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Optimization method for evacuation zone with network reconfiguration based on dynamic simulation

Zhao Xing[1] Ren Gang[2] Zhang Xiaoli[1] Li Yan[3]

([1]College of Civil and Transportation Engineering, Hohai University, Nanjing 210098, China)
([2]School of Transportation, Southeast University, Nanjing 210096, China)
([3]NARI Technology Co., Ltd., Nanjing 210061, China)

Abstract: With a determinate danger zone and evacuation demand caused by an emergency, an optimization method for the evacuation zone with network reconfiguration based on dynamic simulation is proposed. The method contains three modules. First, the network in the evacuation zone is optimized by a model with the integrated strategy of lane reversal and intersection conflict elimination. Secondly, the dynamic evacuation simulation model based on the cell transmission model is applied to simulate the dynamic propagation process of evacuated vehicles in the network in the evacuation zone. The evacuation time for all evacuated vehicles leaving the danger zone is obtained and the setting of the current evacuation zone is fed back. Thirdly, the arrival distributions of evacuated vehicles at critical intersections of the evacuation zone are also obtained to estimate the delay at critical intersection to determine whether the intersection should be taken as the critical intersection in the next iteration. The evacuation zone is expanded gradually through iteration, and the reasonable evacuation zone and the optimal evacuation network is confirmed. Based on the survey of the parking lot and urban street network around Nanjing Olympic Sports Center, the models and the iterative algorithm were applied to obtain the optimal plan of the evacuation zone with network reconfiguration in an evacuation situation to verify the validity of the proposed method.

Key words: evacuation zone; cell transmission model; traffic network reconfiguration; intersection delay

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Once an emergency breaks out, an influence area will be generated accordingly. For those emergencies which need evacuation, there will be an evacuation zone. During the evacuation process, the evacuation zone does not allow flows into it . Meanwhile, in the evacuation zone, managers need to optimize the network by redistributing the capacities of roads and intersections based on the available transport infrastructure, to enable the evacuated vehicles to depart from the danger zone as soon as possible.

Aimed at the components of the evacuation zone and the relationship between each other, Barrett et al. [1] divided the evacuation zone into three parts, namely the immediate response zone (IRZ), protective action zone (PAZ), and precautionary zone (PZ). Hamza-Lup et al. [2] put forward the concepts of the evacuation zone (EZ), secondary zone (SZ) and evacuation exit point (EEP). Hu[3] held the view that once an emergency occurs, the fatality of the incident will increase at a same gradual trend; therefore, the influence area consists of a series of concentric circles whose centers are the event source. Study of the danger zone of evacuation is rare in transportation research. Wilmot and Medufi[4] adopted a set of criteria to design a procedure that mechanically establishes a recommended set of hurricane evacuation zones for an area based on a GIS platform to provide a graphic display of results and to facilitate calculation of the mean and standard deviation of the large number of elevation points involved. The buffer zone is often set according to the distribution and trend of the skeleton network and the location of shelters in evacuation planning. Hamza-Lup et al. [2] made a demarcation for the secondary zone (SZ) where multiple incidents occur simultaneously. They also certified the role and efficiency of the SZ evacuation by an example. Hu et al. [5] proposed a method to determine the traffic influence area caused by an emergency, which determined the buffer zone through the re-assignment of the traffic flow, rolling optimization and evaluation of the scheme.

Existing researches and practices did not develop consistent methods to set the evacuation zone in a certain situation. It is judged empirically, for example in accordance with the severity, spread rate and direction of the hurricane and flood. However, it is more difficult to analyze the traffic influence of an evacuation than that of a new real project and a traffic accident, since evacuation requires routing traffic away from roadway segments inside the affected regions [2]. In most cases, the decision to set up the evacuation zone is empirical, arbitrary and

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Biography: Zhao Xing (1986—), female, doctor, lecturer, bright-0701@163.com.

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rough without quantitative calculations. However, in other models which design the evacuation zone quantitatively, modeling for network optimization and traffic organization in the evacuation zone was not contained. It might make the designated area more extensive than that of real need, leading to unnecessary interference to the area outside of the evacuation zone. Therefore, the optimization method for the evacuation zone with the network reconfiguration in the evacuation zone is the research emphasis of this paper, and it is the priority of emergency evacuation planning as well.

Lane reversal is the most widely used in the evacuation network optimization problem. It improves the capacity of one direction by reversing all or part lanes of the opposite direction, for relieving the traffic pressure from oversaturated flow off the evacuation zone. Plenty of research focused on strategies and algorithms for implementing reversal lane[6-7]. Most traffic delays during an evacuation occur at intersections; therefore, eliminating intersection conflicts would improve the evacuation efficiency[8]. Xie et al. [9-10] made a study on the combination of these two strategies, and proposed an optimization model and algorithm for the evacuation network in a certain evacuation zone. This paper adopts the integrative strategy of lane reversal and conflicts elimination as well.

Based on a determinate danger zone and evacuation demand, this paper proposes an optimization method to determine the evacuation zone with the network reconfiguration by means of dynamic simulation. The dynamic evacuation simulation model based on CTM is applied to simulate the dynamic propagation process of evacuated vehicles on the re-designed network in the evacuation zone[11]. The evacuation time for all evacuated vehicles leaving the danger zone is obtained, and the setting of the current evacuation zone is fed back in the light of a preset threshold value of the evacuation time. The arrival distributions of evacuated vehicles at critical intersections are acquired as well[12]. The delay at critical intersection calculated based on the vehicle arrival is used to design whether the intersection should be taken as the critical intersection in the next iteration. The network in the evacuation zone is optimized by the integrated strategy of lane reversal and intersection conflict elimination. Thus, the evacuation zone is expanded gradually, and the reasonable evacuation zone and the optimal evacuation network will be confirmed.

1 Modeling

1.1 Problem description

The incident occurrence location is defined as the incident node (IN), and EZ is defined to include danger zone (DZ) and buffer zone (BZ) in this paper. Therefore, the DZ is the area under immediate danger, which differs from the nature, category, severity level and controllability of the emergency. The BZ is the indirect impact area, in which the threat of the incident can be controlled reasonably. Nevertheless, for the reason that the network in the DZ will carry a huge traffic volume in a short time, it will result in significant delays on congested road sections and in intersections unless traffic organizations and controls are implemented in a larger area than the DZ during evacuation. Consequently, in order to encourage the traffic flow to depart from the DZ, it should form a certain BZ surrounding the DZ.

Due to the variety of emergency categories, it ought to determine DZs after analyzing the threat levels of different kinds of emergencies, nature conditions and environmental conditions around the IN. We do not discuss this problem in this paper. The BZ, of which the inner boundary is the boundary of the DZ, is taken advantage of to relieve the traffic jam in the DZ, and its outer boundary of the buffer zone is the demarcation of the evacuation zone and safe zone. The demarcation points are defined as the critical intersection (CI), and the vehicles outside of the EZ are not allowed to flow into it.

The existing vehicles on roadways and the potential traffic flow in the DZ create the evacuation demand, because all traffic in the DZ should leave that region. No evacuation demand is generated in the BZ owing to the reasonable control of the threat level caused by the incident in that region.

1.2 Main process of the algorithm

This paper proposes a method to determine the optimal EZ with the network reconfiguration. It can help planners formulate and implement an evacuation plan to make the evacuated vehicles leave the DZ as quickly as possible, and reduce interferences from the evacuation to the traffic in normal operation.

The proposed method contains three modules, which are the evacuation network optimization module, dynamic evacuation simulation module, and intersection delay module. The modules coordinate together and the algorithm process of the method based on the modules is shown in Fig. 1.

The expanding procedure of the EZ is as follows: If the delay at a current CI is larger than the preset threshold value, set the neighboring intersections of the CI which are outside of the EZ as the new CIs in the next iteration. The initial EZ is the DZ. The convergence criterion of the iterative algorithm is that the time for all evacuated vehicles leaving the DZ or the delays at all CIs meets the requirement.

1.3 Evacuation network optimization model

Aiming at the issue of evacuation network optimization in the EZ, the network is re-designed by the integrative strategy of lane reversal and intersection crossing conflicts

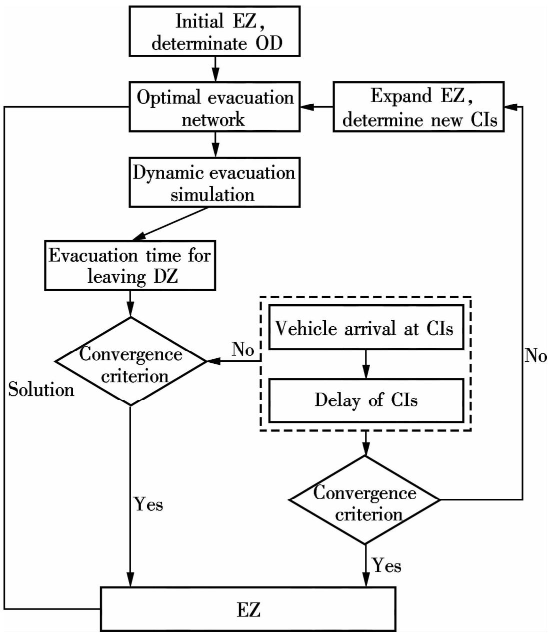


Fig. 1 Flow chart of the proposed method

elimination based on the available traffic facilities. In this model, it takes the points of traffic generation as the origins and the CIs as destinations. For the strategy of lane reversal, the constraints for the road section as shown in Fig. 2 are as follows:

$$n_{js} = n_{sk} = n_{jk}, \quad n_{lt} = n_{tm} = n_{lm}$$
$$\forall (j, s), (s, k), (l, t), (t, m) \in L \tag{1a}$$

$$n_{jk} + n_{lm} = n(r_{jk, lm}) \qquad \forall (j, k), (l, m) \in L, \ \forall r_{jk, lm} \in R \tag{1b}$$

$$n_{jk}, n_{lm} \geqslant 0 \text{ and integer } \forall (j, k), (l, m) \in L \tag{1c}$$

Eq. (1a) shows that the numbers of lanes should be the same for consecutive link pair; Eq. (1b) means that the sum of the numbers of lanes of two directions is equal to the total number of lanes of the street section; Eq. (1c) shows that the number of lanes of each direction is non-negative integral.

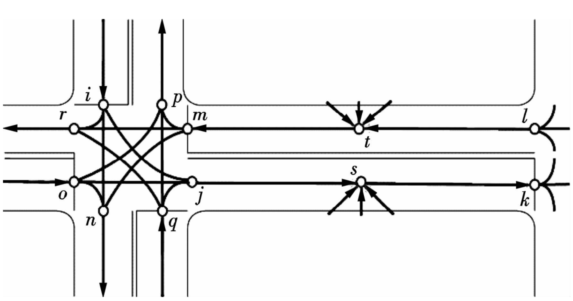


Fig. 2 The network representation

For the strategy of crossing conflict elimination, according to the relative position of the nodes of an intersection, constraints for the intersection as shown in Fig. 2 can be expressed as follows: 1) Non-coexistence of the straight lane groups of two adjacent approaches; 2) Pairwise non-coexistence of the left turn lane groups of two adjacent approaches and the straight lane group of the clockwise approach.

$$y_{mr} + y_{qp} \leqslant 1, \ y_{ij} + y_{mn} + y_{qp} \leqslant 1$$
$$\forall (m, r), (q, p), (i, j), (m, n) \in E \tag{2}$$

where R is the set of road sections, and a road section is the roadway between two adjacent intersections; L is the set of links; E is the set of connectors; $n(r_i)$ is the total number of lanes of road section r_i, $\forall r_i \in R$; n_{ij} is the number of lanes of link (i, j), $\forall (i, j) \in L$ or number of lanes of consecutive link pair $[(i, o), (o, j)]$, $\forall (i, o), (o, j) \in L$; y_{ij} is the connectivity indicator of connector (i, j), $\forall (i, j) \in L$.

This module combines the two above-mentioned strategies effectively, takes the intersection conflicts as the punishment term of the objective function, and conducts the traffic assignment on the basis of the stochastic user equilibrium method. By means of a tabu search algorithm, the optimal evacuation network with the strategies of reversal lane operation and conflict elimination can be obtained.

For optimizing the evacuation network with this model, many road sections on the network are one-way and intersection crossing conflicts are eliminated in the EZ.

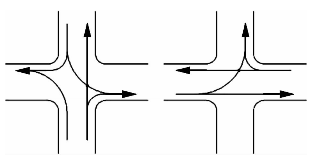
1.4 Dynamic evacuation simulation model

In this paper, the dynamic evolution progress of evacuation traffic flow is simulated by the improved CTM model. The propagation of traffic flow on the evacuation network is embodied in the road sections and intersections. Unlike the traditional CTM model, it does not need the parameter of the green split of each intersection approach, because all the intersections are non-signalized and the traffic flows of all turnings are treated as continuous flows due to intersection crossing conflict elimination of the network optimization model. The traffic propagation rule at intersections can be reflected through different constraints of the first and last cells of the link: The first cell may be an ordinary cell or a merging cell[13], so the traffic capacity of the merging cell decreases; the end cell may be an ordinary cell or a diverging cell. The types of cells which are taken into consideration in the improved CTM model consist of single link, merging link, diverging link and ordinary cells within a link. The equations of traffic flow propagation are introduced by Zhao et al[11].

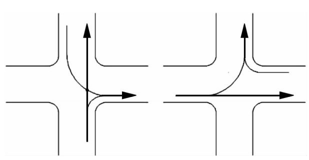
The dynamic evacuation simulation model based on CTM and the stochastic user equilibrium traffic assignment method is applied to simulate the dynamic propagation process of evacuated vehicles on the re-designed network in the EZ; the evacuation time for all evacuated vehicles leaving the DZ is obtained. The calculation of evacuation time is compared with the preset threshold value. If it is smaller, the current EZ and the network reconfiguration is the solution; if it is larger, the arrival distributions of evacuated vehicles at CIs are calculated, which provide a basis for the delay calculation of CIs.

1.5 Intersection delay model

There is at least one leg of CI inside the EZ, and the legs are usually one-way[9]. Meanwhile, there is at least one leg outside of the EZ. Therefore, there can only be two configurations for CI as shown in Fig. 3. It can be found from Fig. 3 that these two kinds of intersections both have opposing conflicts. Due to the high volume of traffic in evacuation situations, CI is usually signalized. The phase setting of signalized intersection varies, involving two phases, three phases, four phases and more. There are different schemes of phase setting for different intersections because of different traffic volumes with different turnings, even if the configurations of intersections are consistent. Fig. 3 illustrates the common settings of two-phase under the corresponding intersection configuration.



(a)



(b)

Fig. 3 Phase settings of CI. (a) One leg in EZ; (b) Two legs in EZ

Vehicles at signalized intersection approaches queue in line during red time and travel during green time. The intersection approaches can be classified according to the traffic conditions by the value of saturation $x = \dfrac{q(k)c(k)}{sg(k)}$. Here, s is the saturation flow rate of an approach, veh/s; $q(k)$ is the vehicle arrival rate of the approach in the interval k, $q(k) = \dfrac{y_{iS}(k)C(k)}{t}$, veh/s; $g(k)$ is the effective green time in the interval k, s; $C(k)$ is the duration of the interval k, s; $y_{iS}(k)$ is the traffic volume from approach i to destination S, veh/s; t is the time interval of CTM, s.

The delay at an intersection is the sum of delay values of the intersection approaches, i. e. $D_{IN}(k) = \sum_i D_i(k)$. To obtain the minimum delay at CI, we estimate the delay value while only considering the traffic flows of approaches which are inside of the EZ. The delay values of each CI are compared with the preset threshold value. If any delay value is larger than the threshold values, search for the new CIs by the method mentioned before; if all the delay values are smaller, the EZ and the network reconfiguration is the solution.

2 Case Study

Based on the survey of the parking lot and the urban street network around Nanjing Olympic Sports Center, the proposed method and the above-mentioned iterative algorithm are applied to obtain the optimization plan of EZ with network reconfiguration in an incident scenario to verify the validity of the proposed method.

2.1 Scenario assumption

The incident was assumed to occur during a large-scale event which was held in Nanjing Olympic Sports Center. It caused a DZ as shown in Fig. 4, which includes Olympic Sports Center and the intersection 1. According to the usage data supplied by Traffic Administration Bureau, the Olympic Center had an underground parking lot which can park 3 000 vehicles. Therefore, vehicles in the parking lot had to evacuate from the DZ. The managers needed to conduct rational traffic management within a specific zone around the Olympic Sports Center to handle the large traffic demand of short-term traffic evacuation.

For the sake of simplicity, we assume that the evacuation traffic demand is 3 000 and all evacuated vehicles load at the origin node at the beginning of the evacuation. The traffic network and the specific parameters of road infrastructures around the Olympic Sports Center are shown in Fig. 4 and Tab. 1. The circles represent intersections, and the gray circle represents the starting point.

Considering the driver behavior characteristics in an

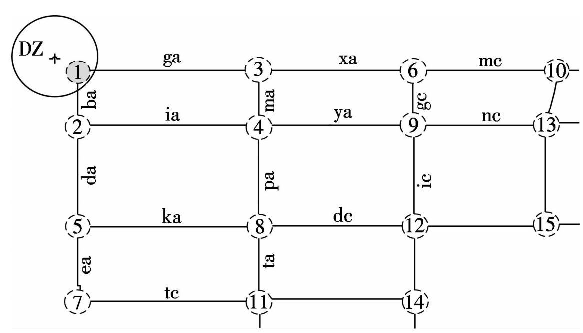


Fig. 4 Street network

Tab. 1 Basic information of the street section

Street	Length of street/m	Number of lanes	Street	Length of street/m	Number of lanes
ba	300	10	da	600	10
ea	450	10	ga	1 050	11
ia	1 050	8	ka	1 050	6
ma	300	8	pa	600	8
ta	450	8	xa	900	11
ya	900	8	dc	900	6
gc	300	8	ic	600	8
mc	825	10	nc	750	8
tc	1 050	10			

evacuation situation and based on the existing studies, we set the values of all the above parameters as Tab. 2.

Tab. 2 Parameter values

Parameter	Value
Free-flow speed/(km · h^{-1})	54
Road capacity(veh · (h · lane)$^{-1}$)	2 160
Merging capacity of a cell/(veh · (interval · lane)$^{-1}$)	2.7
Carrying capacity of a cell/(veh · lane^{-1})	15
Length of time interval/s	5
Jam density/(veh · m^{-1})	0.2
Backward propagation speed/(m · s^{-1})	6

2.2 Calculations

The solution algorithm presented above is coded in Microsoft Visual C++ and run on a desktop personal computer with a CPU of Intel Core(TM) 2 2.2 GHz and RAM of 2 GB. The computational time required to converge is about 11.8 min.

According to this method, after four iterative processes of expansion of the EZ, the final solution of the optimization plan of EZ with the network reconfiguration is eventually obtained. In each iteration, we can acquire the optimal network with lane reversal and crossing conflicts elimination strategies in the current EZ, the arrival distributions of evacuated vehicles at CIs, and the minimum delay at each CI.

2.2.1 Optimal evacuation network in the EZ

For the final solution, the roads within the region are all set as one-way during evacuation, and compose a closed region allowing traffic to flow out only; the permitted turnings at each intersection approach are shown in Fig. 5. The optimal networks of four iterative processes are all contained in this figure. For intersection 4, in order to avoid conflicts with the link "ia", straight ahead is forbidden for the link "ma" in the third and fourth iterations.

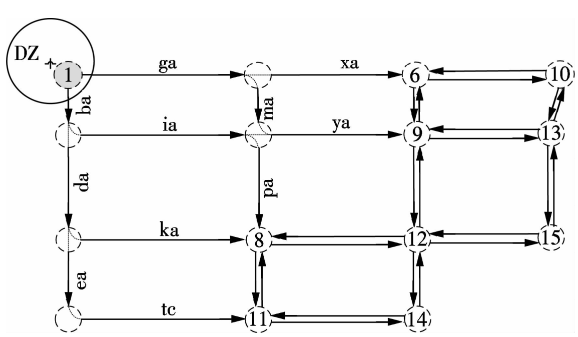


Fig. 5 Optimal evacuation network in the EZ

2.2.2 Delays at CIs

Delay values of each approach of CI and delays at CIs in each iteration are shown in Tab. 3. In this case, the threshold value of intersection delay for convergence criterion is set to be 50 s. Calculation does not terminate until the fourth iteration, in which the delay of each CI meets the threshold value.

Tab. 3 Delays at CIs

Iteration	Intersection	Approach	Delay at approach/s
1	2	aa	324.798
	3	fa	90.072
2	5	da	72.292
	4	ia	266.499
		ma	238.548
	6	xa	32.313
3	6	xa	41.082
	7	ea	65.394
	8	pa	39.729
		ka	31.534
	9	ya + gc	0
4	6	xa	47.045
	8	pa	45.447
		ka	36.876
	9	ya	0
	11	tc	0

2.2.3 Departures of evacuated vehicles from DZ

In this case, the threshold value of the time that all evacuated vehicles leave the DZ is set as default. The evacuation time for all evacuated vehicles leaving the DZ is 250, 270, 300, and 350 s in each iteration, respectively; the distributions of the numbers of remaining vehicles in DZ in each iteration can be obtained after further statistics as shown in Fig. 6. The curves of zones 1 to 4 represent the departure conditions of evacuated vehicles from DZ under the optimal EZ with network reconfiguration in iterations 1 to 4, respectively.

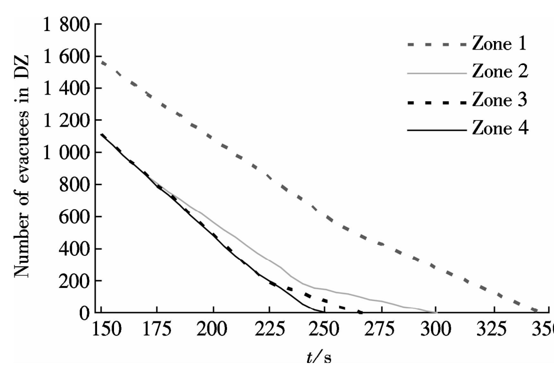


Fig. 6 Departures of evacuated vehicles from DZ

Only distributions in time intervals 30 to 70 s are shown Fig. 6, since the distributions in time intervals 0 to 30 s are extensions of the two lines in 30 to 36 s. As shown in Fig. 6, on the one hand, the evacuation time for all evacuated vehicles leaving the DZ decreases along with the expansion of the EZ. For example, compared with zone 1, the evacuation time of zone 4 decreases by 28.6%. On the other hand, as the EZ is expanded, there may be fewer remaining vehicles in the DZ for each time interval.

3 Conclusion

Focusing on EZ which is composed of DZ and BZ, this paper proposes an optimization method to determine the EZ with the network reconfiguration. The proposed method contains three modules, which are the evacuation network optimization module, the dynamic evacuation simulation module, and the intersection delay module. The proposed method can help planners formulate and implement the evacuation plan to enable the evacuated vehicles leave the DZ as quickly as possible, and reduce interference from the evacuation to the traffic in normal operation. To demonstrate the effectiveness of the proposed method, the proposed method and the iterative algorithm are applied based on the survey of the parking lot and the urban street network around Nanjing Olympic Sports Center, to obtain the optimization plan of the EZ with network reconfiguration in an incident scenario. For further research, the integration of the modules mentioned in this paper with the aid of Visual C++ to realize the program design will be enhanced.

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基于动态仿真与路网优化的疏散区域确定方法

赵 星[1] 任 刚[2] 张小丽[1] 李 岩[3]

([1] 河海大学土木与交通学院, 南京 210098)
([2] 东南大学交通学院, 南京 210096)
([3] 国电南瑞科技股份有限公司, 南京 210061)

摘要:在确定的突发事件危险区域与疏散需求基础上,提出了基于动态仿真与路网优化的疏散区域确定方法. 该方法包含3个模块:运用车道反向设置与消除交叉口冲突综合策略,对疏散区域内的路网进行优化;应用基于元胞传输模型的动态疏散仿真模型,对待疏散车辆在疏散区域内路网上的动态运行状况进行模拟,获取临界交叉口车辆到达的估计值和待疏散车辆离开危险区域的时间,并对当前疏散区域范围的设置进行反馈;基于疏散车辆到达临界交叉口的状况,计算临界交叉口延误,并将其作为该交叉口是否仍旧为下一次迭代的临界交叉口的判定值. 通过迭代,疏散区域范围逐渐扩大,最终确定合理的疏散区域与区域内的路网优化方案. 应用上述模型与迭代算法,基于南京奥体中心周边停车设施、道路网络分布与道路基础设施现状调查,获取疏散状况下的疏散区域与路网重构方案,验证了所提方法的有效性.

关键词:疏散区域;元胞传输模型;路网重构;交叉口延误

中图分类号:U491.1