Evacuation in Large-scale Transportation Network: A Bi-Level Control Method with Uncertain Arterial Demand

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Word count: Text (5492) + Table and figures (8) = 7492
Submission date: November 14, 2012

ABSTRACT

To improve the efficiency of large-scale evacuation, a network aggregation method and a bi-level optimization control method are proposed in this paper. The network aggregation method indicates the uncertain evacuation demand on the arterial sub-network and balances accuracy and efficiency by refining the local road sub-networks. The bi-level optimization control method is developed to reconfigure the aggregated network from both supply and demand sides with contraflow and conflict elimination. The main purpose of this control method is to make the arterial sub-network to be served without congestion and interruption. Then, a corresponding bi-objective network flow model is presented in a static manner for an oversaturated network, and a GA-based solution method is used to solve the evacuation model. The numerical results from optimizing a city-scale evacuation network for a super typhoon justify the validness and usefulness of the network aggregation method and optimization control method.

INTRODUCTION

Evacuation is currently an issue of major importance due to the increasing risks from natural and man-made disasters. The evacuation planning of advance-notice emergencies (such as hurricane and flood) with long warning time and large geographic scale is a challenging problem because of the unexpected traffic demand, complex road network and uncertain driver behaviors. A significant amount of research has been conducted on this problem during the last decade. Among all these efforts, contraflow and conflict elimination are considered to be two effective strategies for improving the performance of urban evacuation.

Contraflow is generally the use of one or more lanes of inbound travel for traffic movement in the outbound direction, which increases the operational evacuation capacity (*1*). The research regarding contraflow has concentrated on the effectiveness and feasibility by simulation or numerical analysis. Using microscopic simulation, Theodoulou and Wolshon (2004), Lim and Wolshon (2005) and Williams et al. (2007) assessed the adequacy of the contraflow plan in terms of effectiveness or termination design (*2,3,4*). On the aspect of numerical analysis, heuristic algorithms are usually used to solve the evacuation contraflow problems, such as tabu-based (*5*), greedy-based and bottleneck relief (*6*) and genetic algorithm (*7*).

During an evacuation, most traffic delays are caused by stop-and-go control (e.g., signal control and stop sign control) which occurs at intersections (*8*). Conflict elimination has been discussed as a potential remedy to reduce such delays by converting an intersection with interrupted flow conditions to an uninterrupted flow facility (*9*). Cova and Johnson (2003) first suggested this strategy to generate routing plans that trade total vehicle travel-distance against merging-conflicts, while preventing traffic crossing-conflicts at intersections (*10*). Bretschneider and Kimms (2011) developed a basic mixed-integer programming model which aimed to minimize the evacuation time while prohibiting conflicts within intersections (*11*). Recently, the integration of conflict elimination with contraflow was investigated by Kalafaras and Peeta (2008) and Xie et al.(2010) (*12,13*).

Three limitations are apparent in prior studies. The first limitation is the insufficient optimization of the joint use of these two strategies. Recent research (*12,13*) only eliminated crossing conflicts without reducing merging conflicts in their models. And the merging delay and the potential accidents would reduce the evacuation efficiency of the network. The second limitation is the fixed evacuation demand on arterials. In most large-scale (e.g., city-scale) evacuation studies, network origin node was located on arterials with a fixed evacuation demand. However, as evacuees actually have the choice of accessing different adjacent arterials, it is very difficult to determine the accurate evacuation demand on each arterial origin node. The third limitation is the undersaturated network conditions. Evacuation network would usually be oversaturated for a long time during a large-scale evacuation (*14*). The road capacity constraints in the prior evacuation models (usually system optimization model or user equilibrium model) would lead to the failure of these models once the network could not recover from overload by traffic assignment. To avoid this failure, time-fixed traffic flows were generated at origin nodes to ensure the network to be undersaturated. However, this time-fixed traffic flows did not match actual conditions as most evacuees would enter the network in the first few hours (*15*).

To address these challenges in evacuation planning, we pursue three objectives in this study: a) develop a network aggregation method to illustrate the uncertain evacuation demand on the arterial sub-network; b) present a network overload degree index to fit the oversaturated evacuation conditions; c) devise a bi-level control method that optimizes the evacuation network with contraflow and conflict elimination, and then establish a corresponding static bi-objective evacuation model.

The rest of the paper is organized as follows: The nest section first presents the new network aggregation method and the bi-level control method incorporating the contraflow and conflict elimination. In the model formulation section, we define the index of network overload degree and describe the bi-objective evacuation model which aims to minimize network overload degree and total evacuation cost. Specific algorithmic designs of our solution method are then elaborated. In the case study section, we test the performance of the bi-level control method in solving a real evacuation planning problem. And the last section summarizes and concludes with a discussion of future work.

PRINCIPLES

Network Aggregation Method

Because of the large number of intersections and streets in urban areas, it is impossible to cover the whole urban network in network design problems. It is also the challenge for evacuation network design. Researchers usually abstract arterial sub-network for optimization design from the whole network. Under this kind of network representation, as shown in Figure 1(a), origin nodes of the network are located on arterials and each node has a fixed evacuation demand. This representation yields inaccurate estimates of the evacuation demand distribution. Evacuees actually live in the zone surrounded by arterials and have the choice of accessing different adjacent arterials, thus it is very hard to determine the fixed demand at arterial origin nodes. In other words, the evacuation demand of an arterial origin node is usually uncertain. To add this characteristic in network representation, a network aggregation method is presented, as shown in Figure 1(b), which aims to balance accuracy and efficiency by refining the zone evacuation demand and the local roads.

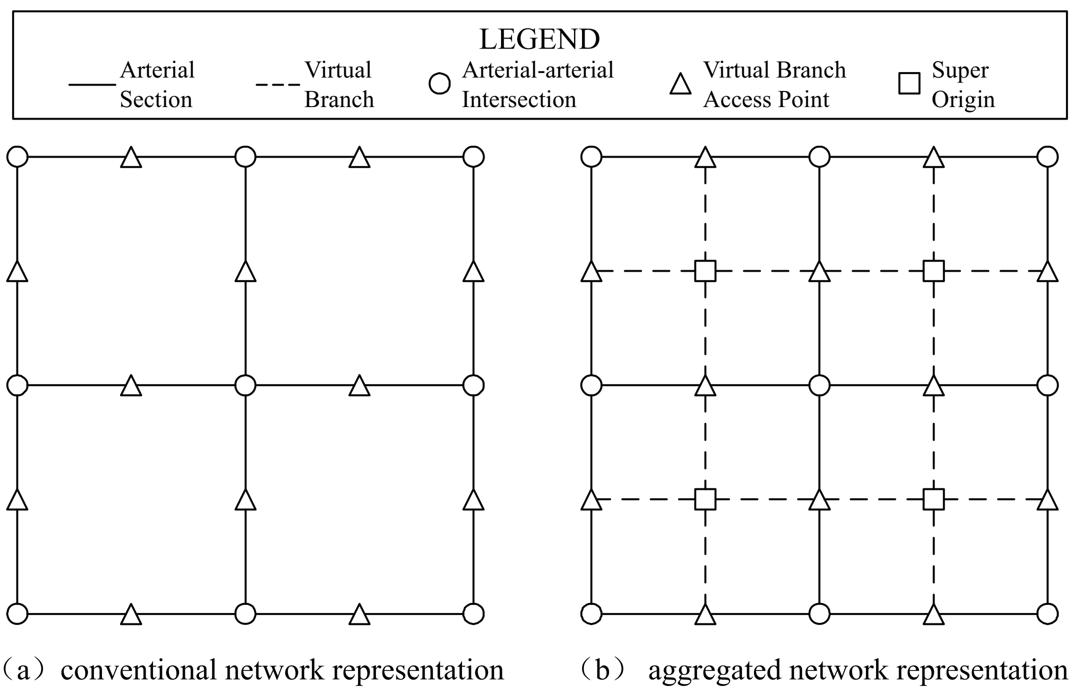

FIGURE 1 Comparison of network representation methods during evacuation.

Before proceeding to the details of this aggregation method, it is worthwhile defining the road functional classification during evacuation first. Two basic classes of roads have been considered in this study: arterials and local roads. Arterials have no direct connection with origin nodes, and they provide mobility that evacuees need to reach network destinations as quickly and safely as possible. Local roads are direct connected with origin nodes, and they only serve local traffic access to arterials. Based on this classification, the evacuation network is divided into two parts: an arterial sub-network and a number of simple local road sub-networks. A local road sub-network is a closed zone bounded by arterial segments (e.g., the four squares surrounded by solid lines in Figure 1(b)).

This division shows another major advantage of the network aggregation method: the flexible definition of road classification. If the network is very large or just a rough result is needed, the range of arterials can be restricted to a higher level (e.g., arterials with median barrier). If it is a district network or detailed result is needed, the collectors can also be included in the range of arterials. This method is also the basis of the bi-level control method, which is described in the next subsection.

Each driver follows a similar two-stage evacuation process. First stage is from an origin location (e.g., home) to an arterial access point, within a local road sub-network. Second stage is from an arterial access point to a destination via the arterial sub-network. It is obvious that the evacuation distance of the second stage is much longer than that of the first stage. Thus, the arterial sub-network is more important to the evacuation, and those measures on arterial are cost effective. Thus, we leave this sub-network unaggregated to ensure the accuracy of the results. In addition, as the travel time on local road have little effect on the evacuation time, a local road sub-network can then be aggregated to one super origin node and several virtual branches.

The aggregation process works as follows: firstly, a super origin node is set to accommodate the entire evacuation demand in each zone; secondly, a virtual branch access point is used to represent the whole local road access points on an arterial segment (i.e., the road section between two adjacent arterial-arterial intersections); thirdly, virtual branches connecting super origin node with adjacent virtual branch access points are introduced to describe the paths accessed into the relevant arterial segments.

Bi-Level Control Method

The proposed bi-level control method aims to manage the evacuation network on both supply (up-level control) and demand (low-level control) sides. It is an integration of contraflow and conflict elimination, which can be used to optimize the evacuation at the levels of the roadway sections and network joints (e.g., intersections and access points), respectively. The effects and application of the two strategies are described briefly below.

The use of contraflow is based on the phenomenon that the inbound flow during evacuations is very low, while the outbound demand often exceeds the available capacity of the outbound roads (*3*). Thus, the reverse of underused inbound lanes is a highly cost effective since significant capacity gains can be achieved without any major infrastructure changes. In this study, this strategy is applied on the arterial segments to increase the available capacity of the evacuation network.

Removing conflict points can reduce network joint delays, total evacuation time and potential accident points (*10*). It can be realized by controlling turning latitude at intersections, which is named conflict elimination. This strategy also limits the alternative routes for evacuees, thus eases the complexity of prediction and management for evacuation managers. There are two kinds of network joints in the proposed aggregated network: arterial-arterial intersections and virtual branch access points, as shown in Figure 1(b). The specific control properties of conflict elimination vary with different joint types.

As shown in the above, the arterial sub-network is more essential for evacuation planning. Thus, the optimization of arterial sub-network is chosen as the objective of the bi-level control method. The up-level control reconfigures the arterial sub-network from the supply side, while the low-level control regulates the saturation of the arterial sub-network from the demand side. Based on this bi-level control method, the arterial sub-network can be served without congestion and interruption.

The up-level control (i.e., supply control) aims to increase the capacity of arterial sub-network and reduce the delay at arterial-arterial intersections. It is realized by the joint use of contraflow and conflict elimination, as shown in Figure 2. The crossing-conflicts are eliminated in the arterial sub-network, so the intersections are transformed into uninterrupted flow facilities with no stop delay. The merging-conflicts are also reduced to a preferred number (named upper bound on the total number of intersection merges), so a lower deceleration delay at intersection merges can be acquired.

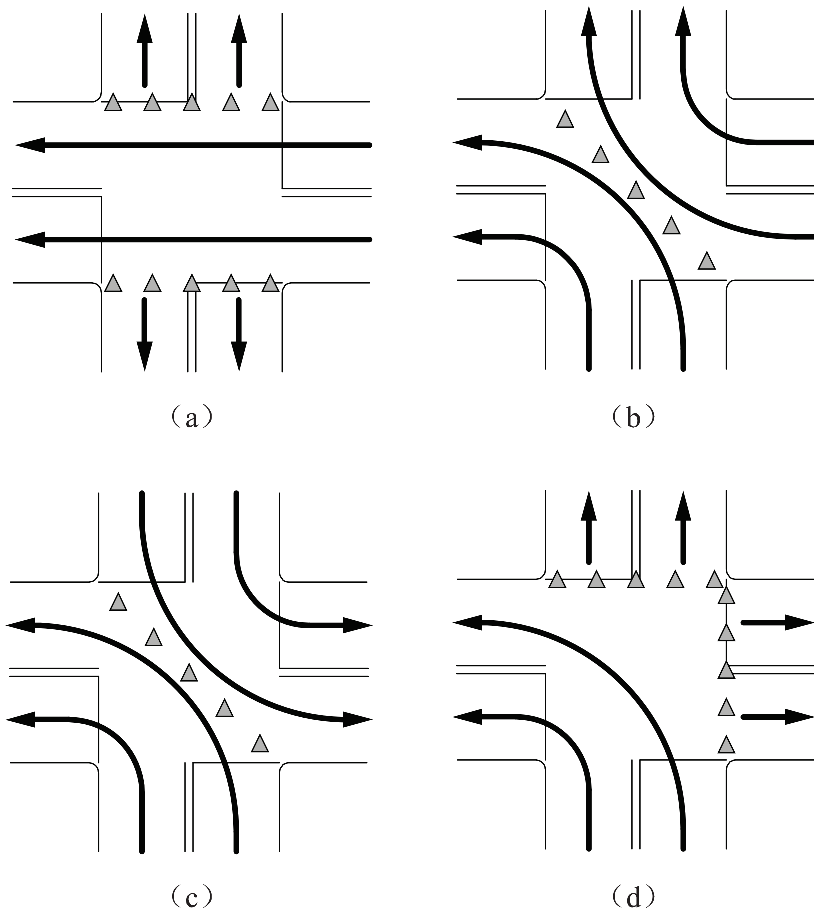

FIGURE 2 Examples of up-level control at arterial-arterial intersections.

The low-level control (i.e., demand control) aims to prevent the arterial sub-network from congestion. It is realized by the control of virtual branch access, and traffic signal is used in each access point to limit the number of vehicles allowed to enter, as shown in Figure 3. Therefore, delay is only at virtual branches and the arterial sub-network can stay at its best performance. Some virtual branches may have a zero volume which means these virtual branches are closed during evacuation by the use of traffic pylons (as shown in Figure 3(a)). This is because evacuees are guided to other virtual branches by traffic manager (for minimizing network clearance time and the number of access points). The allowed flow (evacuation volume per hour) on each virtual branch can be calculated using the evacuation model presented in the next section.

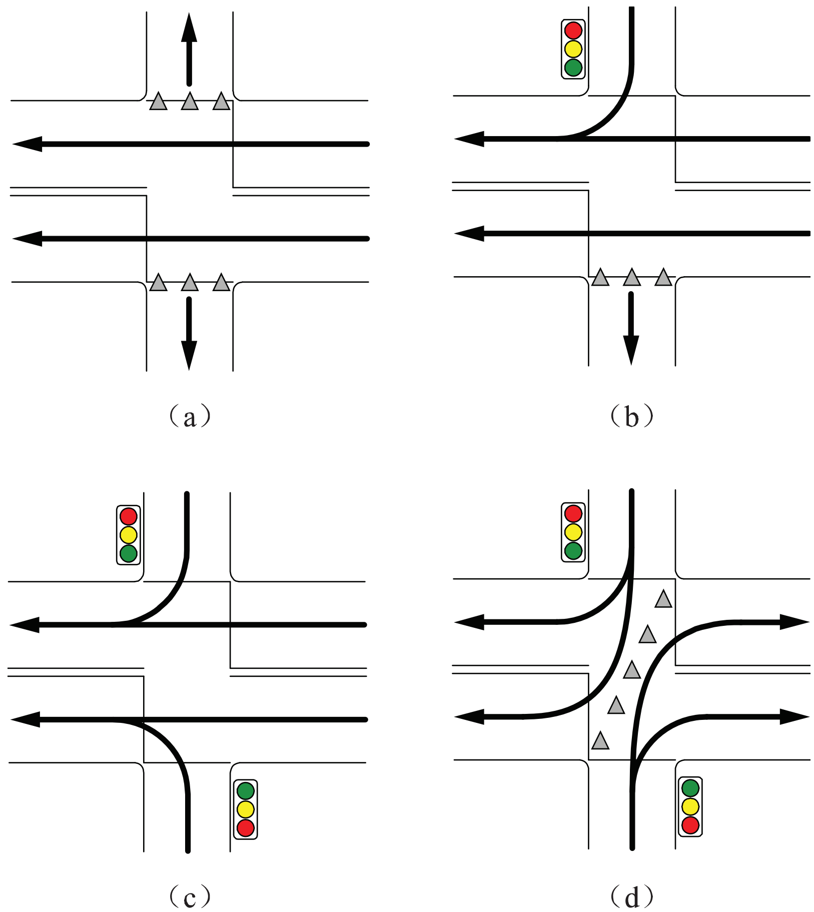

FIGURE 3 Examples of low-level control at virtual branch access points.

MODEL FORMULATION

Network Notation

The network notation is listed below:

Sets	
N	Set of nodes
N_S	Set of super origin nodes of the zones
N_A	Set of virtual access nodes (virtual branch access point) of the arterials
N_I	Set of intersection nodes
N_D	Set of destination nodes
Γ_j	Set of downstream nodes of node j, $\forall j \in N$
Γ_j^{-1}	Set of upstream nodes of node j, $\forall j \in N$
A	Set of links
A_R	Set of roadway-section links
A_B	Set of virtual branch links
A_I	Set of intersection links

Parameters	
c_{js}	Capacity of link (*j*,*s*), $\forall(j,s)\in A$
c_m	Destination node capacity of node *m*, $\forall m \in N_D$
l_{js}	Lengh of link (*j*,*s*), $\forall(j,s)\in A_R$
v_{js}	Design speed of link (*j*,*s*), $\forall(j,s)\in A_R$
d_h	Demand volume of node *h*, $\forall h \in N_S$
Variables	
μ	Network overload degree
μ_{js}	Link Overload Degree on link (*j*,*s*), $\forall(j,s)\in A$
x_{js}	Evacuation volume on link (*j*,*s*), $\forall(j,s)\in A$
w_j	Number of traffic streams that merge at node *j*, $\forall j \in N_I$
W	Upper bound on the total number of intersection merges
y_{js}	Connectivity indicator of link (*j*,*s*), $\forall(j,s)\in A_R \bigcup A_I$, where y_{js}=0 or 1

A graph $G=(N,A)$ is defined to represent an aggregated evacuation network, where N and A are the sets of nodes and links, respectively. As both node set N and link set A are made up of their own component parts, an example is illustrated in Figure 4. The node set N includes four exclusive parts: super origin node set N_S, virtual access node set N_A, intersection node set N_I and destination node set N_D, where $N=N_S \bigcup N_A \bigcup N_I \bigcup N_D$. Accordingly, the link set A includes three exclusive parts: roadway-section link set A_R, virtual branch link set A_B and intersection link set A_I, where $A=A_R \bigcup A_B \bigcup A_I$.

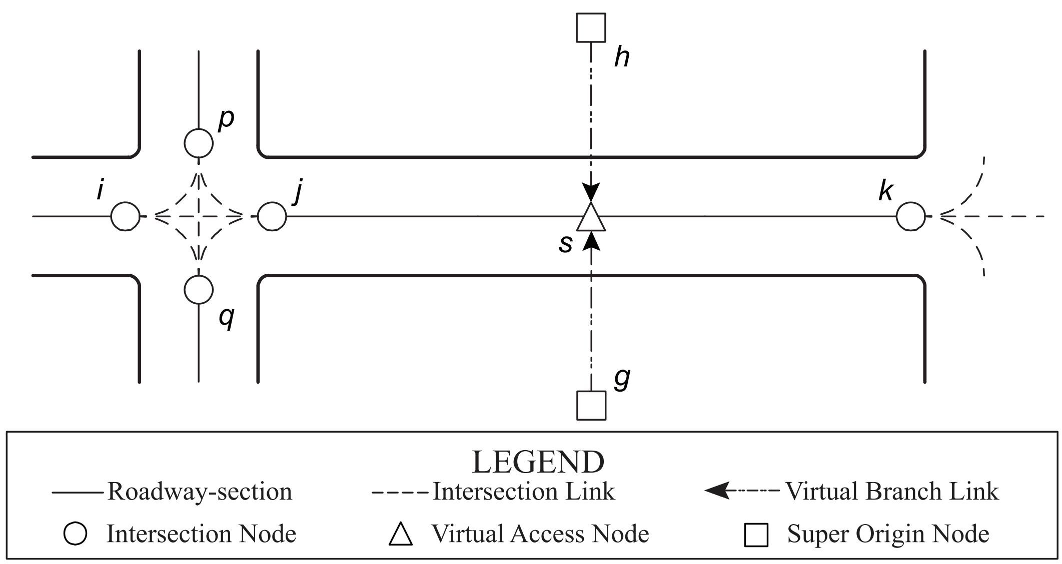

FIGURE 4 Network representations.

As each component part of node set and link set has its own characteristics, some assumptions are needed to make definite notation and simplify the calculation. These assumptions can be classified as one of the following four groups:

- One way assumption
- Virtual access assumption
- Link property assumption
- Destination capacity assumption

One-way assumption: The optimization models proposed by many researchers changed most of the arterials into one-way roads during large-scale evacuation (*5,6,16*). In addition, the research results of Shekhar (2006) and Xie (2010) proved that 100 percent Degree of Contraflow (i.e., two-way roads are all converted to one-way roads) was one of the optimum or near optimum solutions to their network design problems (*17,9*). Therefore, all arterial segments are one-way sections in the evacuation network in this study. This assumption can reduce the computation complexity of proposed models; and can diminish the confusion of evacuees and simplify the intersection control strategies in actual applications.

Virtual access assumption: An arterial segment is divided into two roadway-section links by the virtual access node, and these two links are assumed to have the same length (i.e., the node is located in the middle of this section). Also these two links can have opposite operation directions during evacuation.

Link property assumption: The link properties are determined by the link functions. A roadway-section link is used for calculating network clearance time, thus it is treated as an ordinary graphical link, associated with capacity, length and other travel attributes. A virtual branch link provides access to the arterial sub-network, so its link properties contain capacity, direction but no travel cost. An intersection link is defined as an impedance-free link for the purpose of specifying turning movements at intersections.

Destination capacity assumption: During large scale evacuation, the destinations of urban network are usually the access points to the highway system for further evacuation. Thus, destination capacities are used to represent the capacities of accessed highways to show their impact on urban evacuation.

Bi-Objective Evacuation Model

When the evacuation network cannot recover from overload by traffic assignment, it is very hard for the traditional models to calculate the network clearance time and total evacuation time. This is because the road capacity constraints prohibit the link flow from exceeding its capacity. To address this challenge in model formulation, we first define an index, the network overload degree, to quantify the severity of network overload conditions. This term is based on the concept of reserved capacity, which is favorable for uncertain traffic demand problem (*18*). A number of studies have applied reserved capacity in the network design problems, with different optimization goals and solution methods (*19*,*20*,*21*). The definition of this term is given as follows:

Link Overload Degree: $\mu_{js} = x_{js} / c_{js}$

Network Overload Degree: $\mu = \max(\mu_{js})$

This index can be used to find the bottleneck in the evacuation network, as a maximal link overload degree signifies a longest time to finish the evacuation of this link. Thus, network overload degree can be considered as a key determinant of the network clearance time. The primary objective function, Equation (1), aims to reduce network clearance time by minimizing the network overload degree. The assignment process can be summarized as follows: For each link, the overload degree is multiplied by the link capacity to get a virtual link capacity, and thus the over-saturated network is converted to an undersaturated network with virtual link capacity. Then, the traffic assignment is applied on the reconfiguration network to minimize the network overload degree.

The secondary objective function, Equation (2), is based on the minimum-cost flow model (*22*), which is one of the most basic and useful methods for traffic assignment problems. This objective function aims to route vehicles to their closest evacuation exits based on a certain network overload degree.

With these analyses, the evacuation model has been formulated in a static manner:

$$\min Z_O = \mu \tag{1}$$

$$\min Z_D = \sum_{(j,s)\in A_R} x_{js} l_{js} / v_{js} \tag{2}$$

Subject to:

$$\sum_{j\in\Gamma_s} x_{sj} - \sum_{k\in\Gamma_s^{-1}} x_{ks} = 0, \quad \forall s \in N_A \bigcup N_I \tag{3}$$

$$\sum_{s\in\Gamma_h} x_{hs} = d_h, \quad \forall h \in N_S \tag{4}$$

$$x_{js} \le \mu c_{js}, \quad \forall (j,s) \in A_R \bigcup A_B \tag{5}$$

$$\sum_{i\in\Gamma_m^{-1}} x_{im} \le \mu c_m, \quad \forall m \in N_D \tag{6}$$

$$y_{js} + y_{sj} \le 1, \quad \forall (j,s),(s,j) \in A_R \bigcup A_I \tag{7}$$

$$y_{ji} + y_{pq} \le 1, \quad \forall (j,i),(p,q) \in A_I \tag{8}$$

$$\sum_{i\in\Gamma_j^{-1}} y_{ij} \le w_j + 2, \quad \forall j \in N_I \tag{9}$$

$$\sum_{j\in N_I} w_j \le W \tag{10}$$

$$x_{js} \le K y_{js}, \quad \forall (j,s) \in A_R \bigcup A_I \tag{11}$$

$$0 \le x_{js}, \quad \forall (j,s) \in A \tag{12}$$

Constraints (3) and (4) describe the flow conservation constraints, meaning that inflow volume equals outflow volume. Constraints (5) and (6) are used to ensure the proper allowed amount of volume on each link based on the values of the link capacity and network overload degree. Constraint (7) is a contraflow constraint, and it restricts that arterial segments are all converted to one-way sections. The connectivity indicator, y_{js}, $\forall (j,s) \in A_R \bigcup A_I$, is a 0-1 dummy variable. Constraint (8) prevents crossing-conflicts and works on all link (*j*, *i*) that cross link (*p*, *q*) within the intersection (as shown in Figure 4). Constraints (9) and (10) impose restrictions on intersection merging-conflicts: the former records the number of merges at intersection node *j* with a potential merge, and the later places an adjustable upper bound of the total intersection merging number allowed in an evacuation plan. Constraint (11) shows the inherent relationship between the connectivity indicator of a link and its evacuation volume. *K* is a large number satisfying $K \ge \max x_{js}$. When $y_{js} = 1$, it indicates that a positive flow on link (*j*,*s*) is allowed; when $y_{js} = 0$, it indicates that link (*j*,*s*) is blocked and accordingly $x_{js} = 0$. Constraint (12) places the lower bound on all evacuation volume variables.

The proposed model can achieve the bi-level control method described above. For the up-level control, the connectivity indicator y_{js} indicates the optimal configuration of arterial sub-network. And for the low-level control, the allowed flow for each virtual branch is set to x_{js}/μ, $\forall(j,s)\in A_B$ to prevent the arterial sub-network to be oversaturated, which means the evacuation demand is divided into μ parts through the use of traffic signal. Thus, the network overload degree μ could also be considered as the duration of network congestion.

SOLUTION METHOD

The combinatorial optimization problem described in this study is a Discrete Network Design Problem (DNDP), which is usually solved using heuristic algorithms (*23*). We propose a two-stage approach to tackle this bi-objective optimization problem. Firstly, genetic algorithm (GA) is applied to search for the optimal network overload degree. Then, the minimum-cost flow problem is solved over the network overload degree and connectivity. In this section, the detailed descriptions of algorithms are presented.

Stage 1

GA is a population-based metaheuristic inspired by the genetic evolution process of species in the nature, which was first introduced by Holland (1975) (*24*). It has been widely used to solve the one-way or contraflow design problem, Drezner and Salhi (2002), Zargari and Taromi (2006), Miandoabchi and Farahani (2011) and Karoonsoontawong and Lin (2011) have applied GA with various fitness functions in their studies (*25,26,23,7*). The general procedure of the algorithm is presented below.

Step 1: Generate a population of chromosomes subject to certain constraints

Step 2: Calculate the fitness values for the initial population

Step 3: Select a pair of parent solutions randomly from the population

Step 4: Do crossover operations to produce offspring solution set

Step 5: Check the network connectivity of each offspring and discard any disconnected one

Step 6: Compare the fitness values of offspring and parent and update population

Step 7: Go back to Step 3 when the generation is less than demand

Step 8: Select the chromosomes with best fitness value

Based on the general procedure, four specific elements of the GA-based approach are introduced in details:

- Solution encoding
- Fitness function
- Crossover operator
- Connectivity checking

Solution encoding: Discrete decision variables (i.e., link directions) are coded as chromosomes. The chromosomes are 2-row matrices, in which columns correspond to network links and rows correspond to their directions. When the binary variable is 1, it means the operation of this link direction. Otherwise, it means that this link direction is closed. The length of each chromosome is equal to the total number of roadway-section links and intersection links.

Fitness function: The fitness function is defined to obtain the minimum network overload degree, which can be calculated by solving a sub-problem with fixed values of discrete variables. The corresponding sub-problem is defined as follows:

$$\min Z'_O = \mu \tag{13}$$

Subject to:

Constraints 3-6,12

$$x_{js} \le K y^*_{js}, \quad \forall (j,s) \in A_R \cup A_I \tag{14}$$

y^*_{js} is a fixed set of link connectivity indicator variables represented by a chromosome. And the sub-problem is a linear programming problem that can be solved using the well-know simplex method.

Crossover operator: Because of the connectivity demand of the network, we adopted the crossover operator developed by Drezner and Wesolowsky (*27*). The operator attempts to merge two parents in a way that the set of links taken from each parent forms a connected set. Such a connected set is built by selecting one node in the network as the "pivot" node. For each pivot node, each link of the network is endowed with a count which represents the minimum number of links needed to get to pivot node. Then, the design of links with a count below the median is taken from one parent while the design of links with a count above the median is selected from another parent. Based on the partitioning method described, the connectivity of two half networks can be inherited by the next generation. For more detailed information, please refer to (*23*,*27*).

Connectivity checking: Two types of network connectivity are checked in our study. Equation (15) checks the node connectivity by judging if each node has at least one outgoing link. Equations (16-18) check the conflict elimination by judging if crossing-conflicts or overmuch merging conflicts exist in the network. And the special crossover operator described above greatly increases the number of surviving offspring.

$$\sum_{s \in \Gamma_j} y^*_{js} \ge 1, \quad \forall j \in N_A \cup N_I \tag{15}$$

$$y^*_{ji} + y^*_{pq} \le 1, \quad \forall (j,i),(p,q) \in A_I \tag{16}$$

$$y^*_{pj} + y^*_{ij} + y^*_{qj} \le w_j + 1, \quad \forall (p,j),(i,j),(q,j) \in A_I \tag{17}$$

$$\sum_{j \in N_I} w_j \le W \tag{18}$$

Stage 2

One or more network design schemes with the lowest network overload degree μ^* are selected in stage 1. Stage 2 aims to find the optimization plan and the corresponding traffic distribution. Thus, for each scheme, a minimum-cost flow problem is solved using the simplex method. The scheme solutions are then compared and the best one is selected to be the final output. The minimum-cost flow problem is defined as follows:

$$\min Z'_D = \sum_{(j,s) \in A_R} x_{js} l_{js} / v_{js} \tag{19}$$

Subject to:

Constraints 3-4,12,14

$$x_{js} \le \mu^* c_{js}, \quad \forall (j,s) \in A_R \cup A_B \tag{20}$$

$$\sum_{i \in \Gamma_m^{-1}} x_{im} \le \mu^* c_m, \quad \forall m \in N_D \tag{21}$$

CASE STUDY

Network Building and Experiments Design

To have a better understanding of the methods and models, it is necessary to carry out experiments in networks with realistic topology and size. Zhoushan City, located on an offshore island in China, is selected for the case study. This island city suffers an average of 4.1 typhoons each year, and all residents should be evacuated when a typhoon red warning is triggered. The evacuation network covers the urban area of Zhoushan City, which is approximately 35km by 20km in size. The destinations are the access points to the intercity highway system, whose capacity is determined according to the Anti-typhoon Action Plan of Zhoushan City (*28*).

Using the proposed network aggregation method, the evacuation network is represented as Figure 5. This aggregated network contained 5 destinations, 20 super origin nodes (neither crossing-confliction nor merging-confliction), 24 arterial-arterial intersections and 42 roadway sections. The network geometric data (such as section length, number of lanes, design speed) was set according to the Synthetically Traffic Planning of Zhoushan City (2007-2020) (*29*).

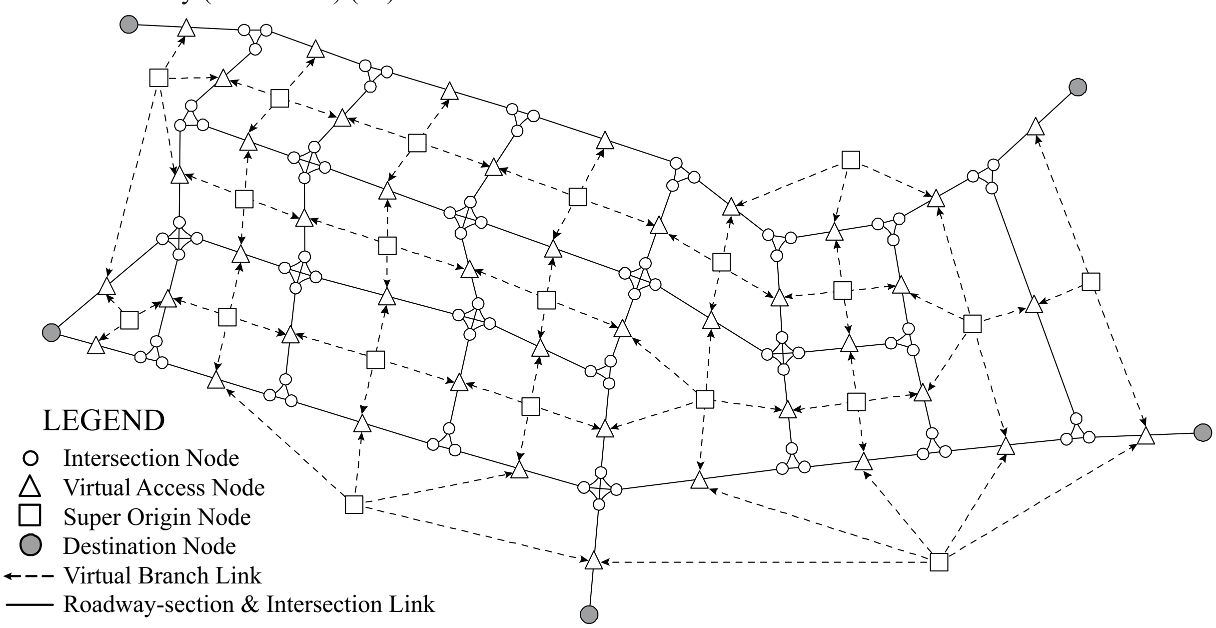

FIGURE 5 Evacuation network of Zhoushan City study area.

Assuming a typhoon red warning in which all residents are required to evacuate, the demand of a super origin node was set to the total number of vehicles in the zone. These numbers could be calculated using the data provided by the Synthetically Traffic Planning of Zhoushan City (2007-2020) (*29*). The total demand is 101,100 vehicles for this network.

The proposed solution algorithm was implemented by Matlab. A series of pilot tests were run to select appropriate parameters for the GA model. The population number was set to 50, and the number of generations was set to 300. And due to the trade-off between solution quality and computational effort, the number of "pivot" nodes in each generation was chosen to be equal to 1/5 of the population with random selection.

Six groups of experiments were performed to compare the effects of various upper bounds of the total number of intersection merges. We adjusted the value from 0 to 5, and the solution algorithm was run five times for each value. The best solution of the five runs was then selected as the final plan which was used for the result analysis summarized in the following subsection.

Result Analysis

Six best plans were obtained from comparative experiments, with each one corresponding to a particular upper bound value of the total number of intersection merges. Each plan produced a minimum network overload degree and a minimum total evacuation cost, which were the two objectives of the proposed evacuation model. The optimal values of the objectives are summarized in Figure 6.

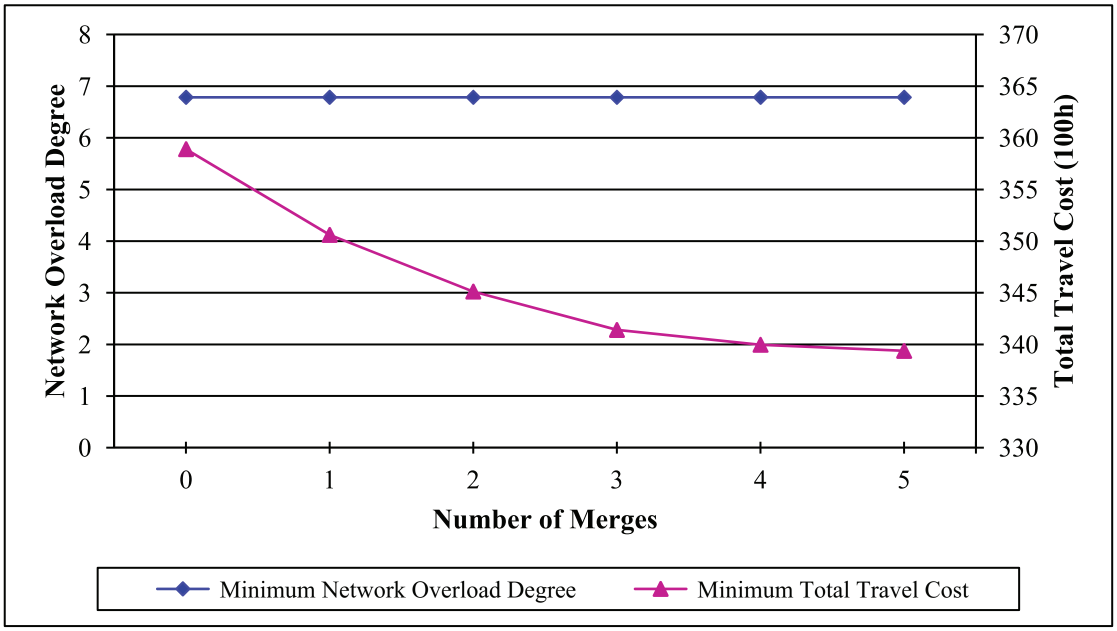

FIGURE 6 Results of comparative experiments for test network.

From the figure, we can see that the minimum network overload degree is stable at 6.79 regardless of the number of merges. This means that the duration of local road sub-network congestion (i.e., the maximum waiting time of evacuees before entering the arterial sub-network) is the same (6.79 h) for all six optimization problems. The minimum total travel cost, however, presents a decreasing from 35,891 h to 33,938 h with the increasing of the number of merges. When the duration of local road sub-network congestion is kept constant, a lower evacuation cost will generate a shorter network clearance time; and a network with a high upper bound of intersection merges seems to be more efficient during evacuation. However, in consideration of the increased merging delay and potential accidents, a trade-off between efficiency and merging should be made.

This trade-off can be considered from the reduced rate of decline of minimum total travel cost. As shown in Figure 6, the increased efficiency obtained with the adjustment of allowed merges from 0 to 1 is about 14 times higher than that obtained with the adjustment from 4 to 5. Thus, the control of total merges to a low number may yield a better balance between efficiency and merging.

A comparison of evacuation routes is presented along with a more detailed analysis. Figure 7 and Figure 8 shows the optimal evacuation plans for 0 and 2 allowed merges, respectively. These two plans have several features in common: Firstly, only part of the arterial sub-network is used for evacuation, while a large number of roadway sections are closed. This can be explained using the well-known theorem by Ford and Fulkerson (1962), which states that the value of the max-flow in a capacitated network is equal to the value of the min-cut (*22*). The min-cut in the evacuation network is a choke capacity which is made up of a series of bottlenecks; and the closure of several redundant roadway sections except the bottlenecks has little effect on the evacuation efficiency. Conversely, this action reduces the network complexity and the potential merges. It also relieves anxiety and panic in evacuees as their evacuation routes are fairly clear. Secondly, some virtual branches are also closed. This reduces the number of total access points in the arterial sub-network and guides evacuees to the appropriate access points in a local road sub-network. Thirdly, some evacuees would be routed significantly further than their closest exit to avoid merging and crossing conflicts. Although the evacuation time of an individual increases, the efficiency of the total network are improved.

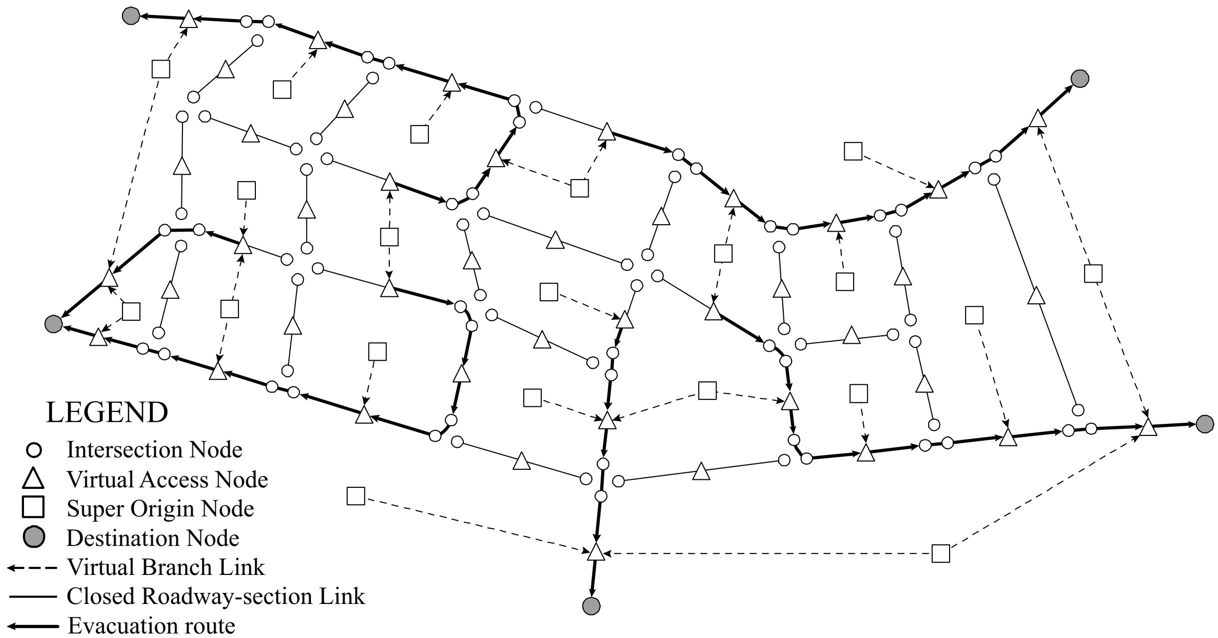

FIGURE 7 Optimal evacuation plan under the constraint of 0 allowed merges.

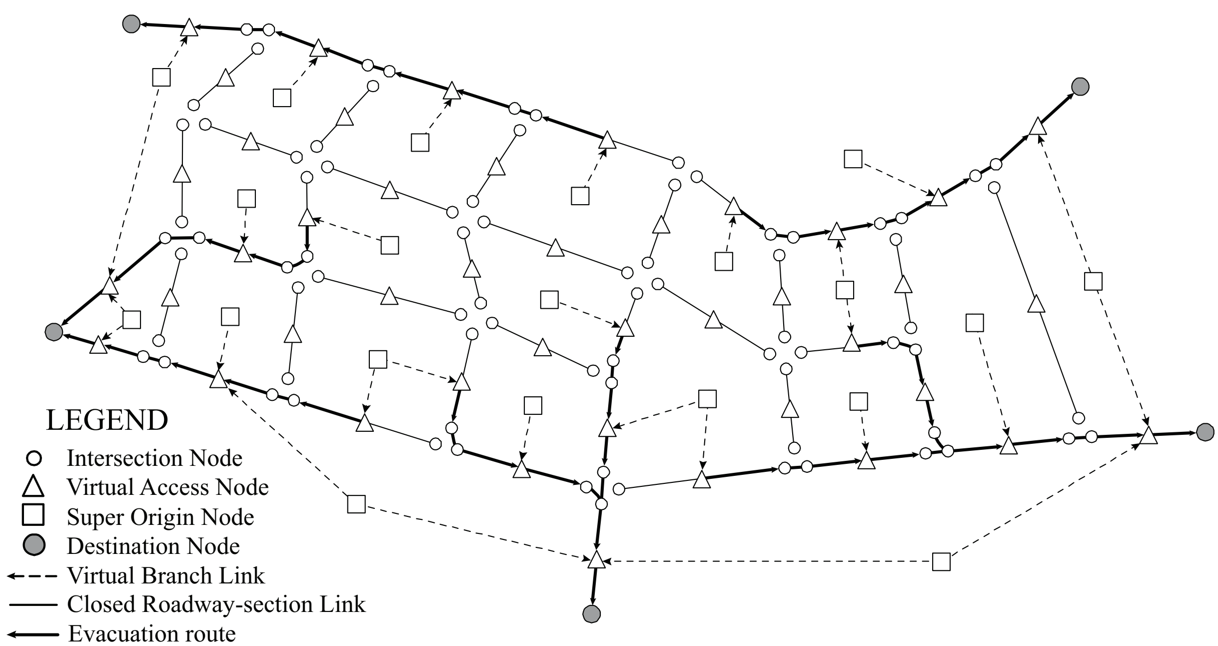

FIGURE 8 Optimal evacuation plan under the constraint of 2 allowed merges.

In spite of both evacuation plans require evacuees to travel further than their closest exit in some cases, the plan with two merges, as show in Figure 8, indicates an improvement in circuitous population and circuitous length. Another difference is reflected in the local road sub-networks, which shows that the open-and-close control of the virtual branches is part of the optimization problem. It also indicates the advantage of the proposed network aggregation method.

CONCLUSIONS

The purpose of evacuation is to relocate people from the danger zone to safe places within the shortest possible time (*30*). For an evacuation of advance-notice emergency, appropriate traffic management can significantly reduce the network clearance time. With this purpose in mind, this study presents an evacuation network control method that optimizes the evacuation network with two strategies: contraflow and conflict elimination. The contraflow strategy can increase the evacuation capacities of arterial segments; and the conflict elimination can reduce merging-conflicts while preventing crossing-conflicts at network joints.

In order to better reflect the real world evacuation, a new network aggregation method and a network overload degree index were also described in this study. The arterial sub-network was a large-scale network with uncertain evacuation demand, as evacuees actually have the choice of accessing adjacent arterials through the local road sub-network. However, it was impossible to optimize an evacuation network containing all arterials and local roads. The network aggregation method in this study was a balance between accuracy and efficiency. The arterial sub-network was left unaggregated to ensure the accuracy of the results, while the local road sub-networks were aggregated to simplify the representation and calculation. This method also had a flexible definition of road classification, as the range of arterials could be varied with network scale or accuracy requirement. The aim of introducing the index of network overload degree was to fit the oversaturated evacuation conditions and to identify network bottlenecks. These bottlenecks were the roadway sections whose link overload degree equaled to network overload degree. And this degree could also be considered as the duration of network congestion, which is a key determinant of the network clearance time.

Based on these two improvements, we proposed a bi-level control method of integrating contraflow and conflict elimination. The main purpose of this method is to make the arterial sub-network to be served without congestion and interruption. Thus, the up-level control reconfigured the arterial sub-network from the supply side, while the low-level control regulated the saturation of the arterial sub-network from the demand side.

A bi-objective network flow model was then developed for identifying optimal evacuation routing plans using the proposed bi-level control method. The two objectives were the minimization of the network overload degree and the total evacuation cost. The former objective aimed to reduce network clearance time by minimizing the network overload degree as this degree indicated the bottlenecks in the evacuation network; and the latter objective aimed to route vehicles to their closest evacuation exits based on a certain network overload degree. After that, a GA-based solution method was applied to solve the network flow model.

A case study was conducted to test the bi-level control method using a real world large-scale evacuation network. The results showed that the control method could eliminate all crossing-conflicts and minimized network clearance time with a fixed number of intersection merges. And through the comparison of the results for different number of allowed intersection merges, it could be found that that the control of total merges to a low number might yield a better balance between efficiency and merging.

There are a number of directions to pursue in the context of this study. The realization of the proposed method in real world evacuation should be analyzed in the future. For example, some constraints can be added on the proposed model to reflect the real evacuation environment. The use of the closed roadway sections can also be discussed. For example, these sections can be used for the evacuation of transit-based residents. Staged evacuation may also be incorporated into the integrated control system for the further reduction of the access point number. Finally, the application of the proposed strategy or a simplified one in peak period traffic assignment is another interesting topic.

ACKNOWLEDGEMENTS

This research is supported by the National High Technology Research and Development Program of China (2011AA110302) and the National Natural Science Foundation of China (No. 51078086). The authors appreciate the Jiangsu Provincial Key Laboratory of Transportation Planning and Management of Southeast University.

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