fault edge } f \\ 0, \text{otherwise} \end{cases} \quad (10)$$

$$\mathrm{R}_\xi^{f} = \begin{cases} 1, \text{if the fault edge } f \text{ needs the skill } \xi \\ 0, \text{otherwise} \end{cases} \quad (11)$$

Equations (12)-(13) are time constraints. Minimizing the maintenance time is treated as the objective function, which is obtained by

$$f^{*f} = t^f + \sum_{\xi \in a} t_\xi^{fw} = \max_{w \in G}\{t^{fw}\} + \sum_{\xi \in a} t_\xi^{fw}. \quad (12)$$

In Equation (10), f^{*f} represents the completion time of edge f. t^{fw} is the time that repairman w arrives at failed edge f. $t^{fw} = t^{jw} + t^{jfw}$. t^f is the start time of repairing failed edge f, which is also the time when all repairmen recovering edge f arrive. G is the collection of repairmen who maintain the same edge.

$$T_\varphi = \max_{f \in Q_\varphi}\{f_\varphi^{*f}\} \quad (13)$$

In Equation (13), T_φ represents the completion time of the area.

Through the above maintenance skills and time constraints, the constraints model of intra-area maintenance is as follows. The optimized objective function is specifically described as

$$\min_{M_\varphi} T = \min_{M_\varphi}\left[\max_{f \in Q_\varphi}\left\{\max_{w \in G}\{t^{fw}\} + \sum_{\xi \in a} t_\xi^{fw}\right\}\right]. \quad (14)$$

Subject to

$$\sum_{\xi \in a} \mathrm{B}_{t\xi}^w \le 1, \forall w \in S_\varphi, \quad (15)$$

$$\max_{w \in S_\varphi}[Y_\xi^{fw}] = R_\xi^f, \forall f \in Q_\varphi, \quad (16)$$

$$\sum_{w \in S_\varphi} \mathrm{S}_{\xi\theta}^{wf} = Q_{\xi\theta}^f, \forall f \in Q_\varphi, \forall \xi \in a, \quad (17)$$

$$\mathrm{Y}_\xi^{fw} \le \psi_\xi^w, \forall f \in Q_\varphi, \forall w \in S_\varphi, \forall \xi \in a, \quad (18)$$

$$\sum_{f \in Q_\varphi} \mathrm{Z}_t^{fw} \le 1, \forall w \in S_\varphi, \quad (19)$$

$$2 \le |\Omega| \le Q_\varphi - 1, \Omega \subset Q_\varphi. \quad (20)$$

Eq. (15) restricts the repairmen to use one skill at a certain time. Eq. (16) screens out repairmen who meet the skills required for a failed edge. Eq. (17) restricts the number of skills used by repairmen in an edge to meet the number of skills that this edge need. $\mathrm{S}_{\xi\theta}^{wf}$ is the number of skills used by a repairman in an edge. $Q_{\xi\theta}^{f}$ is the number of skills needed by an edge. The collection of the number of skills is $J = \{J^1, J^2 \dots J^\theta\}$. Eq. (18) prevents sending a repairman who does not have skill ξ to fix it.

Eq. (19) restricts the repairmen to be at one fault edge at a certain time. Eq. (20) is used to eliminate the sub-loop constraint. $|\Omega|$ is a number of elements in set composed of all subsets of the fault edge set, which eliminates the solution that satisfies other constraints but does not constitute a complete path.

4.2.Inter-area maintenance

Inter-area maintenance is the scheduling process controlled by MCs in their areas. The collection of repairmen is $S = \{S_1, S_2 \dots S_\varphi \dots S_n\}$. The collection of maintenance tasks is $Q = \{Q_1, Q_2 \dots Q_\varphi \dots Q_n\}$. The decision matrix of maintenance time is obtained by

$$\mathrm{T}^* = \begin{bmatrix} t_1^{Q_1^1 S_1^1} & t_1^{Q_1^1 S_1^2} & \cdots & t_1^{Q_1^1 S_1^w} & \cdots & t_1^{Q_1^1 S_1^W} & \cdots & t_1^{Q_1^1 S_n^W} \\ t_2^{Q_1^2 S_1^1} & t_2^{Q_1^2 S_1^2} & \cdots & t_2^{Q_1^2 S_1^w} & \cdots & t_2^{Q_1^2 S_1^W} & \cdots & t_2^{Q_1^2 S_n^W} \\ \vdots & \vdots & & \vdots & & \vdots & \vdots & \vdots \\ t_\xi^{Q_1^f S_1^1} & t_\xi^{Q_1^f S_1^2} & \vdots & t_\xi^{Q_1^f S_1^w} & \vdots & t_\xi^{Q_1^f S_1^W} & \cdots & t_\xi^{Q_1^f S_n^W} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ t_Z^{Q_1^F S_1^1} & t_Z^{Q_1^F S_1^2} & \vdots & t_Z^{Q_1^F S_1^w} & \vdots & t_Z^{Q_1^F S_1^W} & \cdots & t_Z^{Q_1^F S_n^W} \\ \vdots & \vdots & \cdots & \vdots & \cdots & \vdots & \vdots & \vdots \\ t_Z^{Q_n^F S_1^1} & t_Z^{Q_n^F S_1^2} & & t_Z^{Q_n^F S_1^w} & & t_Z^{Q_n^F S_1^W} & \cdots & t_Z^{Q_n^F S_n^W} \end{bmatrix}. \tag{21}$$

Equation (21) denotes the time that the inter-areas repairmen used a skill to repair a failed edge.

The optimized objective function is specifically described as

$$\min_M T^* = \min_M \left[\max_{f \in Q} \left\{ \max_{w \in G} \{t^{fw}\} + \sum_{\xi \in a} t_\xi^{fw} \right\} \right]. \tag{22}$$

Subject to

$$\sum_{\xi \in a} \mathrm{B}_{\varphi t \xi}^{w} \le 1, \forall w \in S, \forall \varphi \in M, \tag{23}$$

$$\max_{w \in S_\varphi} Y_{\varphi\xi}^{fw} = R_{\varphi\xi}^{f}, \forall f \in Q_\varphi, \forall \varphi \in M, \tag{24}$$

$$\sum_{w \in S_\varphi} \mathrm{S}_{\varphi\xi\theta}^{wf} = Q_{\varphi\xi\theta}^{f}, \forall f \in Q_\varphi, \forall \varphi \in M, \forall \xi \in a, \tag{25}$$

$$\mathrm{Y}_{\varphi\xi}^{fw} \le \psi_{\varphi\xi}^{w}, \forall f \in Q_\varphi, \forall \varphi \in M, \forall \xi \in a, \tag{26}$$

$$\sum_{f \in Q_\varphi} \mathrm{Z}_{\varphi t}^{fw} \le 1, \forall w \in S_\varphi, \forall \varphi \in M, \tag{27}$$

$$2 \le |\Omega| \le Q_\varphi - 1, \Omega \subset Q_\varphi, \forall \varphi \in M. \tag{28}$$

4.3.Optimization algorithm

The algorithm is used to solve the above two models and obtained the optimal maintenance plan [12, 5]. It works by coding and searching multiple peak values in parallel to find a globally optimal solution [15]. In the diploid algorithm, two populations exchange the genetic information carried by excellent individuals [16]. They break the balance within the population and achieve a higher equilibrium state, which is conducive to the algorithm out of the local optimal solution [14].

Considering the maintenance sequence of fault edges and the failure causes, this paper takes multi-skilled repairmen as the research object and seeks an optimal maintenance plan. Table 1 shows the algorithm process of the maintenance model of urban transportation networks.

Table 1. The algorithm process of protection model of urban transportation networks.

Input	Urban transportation network and the process parameters
Output	The minimum total maintenance time (T and T^*)
1	Construct $G = (V, E)$ in GA
2	Initialize: parameter set $\{C, F, N, p_c, p_m, \tau, \sigma\}$
3	$GEN = 0$
4	**while** $GEN \le \sigma$ **do**
5	**for** $i = 1$ to N **do**
6	$fitness = \frac{1}{T}$;
7	**end for**
8	**for** $i = 1$ to N **do**
9	$i = max\ fitness(k), k \in N$;
10	repeat step 6 **until** $\sum i = N$;
11	**end for**
12	**for** $i = 1$ to N **do**
13	crossover operation to GEN
14	**end for**
15	**for** $i = 1$ to N **do**
16	mutation operation to GEN
17	**end for**
18	$GEN = GEN + 1$
19	**end while**
20	**end**

5. Case study

This section verifies the proposed model by analyzing the transportation network of a city in China. Section 5.1 illustrates the basic information about the network. Section 5.2 analyzes the process of the cascading failures. Section 5.3 obtains the maintenance plans under intra-area maintenance and inter-area maintenance.

5.1.Urban transportation network

A complex network consisting of 280 edges and 170 nodes is obtained by the map company whose official website is https://report.amap.com. Fig. 5 shows the intercepted network is bounded by expressways and includes city loops, national roads, and provincial roads inward. Fig. 6 shows nodes and edges in the intercepted network. The simulation is divided into 2 steps: (1) cascading failures analysis; (2) maintenance optimization.

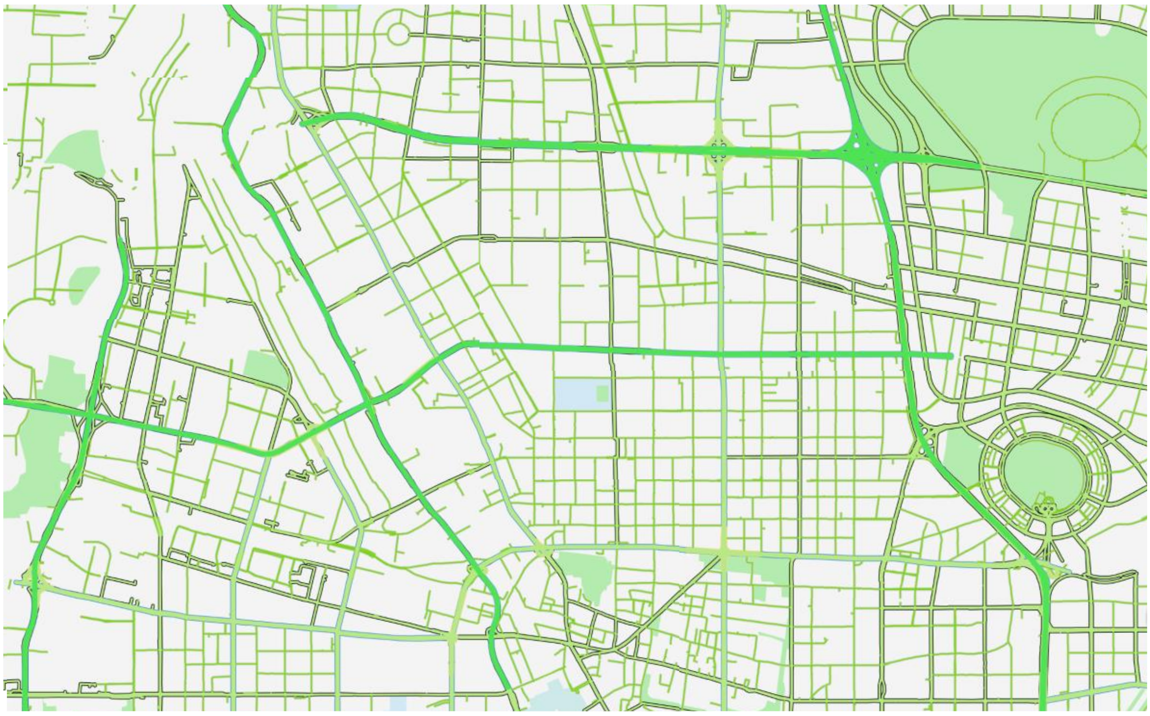

Fig. 5. Transportation network consisting of 280 edges and 170 nodes.

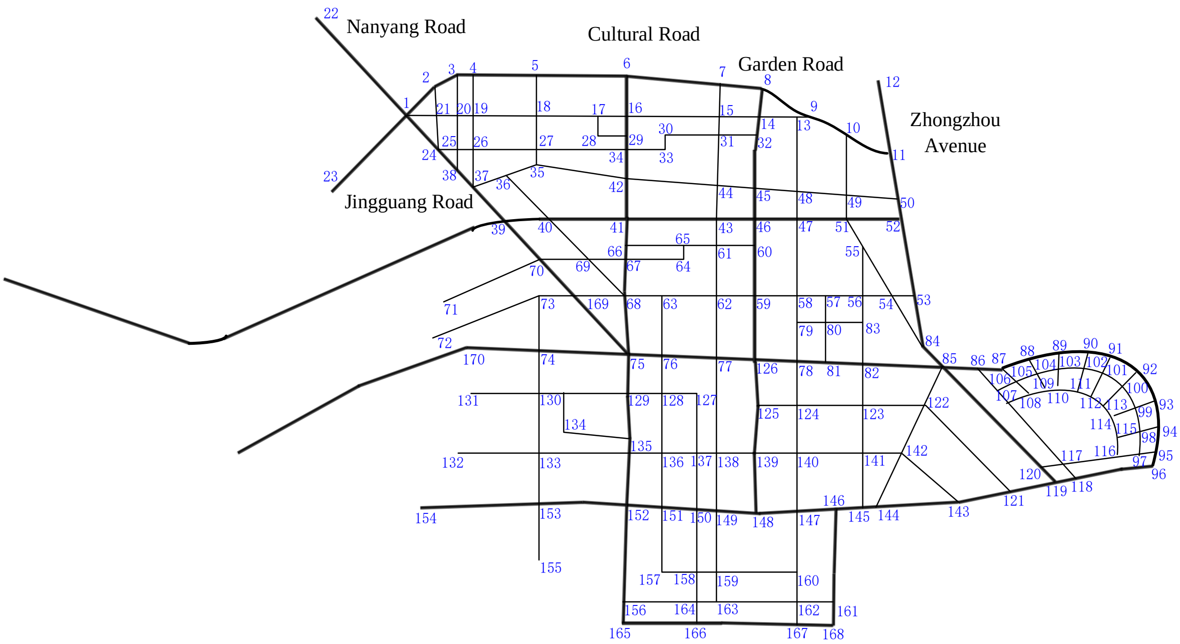

Fig. 6. Nodes and edges in the intercepted network.

5.2.Cascading failures analysis

Fig. 7 shows the congestion degree, causes, and required skills for the initial faulty edges. Fig. 8 shows the maintenance skills repairmen have. An MC has four repairmen whose numbers are S^1, S^2, S^3, and S^4.

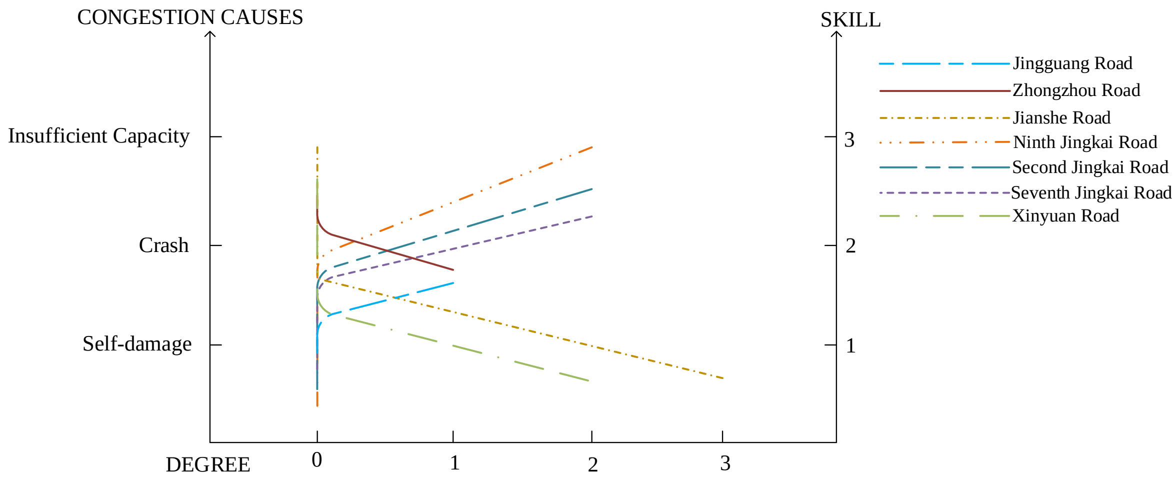

Fig. 7. The congestion degree, causes, and required skills for the initial faulty edges.

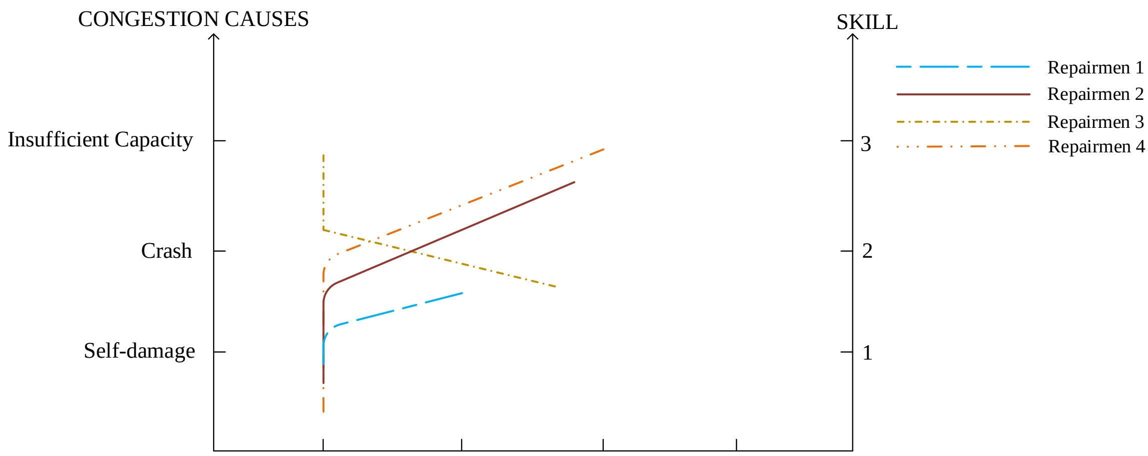

Fig. 8. The maintenance skills repairmen have.

Table 2 shows the weighted value of edges. According to the proposed traffic distribution model, the initial fault edges are e (119,120), e (1,23), e (150,151), e (85,122), e (78,79), e (32,45), and e (59,62).

Table 2. The weighted value of edges.

Roads	Edges	Weighted value	Edges	Weighted value
Zhongzhou Avenue	e (11,12)	2	e (53,84)	6
	e (11,50)	4	e (84,85)	8
	e (50,52)	4	e (85,120)	8
	e (52,53)	4	e (119,120)	4
Jingkai Road	e (58,79)	6	e (78,79)	6
Xinyuan Road	e (63,68)	8	e (62,63)	6
	e (59,62)	9	-	-
Jianshe Road	e (150,151)	9	e (149,150)	9
	e (148,149)	6	-	-
Jingkai Road	e (14,32)	6	e (32,45)	6
	e (45,46)	9	-	-
Jing guang Road	e (1, 2)	6	e (2,3)	4
	e (3,4)	4	e (4,5)	4
	e (5,6)	4	e (6,7)	4
	e (7,8)	4	e (8,9)	4
	e (9,10)	4	e (10,11)	4
	e (1,23)	8	-	-
Jingkai Road	e (142,144)	6	e (122,142)	9
	e (85,122)	12	-	-

Table 3 shows the faulted edges at each level. The flow of initial fault edges is greater than its capacity. Excess flow propagates from the initial fault edges to the second-level fault edges. Second-level fault edges propagates third-level fault edges. The propagation time at each level is the average time to pass the two edges. Fig. 9 shows congestion areas in the transportation network. There is one cascading failure in Area 1, and two in Area 6. The failed edge e (45, 46) in MC2 and e (46, 60) in MC4 are connected to form inter-area congestion.

Table 3. The fault edges at each level.

	Zhongzhou avenue	Jingguang road	Jianshe road	Ninth Jingkai	Second Jingkai	Seventh Jingkai	Xinyuan road
Second-order edges	e (117,120) e (118,119)	e (1,2) e (1,21)	e (149,150) e (137,150) e (151,157)	e (122,123) e (85,120) e (122,142)	e (58,79) e (79,80) e (78,126)	e (31,32) e (14,32) e (44,45)	e (59,60) e (62,63) e (59,126)
Third-order edges	e (119,121)	e (2,3) e (2,21) e (20,21)	e (148,149) e (138,149) e (137,138) e (136,151) e (151,152)	e (121,122) e (84,85) e (142,143)	e (57,58) e (77,126)	e (31,44) e (26,30) e (30,33) e (33,34) e (42,44) e (13,14) e (45,48) e (45,46)	e (60,61) e (61,62) e (58,59) e (77,126)
Fourth-order edges	-	e (3, 20) e (19, 20)	e (135,136) e (136,137) e (138,139) e (139,148)	e (121,143) e (143,144)	e (57,80)	e (34,42) e (41,42) e (46,60) e (13,48) e (9,13) e (48,49) e (47,48)	e (46,60)

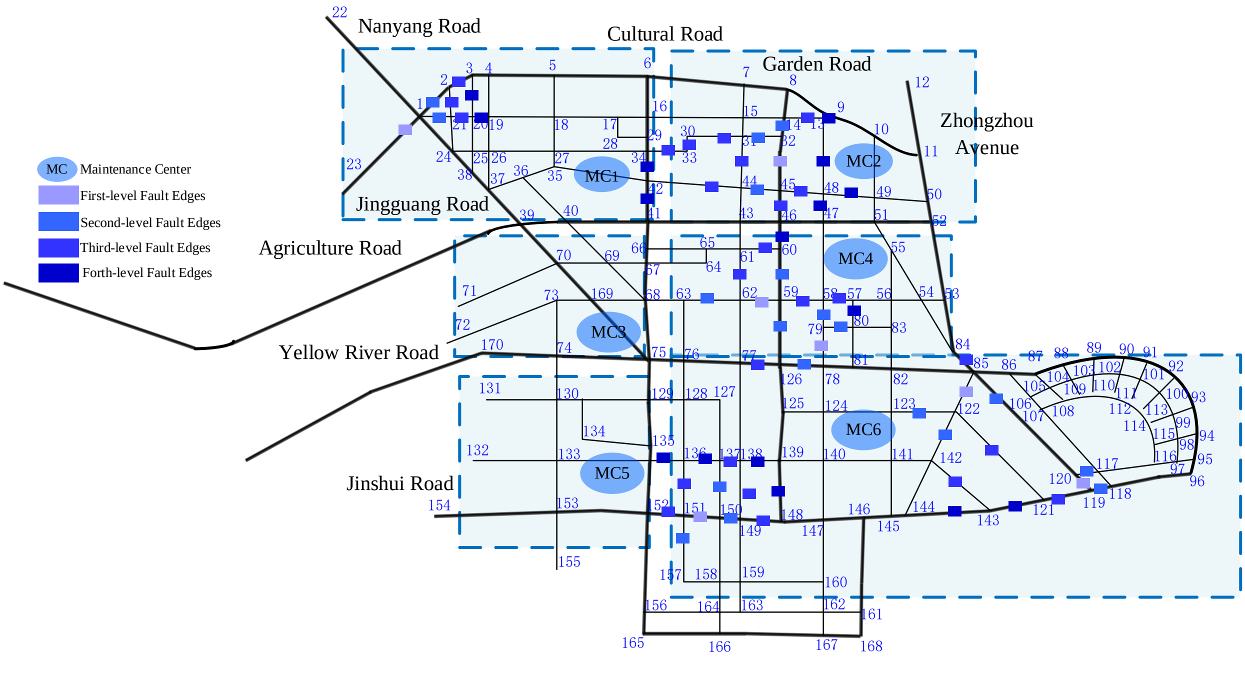

Fig. 9. Congestion areas in the transportation network.

5.3.Maintenance optimization

According to Fig. 9, the fault edges of MC1 are recovered by the intra-area maintenance mode. MC3 and MC5 have no congestion. Their repairmen are scheduled in MC4 and MC6. MC2, MC3, MC4, MC5, and MC6 are applicable to the inter-area maintenance mode. Areas controlled by MC4 and MC6 have more than one congestion event, and the congestion propagation caused by different initial fault edges is linked together to form a larger congestion.

Fig. 10 shows the fault degree of edges in MC1, MC2, MC4, and MC6. The horizontal axis is the failure edges. The longitudinal axis is the degree of failure which is divided into level 1, level 2, and level 3. A high degree of failure indicates the need for a greater number of skills. The fault edges in the MC1 are illustrated as an example. In Fig. 10 (a), e (1, 21), e (2, 3), e (3, 20), and e (19, 20) are level 3. e (1, 23), e (1, 2), e (2, 21), and e (20, 21) are level 1. Compared with the latter, the former requires more skills to clear congestion than the latter. Therefore, the repairmen are matched with failed edges according to the fault degree to shorten the recovery time.

The optimization parameters are set as follows. The population size is N = 50. The crossover probability is Pc = 0.9. The mutation probability is Pm = 0.5. The number of iterations is 500. Figs. 7, 8, and 10 is the input value of the models, and the optimization result is finally obtained by GA.

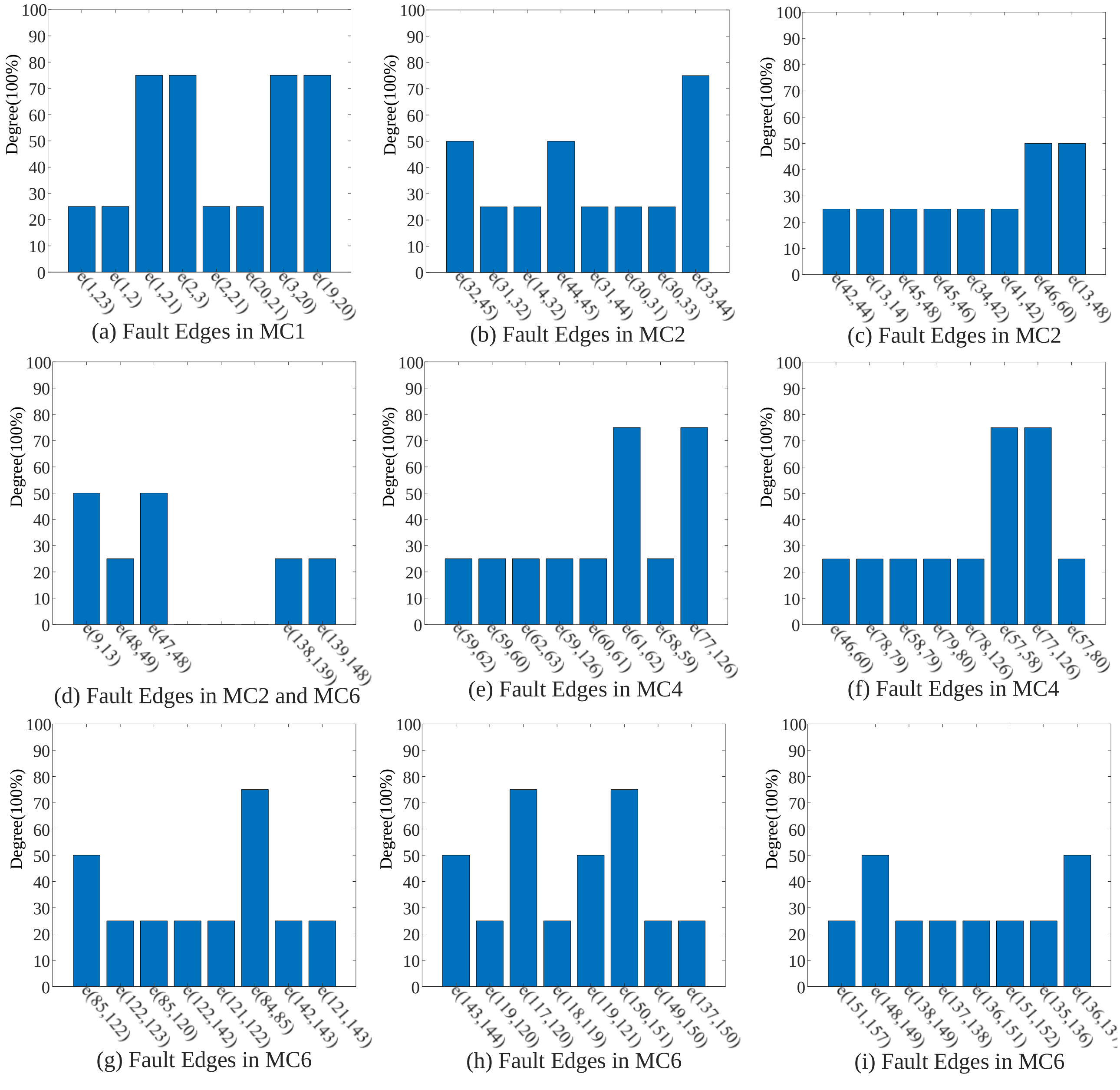

Fig. 10. The fault degree of edges in MCs.

Table 4 shows the result of maintenance optimization. The two congestion areas of MC6 both have 13 congestion edges, but the maintenance time is 8.625 minutes and 14.850 minutes, respectively. The data correspond to the congestion degree of the two, and the congestion area with a short maintenance time has a low congestion degree. MC1 has 8 fault edges and takes 11.951 minutes to recover the edges. The congestion area composed of MC2 and MC4 has 40 congestion edges, but the protection time is close to that of MC1. This indicates that the number of repairmen plays an important role in maintenance, as they have 4 and 12 repairmen, respectively.

Table 5 shows the maintenance sequence and time of repairmen. "2021 China's Major Cities Traffic Analysis Report" data show that the average delay index of the Road network is 1.649, and the average speed in peak periods is 29.54km/h. According to the congestion scale, this model provides area maintenance optimization plans to control the maintenance time within 10 to 30 minutes, saving residents' travel time to the greatest extent. Therefore, the proposed models have certain feasibility.

Table 4. The result of maintenance optimization.

MC	Edges number	Repairmen number	Maintenance time(min)
MC1	8	4	11.951
MC2	40	16	11.298
MC4	40	16	11.298
MC6	13	4	8.652
	13	4	14.850

Table 5. The maintenance sequence and time of repairmen.

Congestion area	personnel number	Repairmen maintenance sequence	Time(min)
1	S_1^1	e (1,23)	—
	S_1^2	e (1,2), e (1,21), e (2,21), e (2,3)	10.071
	S_1^3	e (1,21), e (21,20), e (3,20), e (2,3)	9.093
	S_1^4	e (19,20), e (3,20)	5.499
2	S_2^1	e (59,62)	
	S_2^2	e (41,42), e (34,42), e (33,34), e (30,33), e (30, 31)	7.891
	S_2^3	e (9,13), e (13,14), e (14,32), e (31,32), e (31,44), e (42,44)	10.760
	S_2^4	e (9,13), e (13,48), e (48,49), e (47,48)	3.195
	S_3^1	—	—
	S_3^2	e (77,126), e (59,126), e (59,60), e (46,60)	8.944
	S_3^3	e (77,126), e (78,126), e (78,79)	7.856
	S_3^4	e (32,45), e (45,48), e (44,45), e (45,46)	8.888
	S_4^1	—	—
	S_4^2	e (62,63), e (61,62), e (60,61), e (46,60)	8.821
	S_4^3	e (57,80), e (57,58), e (58,59)	8.130
	S_4^4	e (57,80), e (79,80), e (58,79)	5.494
3	S_5^1	e (150,151)	—
	S_5^2	e (148,149), e (139,148), e (138,139), e (137,138), e (136,137)	8.489
	S_5^3	e (148,149), e (138,149), e (149,150), e (137,150), e (136,137)	7.057
	S_5^4	e (151,157), e (151,152), e (136,151), e (135,136), e (136,137)	8.652
4	S_6^1	e (119,120)	—
	S_6^2	e (118,119), e (119,121), e (121,122), e (121,143), e (143,144)	10.073
	S_6^3	e (84,85), e (85,120), e (117,120)	9.175
	S_6^4	e (84,85), e (85,122), e (122,123), e (122,142), e (142,143)	15.083

6. Conclusions and future work

The maintenance plan is momentous to restore urban transportation networks. This paper proposed a traffic distribution model and area maintenance optimization models to resume a transportation network. The results show that on the premise of dividing traffic areas, the proposed intra-area and inter-area maintenance plans save more time than the previous travel data. Some limitations and our future research directions are as follows.

- The road network has been described as an undirected graph. In the city, there is often a situation where driving one way on a given road takes a different amount of time than the other. We would consider modeling with a directed graph (i.e., dealing with different flows in time depending on the direction).
- Considering the limitations of the current model, some technical aspects of the model would be further developed.
- Consider using different variations of the genetic

algorithm, or even a completely different technique in future research.

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