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RESEARCH ARTICLE

Optimal Design of Multimodal Traffic Strategies in Emergency Evacuation Considering Background Traffic

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ABSTRACT In this work, we present the optimal design method of multimodal traffic strategies in emergency evacuations by considering the background traffic. First, the lane use configuration of public-oriented transport in multimodal evacuation that considers the background traffic is presented. Then, the feasible strategies are proposed based on the application conditions of five evacuation traffic strategies in feasible strategy proposal. Furthermore, the feasible strategies are transformed into optimal strategies by using the optimal strategy design model to minimize the weighted sum of public transport, private cars, and background traffic target values. Finally, the previous case study of Wenling is used to discuss the strategy evolution process, compare other strategies, and analyze the sensitivity of weights. The results presented in this work provide a reference for other researchers on the design and formulation of multimodal evacuation traffic strategies.

INDEX TERMS Multimodal traffic, evacuation strategies, background traffic, optimal design.

I. INTRODUCTION

The unexpected catastrophic events lead to the loss of economy and precious human lives. The strategies for implementing emergency evacuation of traffic are crucial for immediately evacuating people from the affected areas and for the prevention and reduction of causalities [1]. However, many individuals are unable to freely select the appropriate means of transport, such as private cars, due to poor health or financial weakness [2], [3]. These people overwhelmingly depend on the public transport in emergency evacuations. Therefore, an optimal design of multimodal traffic strategies is particularly important for formulating the emergency evacuation plans.

The multimodal evacuation traffic not only considers the optimal design of each single mode, but also analyzes the relationship of optimization results between multiple modes. Moreover, these works do not consider the non-vehicle modes (including walking, bicycle, and electric vehicle) due to the low evacuation speed and efficiency. Therefore, the research regarding multimodal evacuation traffic generally considers both the public and private means of transportation.

During emergency evacuation, the outbound lanes towards the evacuation destination (evacuation direction) usually get congested. On the contrary, the inbound lanes towards the evacuation source have a very low traffic volume. There are few works presented in literature that have applied the reversible lane strategy for improving the traffic capacity towards evacuation destination. Please note that this strategy has been widely used in the hurricane evacuation planning in the Atlantic and Gulf coast of the United States [4]. However, the background traffic, i.e., the existing vehicles before evacuation, also influence the emergency evacuation planning. Therefore, this work presents the design of a

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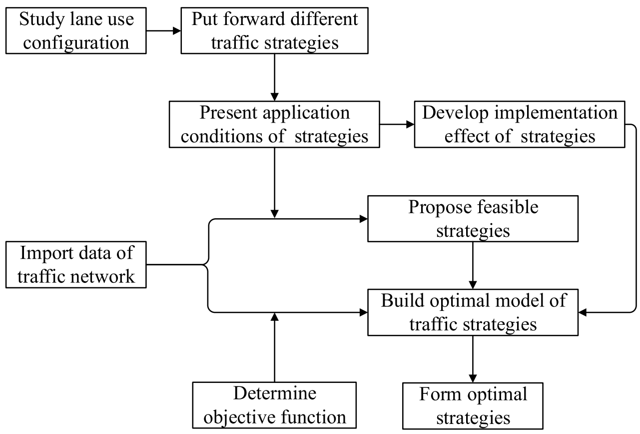

FIGURE 1. **The flowchart of the proposed method.**

public-oriented lane use configuration by considering the background traffic.

As there are only few optimal design models of multimodal evacuation traffic strategies that consider the background traffic, we propose a two-step design of multimodal traffic evacuation strategies for reducing the computational complexity introduced due to the presence of background traffic. First, a feasible strategy referred to as the first-step is proposed based on the application conditions of evacuation strategies. Second, an optimal strategy referred to as the second-step is established to address the problem of relationships among the public transport, private cars, and the background traffic according to the implementation effect of different strategies. Please note that the implementation effect is assumed to set up the association between two steps, i.e., the feasible strategy proposal and optimal strategy design. The results presented in this work can be a reference for the evacuation planers to provide the reasonable evacuation strategies, e.g., the priority of public transport and the influence of background traffic. A simplified flowchart is presented in Fig. 1 to effectively explain the proposed research process.

The rest of the paper is organized as below.

In Section II, we present the related works. Section III presents the study of the lane use configuration. In Section IV, the first-step design is proposed, and the implementation effects of different strategies are presented. In Section V, the second-step design, i.e., optimal model, is established. Section VI analyses the results of a case study applied on the Wenling city. Section VII summarizes the results from the previous sections and discusses the future works.

II. LITERATURE REVIEW

The background traffic is referred to as the vehicles that exist on the road before the onset of an emergency evacuation. The background traffic considerably influences the evacuation efficiency from the affected region, which in turn influences the design of the multimodal traffic strategies. However, it is noteworthy that there are only a few existing works presented in literature that consider the influence of the background traffic [5]–[7]. The authors in [5] proposed a spatio-temporal evacuation model to address multiple vehicle routing problems that can optimize the evacuation of background traffic based on the generated travel cost. In "Mathematics" journal, we presented a practical traffic assignment model for normal traffic [8]. In "IET Intelligent Transport Systems" journal, we proposed the optimal design model of multimodal traffic strategy in normal traffic [9]. In "IEEE Intelligent Transportation Systems Magazine" journal, we put forward a stochastic dynamic traffic assignment model for emergency evacuation that considers the background traffic [7]. In this work, we focus on the optimal design of multimodal traffic strategies under emergency evacuation considering background traffic based on the three aforementioned studies [7]–[9]. The literature review related to this work includes the lane use configuration and optimal design.

A. LANE USE CONFIGURATION

The traditional lane use configuration usually considers the reversible lane strategy to improve the traffic capacity in the affected regions, i.e., setting the inbound lane as the inbound lane [10]–[14]. The author in [10] summarized three types of designs for the implementation of reversible lane strategy, including reversing all lanes, reversing few lanes, reversing the road shoulder only. Lu *et al.* [13] proposed a design for reversible lane assignment that considers the relationship between traffic controllers and drivers based on a bi-level optimization model. Conceição *et al.* [14] presented a non-linear programming model based on reversible lane strategy for addressing the traffic assignment problem. In traditional lane use, a mixture of public and private means of transportation leads to low evacuation efficiency of public transport. Therefore, the multimodal lane use configuration for public transport has been a focus of research community [15], [16]. The authors in these works presented a public-oriented lane use configuration, where one inbound lane is set as the exclusive lane for the return of public transport, another inbound lane is set as the reversible exclusive lane for the evacuation of public transport, and both outbound lanes are set as the exclusive lanes for the evacuation of private cars.

However, please note that the existing methods [15], [16] based on multimodal lane use configuration fail to consider the clearance time of background traffic due to the implementation of evacuation strategy. In this work, we aim to address the aforementioned problems and propose a method that considers the background traffic according to the public-oriented transport multimodal configuration presented in [15] and [16]. Then, different traffic strategies are put forward to provide a theoretical basis for the two-step design of multimodal traffic evacuation strategies (Section IV and V).

B. OPTIMAL DESIGN

Since American 9/11, the traffic strategies for emergency evacuations have been strengthened by a large number works presented in literature that consider the private cars [17]–[27], public transport [28]–[35], and multimodal traffic [36]–[44]. Pyakurel *et al.* [20] presented a technique for earliest arrival and quickest evacuation based on the polynomial algorithm in two terminal road networks of Kathmandu. Ren *et al.* [29] simulated the private car and public transport contraflow lanes on a freeway evacuation by using the ORridor SIMulatio software. Huang *et al.* [40] proposed a multi-agent (including the evacuation strategy, cell movement, and signal control) optimization model to increase the overall evacuation efficiency by using the metro, bus, and car evacuation networks.

Table 1 presents the methodologies of the existing works cited in this paper. The research works that only considered the private cars mainly focused on the improvement of optimal model and solution algorithm or addressed a particular issue. However, these methods fail to consider the low mobility individuals who have to depend on the public transport in emergency evacuations. The research works that only consider the public transport are capable of effectively improving the evacuation efficiency of low mobility individuals. However, these methods assume that the evacuation traffic network is smooth, which is inconsistent with reality, as the evacuation networks are usually congested. The research works that consider the multimodal traffic study a game relationship between the evacuation efficiencies of private cars and public transport. However, these methods have to reduce the evacuation efficiency of public transport in order to optimize the evacuation efficiency of private cars as the public transport has no independent right-of-way.

Table 1 also presents the proposed methodology. This work aims to address the shortcomings of different works presented in literature. For instance, we consider the evacuation efficiencies of private cars and public transport, where the independent right-of-way of public transport is provided based on the lane use configuration. We also consider the influence of background traffic on the multimodal traffic evacuation in terms of preparation (clearance) time and the travel lost (delayed) time due to the presence of background traffic. We present a two-step design process to effectively consider the influence of background traffic and reduce the computational complexity of the solution. We use a simplified tabu algorithm and a heuristics algorithm for solving the proposed two-step design model, which had been tested in [9]. In addition, we compare the proposed optimal strategy with feasible strategy (obtained from the first step), No-PT (without considering the public transport strategy), No-PC (without considering the private cars strategy), and NO-BT (without considering the background traffic) for verifying the feasibility and effectiveness of the proposed research.

III. LANE USE CONFIGURATION

The evacuation traffic usually adopts the reversible lane strategy to improve the traffic capacity from the affected region. The lane use configuration proposed by Wolshon [10] is described in Fig. 2, where an inbound lane is transformed into a reversible lane.

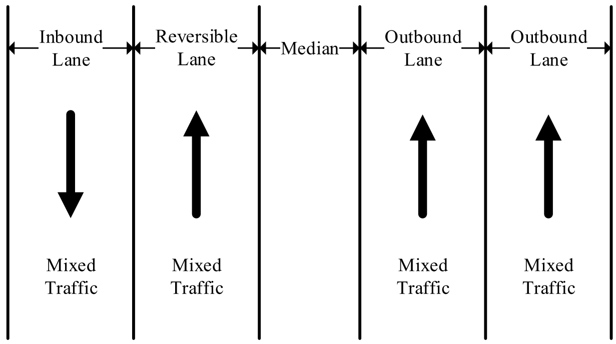

FIGURE 2. The traditional lane use configuration.

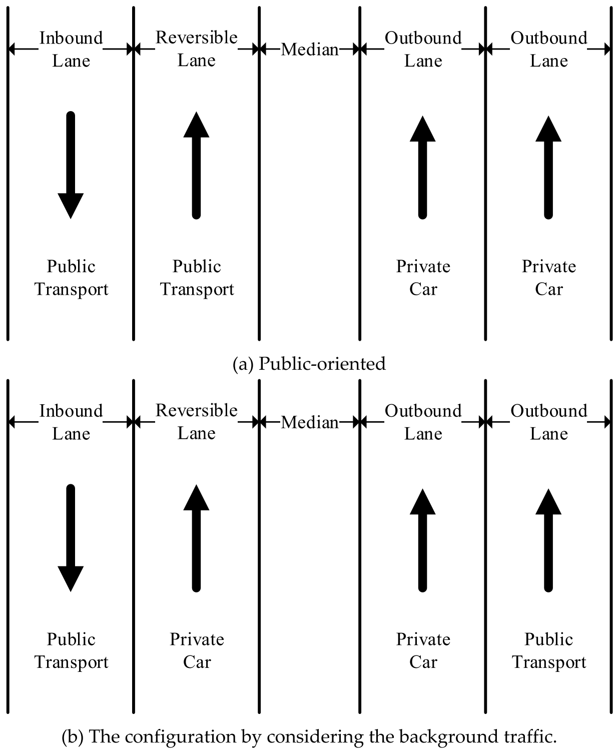

FIGURE 3. The lane use configurations for multimodal emergency evacuation traffic.

Based on the work presented in [15], in this section, we present the public-transport-oriented lane use configuration by considering the background traffic, as presented in Fig. 3. The mixed traffic is separated into public transport and private cars to increase the evacuation efficiency, as presented in Fig. 3a. In this work, three traffic strategies are put forward, including 1) an inbound lane set exclusively for the return of public transport, 2) an inbound lane set as reversible exclusive lane for the evacuation of public transport, and 3) two outbound lanes are set as the exclusive lanes for the evacuation of private cars. In the next section, the three aforementioned traffic strategies are denoted as C, B, and D, respectively.

The right-of-way for the public transport has a priority based on the size of background traffic volume, i.e., the clearance time of the background traffic, as presented in Fig. 3b. If the clearance time of the background traffic on

TABLE 1. The research contents of existing literature and proposed method.

	Consideration mode	Optimization process	Optimization index	Model type	Solution method	Consideration angle
Existing literature	Private car [17]–[27]	One-step [17],[18],[20], [21][23],[25], [27]; Two-step [19],[24],[26].	Travel time [17],[18],[20], [22],[26],[27]; Rescue time [19]; Evacuation risk [21]; Travel delay [22],[25].	Single-objective [17],[18],[21], [27]; Multi-objective [19],[20],[22], [25].	Heuristics [17],[23],[25], [26]; Neighborhood search [19]; Polynomial time [20]; Cell Transmission [21],[27]; Computer simulation [22]; Lagrangian [24].	Path selection [17],[18],[20], [21], [24]–[27]; Network failure [19]; Lane configuration [20],[26],[27]; Road intersections [22] [24] [27].
	Public transport [28]–[35].	One-step [28]–[35].	Travel time [28], [30],[32],[33],[35]; Travel demand [29],[30],[33]; Bus schedule [31],[33]; Travel distance [34]; Travel wait [35];	Single-objective [28]–[32],[34]; Multi-objective [30],[33],[35].	Computer simulation [28]–[30],[32]; Formula derivation [31]; Labeling algorithm [33]; Branch and bound algorithms [34]; Improved shortest path [35].	Path selection [28]–[35]; Lane configuration [29],[35]; Pedestrian [30].
	Multimodal traffic [36]–[44].	One-step [36]–[38], [40]–[44]; Two-step [39].	Travel time [36], [37],[39],[41]–[44]; Evacuation risk [36], [38]; Travel cost [37],[42]; Travel distance [39].	Multi-objective [36]–[44].	Improved shortest path [36]; Tabu Search [37]; Computer simulation [38]–[40], [42]–[44]; Method of successive average [41].	Path selection [36],[38]–[44]; Hospital evacuation [36]; Parking lot [37]; Lane configuration [39]; Road intersections [40]; Evacuee behavior [41]; Health condition [42].
Proposed method	Multimodal traffic	Two-step	Travel time, Preparation time of Background traffic.	Multi-objective	Heuristics (Tabu Search)	Evacuation strategy; Lane configuration; Background traffic.

TABLE 2. The application conditions of evacuation strategies.

No.	Strategy name	Condition
A	Exclusive lane for the evacuation of public transport	$T_e^o \leq 2\times T_r^o$
B	Reversible exclusive lane for the evacuation of public transport	$T_e^o > 2\times T_r^o$
C	Exclusive lane for the return of public transport	$d_{\text{pub}} > N_{\text{pub}} \times Q$
D	Exclusive lane for the evacuation of private cars	$T_{\text{car}} > T_{\text{pub}}$
E	Reversible exclusive lane for the evacuation of private cars	$T_{\text{car}} > \lambda \times T_{\text{pub}}$

the outbound lane is longer as compared to the traffic on the inbound lane, an outbound lane can be set as the exclusive lane for the evacuation of public transport. Correspondingly, four traffic strategies are put forward, including 1) an inbound lane is set as the exclusive lane for the return of public transport, 2) another inbound lane is set as the reversible exclusive lane for the evacuation of private cars, 3) an outbound lane is set as the exclusive lane for the evacuation of private cars, and 4) another outbound lane is set as the exclusive lane for the evacuation of public transport. In the next section, these four traffic strategies are referred to as C, E, D, and A, respectively. Otherwise, the lane use configuration in Fig. 3a is used.

IV. FEASIBLE STRATEGY PROPOSAL

According to the lane use configurations presented in Fig. 3, we obtain five multimodal traffic strategies for emergency evacuation by considering the background traffic in Table 2. The strategy A refers to the allocation of an exclusive lane for the evacuation of public transport; the strategy B refers to the implementation of a reversible exclusive lane for the evacuation of public transport; the strategy C refers to the allocation of an exclusive lane for the return of public transport; the strategy D refers to the allocation of an exclusive lane for the evacuation of private cars; the strategy E refers to the implementation of a reversible exclusive lane for the evacuation of private cars. Similar to the study of normal traffic strategies presented by Zhang *et al.* [9], the feasible strategies are proposed based on application conditions of five evacuation traffic strategies (see Table 2), which is the first step design of multimodal traffic evacuation strategies. If a lane satisfies the application condition of an evacuation traffic strategy, the evacuation traffic strategy is a feasible strategy on the lane. These application conditions are defined according to plan experiences and research requirements. This can simplify the complexity for designing the optimal strategy. Either strategies A or B are implemented based on the comparison of preparation time in terms of p_e^o and p_r^o to effectively improve the evacuation efficiency of public transport. The implementation of strategy C enables the public transport to return to the evacuation source quickly. Both strategies D and E are implemented to consider the evacuation efficiency of private cars.

In Table 2, T_e^o denotes the preparation time for the evacuation strategy A for public transport on the optimal outbound lane towards the destination p_e^o, T_r^o denotes the preparation time for the evacuation strategy B for public transport on the optimal inbound lane towards the evacuation source p_r^o, d_{pub} denotes the evacuation demand of public transport from source to destination, N_{pub} denotes the number of available public transport vehicles participating in the evacuation process, Q denotes the maximum load capacity of each available public transport, T_{pub} denotes the evacuation duration of public transport, T_{car} denotes the evacuation duration of private cars, and λ denotes the determination coefficient of strategy E for the evacuation of private cars. The variables T_e^o and T_r^o are derived based on (1) and (2), respectively, where l denotes a directed link in the evacuation network, L denotes the length of directed link l, q_l^{b} denotes the volume of background traffic on link l, c_l denotes the traffic capacity of automotive vehicle on link l, and η denotes the preparation time of unit length. Note that the preparation time can be regarded as the clearance time of background traffic for the implementation of evacuation strategy. The definition and methods for computing T_e^p and T_r^p are similar to T_e^o and T_r^o.

$$T_e^o = \sum_{l \in p_e^o} (1 + \frac{q_l^{\mathrm{b}}}{c_l}) \times \eta \times L \tag{1}$$

$$T_r^o = \sum_{l \in p_r^o} (1 + \frac{q_l^{\mathrm{b}}}{c_l}) \times \eta \times L \tag{2}$$

However, the implementation of these five strategies significantly affects the travel efficiency of the background traffic. The implementation of strategies A, B, and C increases the evacuation efficiency of public transport and decreases the evacuation efficiency of private cars. The implementation of strategies D and E increase the evacuation efficiency of public transport without influencing the evacuation efficiency of public transport. As a result, these characteristics also affect the evacuation traffic network. Table 3 presents the implementation effect of different evacuation strategies to simplify the complexities faced during the process of designing the optimal strategy (i.e., the second-step design of multimodal traffic evacuation strategies). p_e denotes the outbound lane toward the evacuation destination and p_r denotes the inbound lane toward the evacuation source. v_Δ^{pub} and v_Δ^{car} represent the increase in the speed of public transport or private cars due to the implementation of the aforementioned strategies, respectively. We assume that all the roads consist of two lanes. For instance, if the road has three lanes and the traffic capacity of a single lane is 400 vehicles/h, we change its traffic capacity to 600 vehicles/h after transforming three lanes into two lanes. Considering the actual situation, the values of the cleared background traffic are decided based on the driving direction of evacuation vehicles.

V. DESIGN OF OPTIMAL STRATEGY

The process of proposing a feasible strategy presented in Section III is relatively simple because it does not consider other influencing factors. For instance, it fails to consider the preparation time for the implementation of evacuation strategies in detail, the influence of evacuation strategies (A, B, C) on the operating efficiency of private cars and background traffic, and the influence of evacuation strategies (D, F) on the operating efficiency of private cars and background traffic. In this section, i.e., the second-step design of multimodal traffic evacuation strategies, we address these gaps and establish a linear programming model for obtaining an optimal strategy, which minimizes the weighted sum of public transport, private cars, and background traffic. The objective function is mathematically expressed as follows:

TABLE 3. The implementation effect of different strategies.

No.	Implementation effect on a lane
A	The lane p_e^o is designated, where only the public transport can be driven from the source to destination, half of background traffic volume is cleared. As a result, the speed of public transport on p_e^o increases by v_Δ^{pub} .
B	The lane p_r^o is designated, where only the public transport can be driven from the source to destination, all of background traffic volume is cleared. As a result, the speed of public transport on p_r^o increases by v_Δ^{pub} .
C	The lane p_r^o is designated, where only the public transport can be driven from the destination to the source, half of background traffic volume is cleared. As a result, the speed of public transport on p_r^o increases by v_Δ^{pub} .
D	The lane p_e is designated, where only the private cars can be driven from the source to the destination, half of background traffic volume is cleared. As a result, the speed of private cars on p_e increases by v_Δ^{car} .
E	The lane p_r is designated, where only the private cars can be driven from the source to the destination, all of background traffic volume is cleared. As a result, the speed of private cars on p_r increases by v_Δ^{car} .

$$\min Z = W_{\mathrm{pub}} \times T_{\mathrm{pub}} \times Z_{\mathrm{pub}} + W_{\mathrm{car}} \times T_{\mathrm{car}} \times Z_{\mathrm{car}} + W_{\mathrm{back}} \times T_{\mathrm{eva}} \times Z_{\mathrm{back}} \tag{3}$$

where, Z represents the objective value, Z_{pub} and Z_{car} denote the evacuation time of public transport and private cars, respectively, Z_{back} denotes the travel lost time of background traffic. W_{pub}, W_{car}, W_{back} represent the weights of Z_{pub}, Z_{car}, Z_{back}, respectively. T_{eva} denotes the evacuation duration of multimodal traffic.

Please note that two optimization metrics, namely evacuation duration and evacuation time are combined in (3), where the product of two optimization indexes is set as the target value for designing the optimal strategy. The objective function can be divided into three parts by considering the game relationship among the evacuation efficiencies of public transport, private cars, and background traffic. The first part is the target value of public transport evacuation, the second part is the target value of private cars' evacuation, and the third part is the target value of travel lost time from background traffic. Consequently, the objective function is defined to obtain the minimum value of the weighted sum of three target values. W_{pub}, W_{car}, and W_{back} reflect the trade-off between different evaluation values [45], which can convert the problem of designing an optimal strategy into the solution procedure of multi-objective linear optimization. The constraints of three weights are shown in (4-6), where (4) normalizes three weights to make three evaluation values comparable. The expression presented in (5) illustrates that the priority of optimal design enhances with a decrease in the weight. The expression presented in (6) assists in avoiding the imbalanced participation of three evaluation values by narrowing the differences between three weights.

$$W_{\text{pub}} + W_{\text{car}} + W_{\text{back}} = 1 \tag{4}$$

$$W_{\text{pub}} < W_{\text{car}} < W_{\text{back}} \tag{5}$$

$$W_{\text{back}} - W_{\text{pub}} \leq 1/3 \tag{6}$$

We assume that the evacuation time of each vehicle is greater than the preparation time for an evacuation strategy. The implementation decision coefficient of evacuation strategy s on the lane p (ψ_s^p) is defined to determine if the evacuation strategy s implemented in (7) effectively calculates other variables. ψ_{A}^p, ψ_{B}^p, ψ_{C}^p, ψ_{D}^p, and ψ_{E}^p denotes the implementation decision coefficient of evacuation strategies A, B, C, D, and E on the lane p, respectively.

$$\psi_s^p = \begin{cases} 1, & \text{if the } s \text{ is implemened on the lane } p \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

A. CALCULATION METHODS OF VARIABLES RELATED TO THE DURATION

The evacuation duration of public transport (T_{pub}) denotes the total time from the beginning to the end, as shown in (8), where the calculation process is divided into two parts, i.e., return requirement and without return requirement. $T_{\text{bus}}^{\text{pre}}$ is the preparation time of the evacuation strategy for public transport, as presented in 9, where the strategies A and B are only implemented on the lanes p_e^o and p_r^o, respectively. In addition, either A or B is implemented, i.e., $\psi_{\text{A}}^{p_e^o} + \psi_{\text{B}}^{p_r^o} = 1$ in (10). In (11), N_r denotes the number of return trips of public transport. In (12), N_{last} denotes the number of public transport vehicles on the last evacuation trip from source to destination. In (13), t_{pub} denotes the travel time of public transport using the evacuation optimal lanes p_e^o or p_r^o, and is influenced by the average evacuation speed of public transport (v_{pub}) and the length of the optimal route (L_p^o). p_e^o and p_r^o denote the opposite lanes on optimal route. The lengths of both lanes are equal to L_p^o presented in (14). t_Δ denotes the boarding or alighting time of public transport during the evacuation process.

$$T_{\text{pub}} = \begin{cases} T_{\text{bus}}^{\text{pre}} + t_{\text{pub}} + \dfrac{N_{\text{last}}}{t_\Delta}, & \text{if } N_r = 0 \\ T_{\text{bus}}^{\text{pre}} + (2 \times N_r - 1) \times (t_{\text{pub}} + \dfrac{N_{\text{pub}}}{t_\Delta}) & \\ \quad + 2 \times (t_{\text{pub}} + \dfrac{N_{\text{last}}}{t_\Delta}), & \text{otherwise} \end{cases} \tag{8}$$

$$T_{\text{bus}}^{\text{pre}} = \psi_{\text{A}}^{p_e^o} \times T_e + \psi_{\text{B}}^{p_r^o} \times T_r \tag{9}$$

$$\psi_{\text{A}}^{p_e^o} + \psi_{\text{B}}^{p_r^o} = 1 \tag{10}$$

$$N_r = \text{floor}(\frac{d_{\text{pub}}}{N_{\text{pub}} \times Q}) \tag{11}$$

$$N_{\text{last}} = \text{ceil}(\frac{d_{\text{pub}} - N_{\text{pub}} \times Q \times N_r}{Q}) \tag{12}$$

$$t_{\text{pub}} = \frac{L_p^o}{v_{\text{pub}}} \tag{13}$$

$$L_p^o = \sum_{l \in p_e^o} L = \sum_{l \in p_r^o} L \tag{14}$$

In (15), the method for calculating the evacuation duration of private car (T_{car}) is described as the maximum value of the evacuation duration of private car using different lanes, i.e., T_{car} in (16). T_p^{pre} denotes the preparation time for devising evacuation strategies for private cars on the lane p, which is influenced by the implementation decision coefficients of evacuation strategies D and E (ψ_{D}^p, ψ_{E}^p) and their preparation time (T_e^p, T_r^p) in (17). N_{car}^p denotes the number of private cars assigned to lane p in (18), which is influenced by the total number of private cars (N_{car}) and traffic capacity of private cars on lane p (c_{car}^p) during the process of evacuation. Similar to (13) and (14), the travel time of private cars using lane p (t_{car}^p) and the length of lane p (L_p) are described by (19) and (20), respectively. The calculation method of c_{car}^p presented in (21) refers to the "bucket effect" discussed in [7].

$$T_{\text{car}} = \max_{p \in P} \{T_{\text{car}}^p\} \tag{15}$$

$$T_{\text{car}}^p = T_p^{\text{pre}} + \frac{N_{\text{car}}^p}{c_{\text{car}}^p} + t_{\text{car}}^p \tag{16}$$

$$T_p^{\text{pre}} = \psi_D^p \times T_e^p + \psi_E^p \times T_r^p \tag{17}$$

$$N_{\text{car}}^p = N_{\text{car}} \times \frac{c_{\text{car}}^p}{\sum_{p \in P} c_{\text{car}}^p} \tag{18}$$

$$t_{\text{car}}^p = \frac{L_p}{v_{\text{car}}} \tag{19}$$

$$L_p = \sum_{l \in p} L \tag{20}$$

$$c_{\text{car}}^p = \max_{l \in p} \{c_l\} \tag{21}$$

The evacuation duration of multimodal traffic (T_{eva}) is longer as compared to the evacuation time of public transport and private cars, as presented in (22).

$$T_{\text{eva}} = \max\{T_{\text{pub}}, T_{\text{car}}\} \tag{22}$$

B. CALCULATION METHODS OF VARIABLES RELATED TO THE TIME

The evacuation time of public transport Z_{pub} presented in (23) is the total travel time of all public transport vehicles during the evacuation, including the process of carrying passengers from the source to destination and the time consumed during the return trip from the destination to source.

$$Z_{\text{pub}} = \begin{cases} N_{\text{last}} \times (t_{\text{pub}} + \dfrac{N_{\text{last}}}{t_{\Delta}}), & \text{if } N_r = 0 \\ (2 \times N_r - 1) \times N_{\text{pub}} \times (t_{\text{pub}} + \dfrac{N_{\text{pub}}}{t_{\Delta}}) & \\ \quad + 2 \times N_{\text{last}} \times (t_{\text{pub}} + \dfrac{N_{\text{last}}}{t_{\Delta}}), & \text{otherwise} \end{cases} \tag{23}$$

The evacuation time of private cars Z_{car} presented in (24) is the total travel time of all private cars from the source to the destination during the process of evacuation, i.e., the total travel time of private cars on different lanes p.

$$Z_{\text{car}} = \sum_{p \in P} N_{\text{car}}^{p} \times t_{\text{car}}^{p} \tag{24}$$

The travel lost time of background traffic Z_{back} presented in (25) is the total delayed time of all background traffic due to the implementation of different evacuation strategies. μ denotes the convert coefficient of travel time from background to evacuation traffic. $t_{\text{car}}^{\text{b}}$ denotes the average travel time of background traffic in the original traffic network, which is obtained based on the work presented in [8]. q_s^p denotes the cleared volume of background traffic on lane p due to the implementation of strategy s. According to the implementation effect of different strategies presented in Table 3, q_{A}^p, q_{B}^p, q_{C}^p, q_{D}^p, q_{E}^p are calculated by using (26)-(30), respectively.

$$Z_{\text{back}} = \mu \times t_{\text{car}}^{\text{b}} \times \psi_s^p \times q_s^p, \quad s \in \{\text{A, B, C, D, E}\} \tag{25}$$

$$q_{\text{A}}^p = \sum_{l \in p} \psi_{\text{A}}^p \times \frac{q_l^{\text{b}}}{2} \tag{26}$$

$$q_{\text{B}}^p = \sum_{l \in p} \psi_{\text{B}}^p \times q_l^{\text{b}} \tag{27}$$

$$q_{\text{C}}^p = \sum_{l \in p} \psi_{\text{C}}^p \times \frac{q_l^{\text{b}}}{2} \tag{28}$$

$$q_{\text{D}}^p = \sum_{l \in p} \psi_{\text{D}}^p \times \frac{q_l^{\text{b}}}{2} \tag{29}$$

$$q_{E}^p = \sum_{l \in p} \psi_{\text{E}}^p \times q_l^{\text{b}} \tag{30}$$

C. SOLUTION ALGORITHM

The model of optimal strategy in emergency traffic is similar to the model in normal traffic presented in [9]. Therefore, we also use the tabu algorithm to solve the proposed model of optimal strategy. The performance of this algorithm has been completely verified for obtaining the weight sum of multi-objective linear optimization in [9]. In this work, the mapping times, mapping length, and maximum iterations are set as 2, 8, and 300, respectively. The feasible strategies are defined as the initial current scheme. The processes of neighborhood mapping and tabu criterion are similar to the description presented in [9]. The flowchart of the solution algorithm is shown in Fig. 4, where n denotes the iteration number and N is the maximum number of iterations.

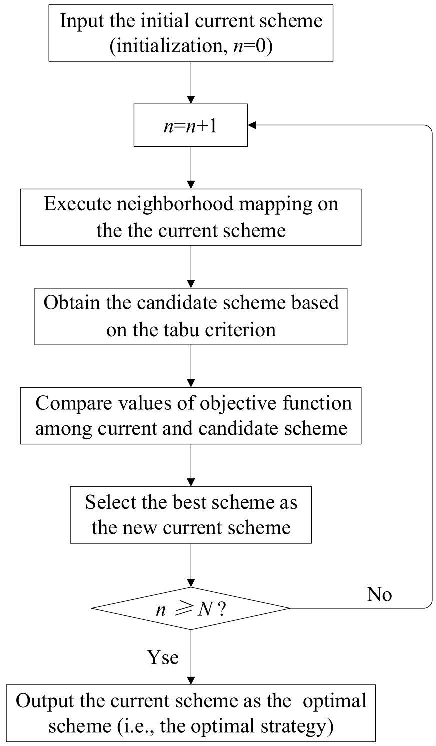

FIGURE 4. The flowchart of the tabu algorithm.

VI. CASE STUDY

In the previous studies [7]–[9], the multimodal traffic assignment model based on the stochastic user equilibrium is verified [8], the multimodal traffic strategies under normal conditions are designed [9], and the dynamic traffic assignment method of emergency evacuation by considering the background traffic is analyzed [7]. In this work, based on the previous studies [7]–[9], we apply the proposed model on the evacuation traffic network of Wenling city [7] to test and verify its validity and feasibility.

A. SCENARIOS

As presented in Fig. 5, there are 188 nodes and 304 directed links in the evacuation road network of Wenling city. The grade of roads includes branch road, subsidiary road, arterial road, and urban expressway. The details of the road network are presented in [8].

In the previous case [7], node 50 represents the evacuation source, and node 84 represents the evacuation destination. There are five paths, i.e., Paths 1-5. The details of the related variables are presented in [7]. Please note that the length of Path 1 is shortest, the traffic capacity of Path 1 is highest, and the background traffic of Path 1 is smallest. Therefore, we consider Path 1 as the optimal path. Then, we transform five paths in the previous case [7] into twenty lanes in this work based on the research requirements of this work (current case), as shown in Fig. 6. So, p can be p_e, p_r, p_e^o, and p_r^o.

The details of the relevant elements or sets, unknown variables, known variables, parameters, and calculation functions in the proposed model are shown in Table 4. The

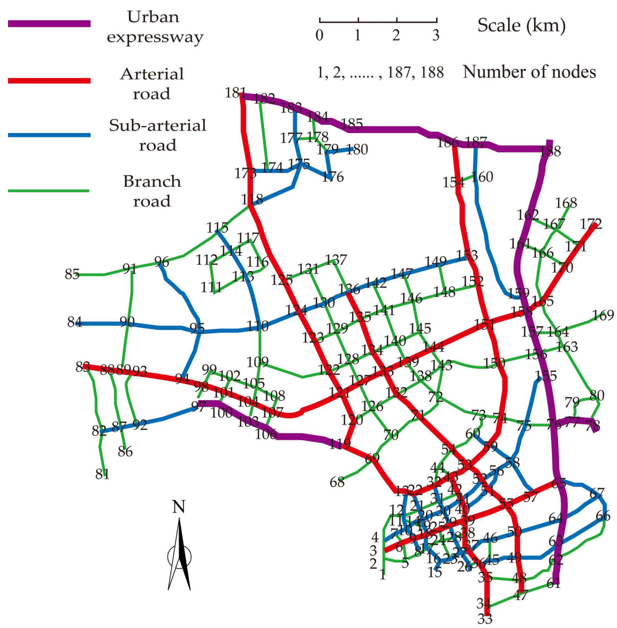

FIGURE 5. The evacuation traffic network of Wenling city.

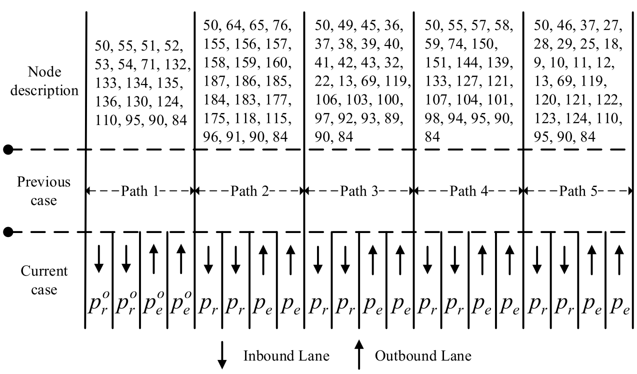

FIGURE 6. The transformation of five paths to twenty lanes.

assignment results of private cars on different paths discussed in [8] are regarded as the background traffic, which are enclosed in the supplemental files of this paper to calculate the preparation time consumed in devising the evacuation strategies.

B. EVOLUTION VALIDATION

1) FROM NONE TO FEASIBLE STRATEGY

First, we calculate $T_e^o = 1.33$ h by using (1), $T_r^o = 1.32$ h by using (2), $T_{pub} = 8.99$ h by using (8), and $T_{car} = 9.26$ h by using (15) in the original multimodal traffic, i.e., no strategy is implemented. Then, the feasible strategies are obtained by considering the application conditions of feasible evacuation strategies presented in Table 2. The layout of feasible strategies is shown in Fig. 7, where the lane symbol corresponds to Fig. 6.

The evacuation duration of different modes, the total evacuation time of PT and PC, travel lost time of BT, and

TABLE 4. The relevant variables and parameters of the proposed model.

Element or Set (an element belongs to a set)		
Symbol	Definition	
l	A directed link in the evacuation network	
p	A directed lane	
P	Set of directed lanes	
p_e	An outbound lane towards the evacuation destination	
p_r	An inbound lane towards the evacuation source	
p_e^o	Optimal outbound lane towards the evacuation destination	
p_r^o	Optimal inbound lane towards the evacuation source	
s	An evacuation strategy, $s \in \{A, B, C, D, E\}$	
Unknown variable		
Symbol	Definition	Unit
L	Length of directed link l	km
T_e	Preparation time for an evacuation strategy on p_e	h
T_r	Preparation time for an evacuation strategy on p_r	h
T_e^o	Preparation time for an evacuation strategy on p_e	h
T_r^o	Preparation time for an evacuation strategy on p_r	h
T_{pub}	Evacuation duration of public transport vehicle	h
T_{car}	Evacuation duration of private car	h
T_{eva}	Evacuation duration of evacuation traffic	h
q_l^{b}	Volume of background traffic on link l in a lane	vehicle/h
c_l	Traffic capacity of automotive vehicle on link l	vehicle/h
c_{car}^p	Traffic capacity of private cars on lane p	vehicle/h
Z	Value of objective function in the optimal strategy design model	h^2
Z_{pub}	Evacuation time of public transport vehicles	h
Z_{car}	Evacuation time of private cars	h
Z_{back}	Travel lost time of background traffic	h
$T_{\text{bus}}^{\text{pre}}$	Preparation time for the evacuation strategy of public transport vehicles	h
N_{r}	Number of return trips of public transport vehicles	
N_{last}	Number of public transport vehicles on the last evacuation trip from source to destination	vehicle
t_{pub}	Travel time of public transport vehicle using the evacuation lanes p_e or p_r	h
L_p^o	Length of the optimal route	km
T_{car}^p	Evacuation duration of private car using lane p	h
T_p^{pre}	Preparation time for evacuation strategies of private car on lane p	h
N_{car}^p	Number of private cars assigned to lane p	vehicle
L_p	Length of lane p	km
$t_{\text{car}}^{\text{b}}$	Average travel time (i.e., average travel lost time) of background traffic in original traffic network	h
q_s^p	Cleared volume of background traffic on lane p due to the implementation of strategy s	vehicle/h

TABLE 4. ***(Continued.)* The relevant variables and parameters of the proposed model.**

Known variables

Symbol	Definition		Unit	Value
d_{pub}	Total evacuation demand of public transport vehicles from source to destination		person	7500
N_{car}	Total number of private cars from source to destination		vehicle	50000
N_{pub}	Number of available public transport vehicles in the evacuation process		vehicle	100
Q	Maximum load capacity of each available public transport vehicle		person/ vehicle	48
η	Preparation time of unit length	$c_{\text{car}}^{p} \leq 1000$	h/km	0.05
		$c_{\text{car}}^{p} > 1000$		0.1
v_{pub}	Average evacuation speed of public transport vehicles		km/h	20
v_{car}	Average evacuation speed of private cars		km/h	35
v_{Δ}^{pub}	Increase in the speed of public transport due to the implementation of strategies		km/h	10
v_{Δ}^{car}	Increase in the speed of private car due to the implementation of strategies		km/h	25
t_{Δ}	Boarding or alighting time of public transport during the evacuation process		h	0.33

Parameter

Symbol	Definition	Value
λ	Determination coefficient of evacuation strategy for the private car $\lambda > 1$	1.5
W_{pub}	Weight of Z_{pub}	0.2
W_{car}	Weight of Z_{car}	0.3
W_{back}	Weight of Z_{back}	0.5
ψ_{s}^{p}	Implementation decision coefficient of evacuation strategy s on lane p	0 or 1
μ	Convert coefficient of travel time from background to evacuation traffic	1

Calculation function

Symbol	Definition
ceil()	Round-up function
floor()	Round-down function

objective value of MT from different cases are presented in Table 5. Moreover, Table 5 also presents the average evacuation time of PT and PC for presenting a visual comparison among different cases. Due to the implementation of evacuation strategies, we observe that the evacuation duration of PT and PC in the feasible strategy is longer as compared to the case where no strategy is present. This is caused due to the preparation time. The average evacuation time of PT and PC in feasible strategy are less than those in None strategy due to the increase of speed, and the travel lost time of BT changes from 0 to 993.77 h. These three changes ensure that the objective value of feasible strategy is better as compared to None proposal. This verifies the effectiveness of feasible strategy proposal of Section IV.

Lane symbol	p_r^o	p_r^o	p_e^o	p_e^o	p_r	p_r	p_e	p_e	p_r	p_r	p_e	p_e	p_r	p_r	p_e	p_e	p_r	p_r	p_e	p_e
Lane number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Feasible strategy	C		A	D			D	D			D	D			D	D			D	D
Optimal strategy	C	E	A	D			D	D		E	D	D	E	E	D	D	E	E	D	D

FIGURE 7. The evolution process of evacuation strategy.

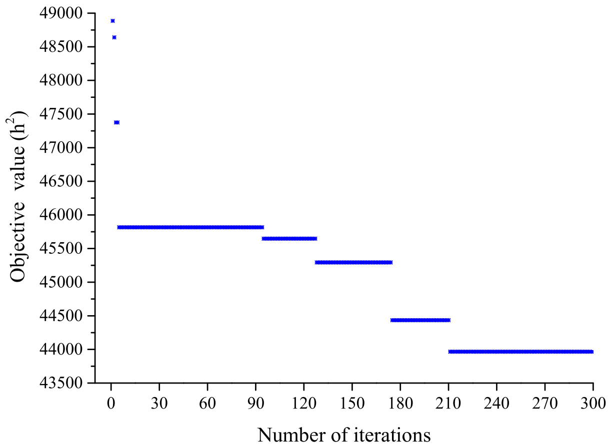

FIGURE 8. The iterative process of optimal strategy.

2) FROM FEASIBLE TO OPTIMAL STRATEGY

The solution procedure based on tabu algorithm is performed iteratively for 30 times in the second-step design of multimodal traffic evacuation strategies, where the maximum iteration N is set as 300. Then, we select the best result as the optimal strategy. The iterative process of the best result is presented in Fig. 8, which proves that the solution obtained using the tabu algorithm is effective based on the previous verification process [9].

The change in layout from feasible to optimal strategy is presented in Fig. 7, where the strategy E is implemented on lanes 2, 10, 13, 14, 17, and 18 in optimal strategy. Table 5 shows that the evacuation duration and average evacuation time of PT in feasible and optimal strategies are equal. This shows that there is no change in the implementation layout of PT between feasible and optimal strategies. Due to the implementation of strategy E on some inbound lanes, the evacuation duration and average evacuation time of PC in the optimal strategy are smaller as compared to the feasible strategy. The objective value of optimal strategy is better as compared to the feasible strategy. This shows the necessity and effectiveness of the optimal strategy.

C. COMPRAED OTHER STRATEGIES

In this section, we define three strategy programs to further prove the effectiveness of the optimal strategy, including No-PT (without considering the public transport strategy, i.e., strategies A, B, and C), No-PC (without considering the private cars strategy, i.e., strategies D and E), and No-BT (without considering the background traffic). Note that the objective functions for No-PT and No-PC are similar to

TABLE 5. **The results of optimal design for different cases.**

Index	Mode (unit)	None strategy	Feasible strategy	Optimal strategy	No-PT	No-PC	NO-BT	Reverse weight	Equal weight
Evacuation duration	PT (h)	8.99	9.85	9.85	8.99	9.85	8.52	9.85	9.85
	PC (h)	9.26	12.43	8.18	8.18	10.45	5.48	7.73	8.12
	MT (h)	9.26	12.43	9.85	8.99	10.45	8.52	9.85	9.85
Total evacuation time	PT (h)	698.66	649.09	649.09	698.66	649.09	649.09	649.09	649.09
	PC (h)	22763.55	13604.08	13183.89	13183.89	23321.29	13393.03	13640.31	13723.17
Average evacuation time	PT (min/person)	5.59	5.19	5.19	5.59	5.19	5.19	5.19	5.19
	PC (min/vehicle)	27.32	16.32	15.82	15.82	27.99	16.07	16.37	16.47
Travel lost time	BT (h)	0	993.77	2099.61	1909.21	137.72	0	2417.96	2162.56
Objective value	MT (h^2)	64524.06	58171.12	43966.05	42191.48	75093.64	46229.46	39601.08	46397.00

Note: PT, PC, BT, and MT represent the public transport, private car, background traffic, and multimodal traffic, respectively.

the objective function of the optimal strategy. Given that the background traffic is not considered in No-BT, the corresponding weight W_{back} should be set as 0. Therefore, in No-BT, we choose weights W_{pub}, W_{car}, and W_{back} as 0.4, 0.6, and 0, respectively, because the sum of the weights W_{pub}, W_{car}, and W_{back} is 1. The results obtained based on the information presented in Table 5 are as follows:

No-PT: The evacuation duration and average evacuation time of PT in No-PT is equal to those in None strategy. The travel lost time of BT in No-PT is smaller as compared to the optimal strategy. The reason of these two results is that the evacuation strategy of PT is not considered during the optimal design process, which indicates the necessity of strategies A, B, and C. The evacuation duration and average evacuation time of PC in No-PT are similar to optimal strategy, which illustrates the effectiveness of the proposed model.

No-PC: The result of No-PC is opposite to the result of No-PT. This is caused due to the non-consideration of private cars in the optimal design process, thus indicating the necessity of strategies C and D.

No-BT: As compared with the optimal strategy, the evacuation duration of PT and PC, and the average evacuation time of PT are smaller in No-BT, as the preparation time of evacuation strategies is not considered in the optimal design process. The average evacuation time of PC increases because the strategy E is implemented in lane 5 of the longest path. These results show the influence of background traffic on the evacuation efficiency of PT and PC in the optimal strategy design.

D. SENSITIVITY ANALYSIS

Considering the existing research, in the proposed model, the important parameters are the weights W_{pub}, W_{car}, and W_{back}, which reflect the trade-off among the target values of PT, PC, and BT. However, other parameters are unable to alter the trend of the objective function and only affect the change the extent of the objective function value. Hence, we focus on the sensitivity of weights in this section.

It is observed that the sum of weights W_{pub}, W_{car}, and W_{back} is equal to 1 according to the constraint (4). The weights W_{pub}, W_{car}, and W_{back} are greater than 0 and less than 1 based on the constraint (6). Given that these two changes related to constraints (4) and (6) have been completely explained and analyzed by [9], [45], [46], we pay close attention to the sensitivity related to the size relation of weights W_{pub}, W_{car}, and W_{back} in this section. Therefore, there are three ways of weight allocations by considering the sensitivity analysis related to weights [9], [46], including optimal strategy (W_{pub}, W_{car}, W_{back} are presented in Table 4, i.e., $W_{pub} < W_{car} < W_{back}$), reverse weight ($W_{pub}$, W_{car}, W_{back} are set as 0.5, 0.3, and 0.2, respectively, i.e., $W_{pub} > W_{car} > W_{back}$), and equal weight ($W_{pub}$, W_{car}, W_{back} are all set as 1/3, i.e., $W_{pub} = W_{car} = W_{back}$).

The corresponding optimization results are presented in Table 5. It is observed that the average evacuation time of PC in reverse weight is greater than that of optimal strategy and less than that of equal weight. Correspondingly, the value of W_{car} in reverse weight is between optimal strategy and equal weight. The travel lost time of BT in optimal strategy is the smallest and the travel lost time of BT in reverse weight is greatest. Correspondingly, the values of W_{back} in optimal strategy and reverse weight are maximum and minimum, respectively. These two results show that when the value of weight is smaller, the corresponding target value is better, which indicates that the proposed weight allocation applied in optimal strategy is superior to other two techniques used for weight allocation. In addition, there is no transformation in the layout of the public transport strategy with the variety of parameters as the strategies A, B, and C are public transport oriented in multimodal emergency evacuation traffic, which further verifies the effectiveness and feasibility of the proposed model.

VII. CONCLUSION

In this work, a two-step design model is proposed to optimize the multimodal traffic strategies in emergency evacuation based on the public-transport-oriented lane use configuration that considers the background traffic. In lane use configuration, the work presented in [15] is improved to consider the influence of background traffic on the efficiency of multimodal emergency evacuation. In the first step design (Section III), the application conditions of evacuation strategies are presented to form a feasible strategy and the implementation effects of different strategies are assumed to simplify the complexities in the process of optimal strategy design. In the second step design (Section IV), the feasible strategy is optimized into the optimal strategy based on the optimal strategy design model, which tends to minimize the weighted sum of public transport, private cars, and background traffic target values.

The model proposed in this work is applied to the evacuation traffic network in Wenling city presented in [7] to verify the effectiveness based on the results, including the evacuation duration, average evacuation time, total lost time, and objective value. The strategy evolution process (from none to feasible strategy to optimal strategy) is analyzed based on the evacuation strategy and solution results. In addition, three strategies (No-PT, No-PC, and No-BT) are defined to further prove the effectiveness of the proposed optimal strategy. The results show that the proposed weight allocation applied in the optimal strategy design model is superior to other two techniques used for weight allocation.

In short, the proposed model is effective and feasible and can be a reference for other researchers. However, there are some improvements that should be implemented in the future work to address the limitations caused by research ability and data sources. For instance, the feasible strategy design method should be considered from additional angles in the first-step design to improve the universality of strategies, e.g., the population characteristics [42] and path choice [47]. The proposed second-step design should be improved in depth from three aspects, including a) the objective function can become a multi-objective nonlinearity function [14], b) the optimal model can try the dynamic evacuation traffic [38], c) the other solution algorithms can be used, e.g., computer simulations [48]. The proposed design model should also be applied on other traffic circumstances (case studies) to adjust the related parameters and variables for justifying its practicability and availability.

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