

## PEDESTRIAN–BUS ROUTE AND PICKUP LOCATION PLANNING FOR EMERGENCY EVACUATION

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**Abstract.** Planning for a bus-based regional evacuation is essential for emergency preparedness, especially for hurricane or flood prone urban environments with large numbers of transit-dependent or transit-captive populations. This paper develops an optimization-based decision-support model for pedestrian–bus evacuation planning under bus fleet, pedestrian and bus routes, and network constraints. Aiming to minimize the evacuation duration time, an optimization model is proposed to determine the optimal pickup nodes for evacuees to assemble using existing pedestrian routes, and to allocate available bus fleet via bus routes and urban road network to transport the assembled evacuees between the pickup nodes and designated public shelters. The numerical examples with two scenarios based on the Sioux Falls street network from North Dakota (United States) demonstrates that this model can be used to optimize the evacuation duration time, the location of pickup nodes and bus assignment simultaneously.

**Keywords:** emergency evacuation, pedestrian–bus network, pickup location optimization, bus resource constraint, safety shelters, evacuation duration time.

### Notations

$b_{m,d}$ – a binary variable, which equals 1 if shelter $d$ is used to evacuate evacuees from pickup node $m$ by bus, and 0 otherwise;	$k_{o,m}$ – a binary variable, which equals 1 if the evacuees at origin $o$ are evacuated to pickup node $m$ , and 0 otherwise;
$bc$ – maximum number of passengers in a bus;	$M$ – set of possible pickup nodes;
$bn$ – the total number of buses;	$m$ – pickup node $m$ , which belongs to set of possible pickup nodes $M$ ;
$cb_{m,d}$ – the total time it takes $n_m$ buses to transport all assembled evacuees at pickup node $m$ to shelter $d$ by round trip mode;	$N$ – the node set of a pedestrian network $G$ ;
$D$ – set of all shelters;	$n_m$ – the assigned number of buses at pickup node $m$ ;
$d$ – shelter $d$ , belonging to set of all shelters $D$ ;	$O$ – set of all demand nodes;
$E$ – set of pedestrian links in a pedestrian network $G$ ;	$o$ – evacuation origin $o$ , which belongs to set of all demand nodes $O$ ;
$G$ – a pedestrian network $G(N, E)$ , where $N$ is the set of nodes and $E$ is the set of links;	$p_o$ – evacuation demand generated from origin $o$ ;
$i$ – node $i$ , which belongs to the node set of a pedestrian network $G$ ;	$t_{i,j}$ – the pedestrian travel time of link $(i, j)$ ;
$j$ – node $j$ , which belongs to the node set of a pedestrian network $G$ ;	$tb_{m,d}$ – the shortest bus travel time from pickup node $m$ to shelter $d$ ;
$(i, j)$ – index of the pedestrian link between adjacent node $i$ and $j$ , $(i, j \in N)$ ;	$tc_o$ – the evacuation time when the evacuees at evacuation origin $o$ is evacuated to a shelter;
	$tt_m$ – the number of bus trips needed for $n_m$ buses to transport all assembled evacuees of pickup node $m$ to a shelter;

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- $upper$  – the upper of all travel cost  $tc_o$ , is also the duration of the evacuation;
- $x_{i,j,o,m}$  – a binary variable, which equals 1 if link  $(i, j)$  is used to assign the pedestrian flow from evacuation origin  $o$  to pickup node  $m$ ,  $(i, j) \in E$ , and 0 otherwise;
- $y_m$  – a binary variable, which equals 1 if node  $m$  is chosen to serve as a pickup node, and 0 otherwise;
- $Z$  – the optimization objective  $z = upper$ .

## Introduction

The efficient operation of public transit system during an emergency evacuation is of fundamental importance in the strategic planning and emergency management for an urban environment. In 2015, a major traffic accident occurred on Shanghai Metro Line 1, and 110 buses were used to evacuate the affected passengers and residents within three hours (CCTV 2017). In 2017, bus transit played vital roles in evacuating people at the subway stations when terrorist attacks occurred in Brussel and London (Henderson, Foster 2017; Hanna 2017). Compared with individual-based evacuation by driving private cars, bus-based evacuation has quite some distinct advantages and characteristics, especially in densely populated areas. Transit can not only move large numbers of evacuee units (humans, animals) from a disaster affected area with relatively few vehicle trips in a speedy and efficient manner but it can also induce as little traffic congestion as possible. Especially, some level of bus priorities (bus lane, special bus signal) in evacuation operation is of benefit to enhance the reliability of evacuation routes. The recent occurrences of emergency events due to extreme weathers and terrorist attacks threatening urban communities with high population densities have served as the motivation to study and develop a novel model of strategic planning of pedestrian–bus evacuation for an evacuation operation of an urban community when information regarding the threats is somewhat available in advance (Heydar *et al.* 2016).

This paper integrates pedestrian evacuation guidance and a bus pickup location problem, and presents a mathematical model to design evacuation routes from evacuation origins to safe areas. The mathematical model combines two networks: pedestrian network and bus network, where evacuees leave for pickup nodes from origins on feet and take buses to designated shelters from pickup nodes. In addition, bus resource constraint is considered in this paper. The objective is to minimize evacuation duration time, which is defined as the time it takes till the last person to be evacuated. In contrast to evacuation models for minimizing the total travel time of all evacuees, this model focuses on avoiding longer evacuation routes.

Although there are many research efforts devoted to emergency evacuation planning in the topic of either bus or pedestrian based evacuation, few studies combine pe-

destrian route, pickup location and bus route together. Furthermore, this study attempts to optimize evacuation duration time under the constraint of bus quantity. Most closely related to this topic, the work of Heydar *et al.* (2016) and Zhang, Chang (2014) determined how the transit-dependent people should be assigned to pickup nodes and identified vehicle routes during the evacuation process, but they assumed that there are enough buses or vehicles to transit the assembled evacuees.

The remainder of this paper proceeds as follows: after the Introduction section, the relevant literatures and previous studies are reviewed in the “Background” section. In the “Modelling...” section, the model variables and modelling process are described. In “Experiments and results”, a small sample network is used to show the effectiveness of the model and solution strategy. Finally, the paper concludes with a summary of observations and findings in “Conclusions”.

## 1. Background

Though some significant contributions have been made to varied evacuation modelling in the past (Murray-Tuite, Wolshon 2013), there are only a limited number of studies discussing the use of public transit to evacuate people in emergency management (Liu, Yu 2012). The current studies approaching to this topic can be divided into two categories, the simulation-based approach and analytical approach. Using VISSIM (<https://www.ptvgroup.com/en/solutions/products/ptv-vissim>) traffic simulation tool, Elmitiny *et al.* (2007) evaluated a current plan and alternative plans by the deployment of transit under an emergency situation in a transit facility such as a bus depot. To reach the best evacuation strategy, nine evacuation scenarios were simulated and analysed. Naghawi and Wolshon (2011) also analysed the performance of their bus evacuation strategies based on simulation software in different aspects.

Comparatively, the analytical approach has been widely used for generating evacuation plans under disaster circumstances (Murray-Tuite, Wolshon 2013). He *et al.* (2009) proposed a stochastic optimal modelling technique to generate an evacuation plan for transit-dependent residents in the event of natural disasters such as the hurricane. In the study of He *et al.* (2009), the transit evacuation operation was converted to a multi-stage location-routing problem with uncertain demands. For the uncertainty of evacuation demand, Kulshrestha *et al.* (2014) presented a decision-support model for transit-based evacuation planning, where the location and number of pickup nodes for evacuees to assemble is optimized by a mixed-integer program.

Another stream of researchers has developed some analytical approaches to obtain the best bus evacuation strategy. Chen and Chou (2009) proposed a bi-level optimization model to determine the waiting locations and corresponding shelters, where the model was extended to contraflow operations, waiting spots and service loca-

tions. Bish (2011) summarized the Bus Evacuation Problem (BEP) as a variant of the vehicle routing problem, and analysed the difference between two proposed mathematical programming models for this problem in detail. In particular, one of Bish (2011)'s models was to optimize the upper bound of evacuation routes, and its actual significance was to minimize the duration of an evacuation. Aiming at bus routes under BEP framework, Goerigk *et al.* (2015) and Dikas, Minis (2016) also improved the model and presented specific solution algorithms.

As discussed above, despite some important contributions of previous studies in BEP, the focus integrating evacuee guidance (from buildings or parking lots to pickup nodes) and bus route (from pickup nodes to shelters) became popular until recently. Heydar *et al.* (2016) presented a mathematical model to plan emergencies in a densely populated urban zone, and it is capable to assign evacuees from buildings or parking lots to pickup nodes and to route buses from pickup nodes to shelters. However, the optimization of evacuation duration time, the constraint of bus quantity and bus capacity was not considered in his study. To better highlight the characteristics of our evacuation model, we would like to further give a summary of several works that have strong correlations to our research.

In comparison to other related papers, our study has some characteristics shown in Table 1. First, in objective function, this paper pays more attention to minimizing evacuation duration time instead of seeking integration optimization, like minimizing the total travel time. Second, this paper integrates the pedestrian network and bus network, and furthermore, optimizes pedestrian and bus routes, pickup locations and shelters simultaneously. Third, bus quantity and capacity constraint are considered as well in this paper. When the total number of buses is insufficient to transport all evacuees once, the bus assignment and transport trips are optimized.

## 2. Modelling: problem description and assumptions

In this section, we describe the framework for pedestrian–bus evacuation planning and propose a mathematical programming formulation to minimize the evacuation duration time. The model determines the optimal pickup nodes for evacuees to assemble, and allocates available buses to transport the assembled evacuees from pickup locations to possible shelters.

The proposed integrated model is depicted in Figure 1 as a (complete) graph in which all evacuation origins, pickup nodes, and shelters are represented by shapes; roads are represented by lines in the network; roads are represented by lines in the network. All evacuees walk in pedestrian network and then are transited to safety shelters by bus in bus network. The intersection nodes of pedestrian network and bus network are pickup nodes, which are the walk destinations of evacuees in pedestrian network and also the bus origin nodes in bus network.

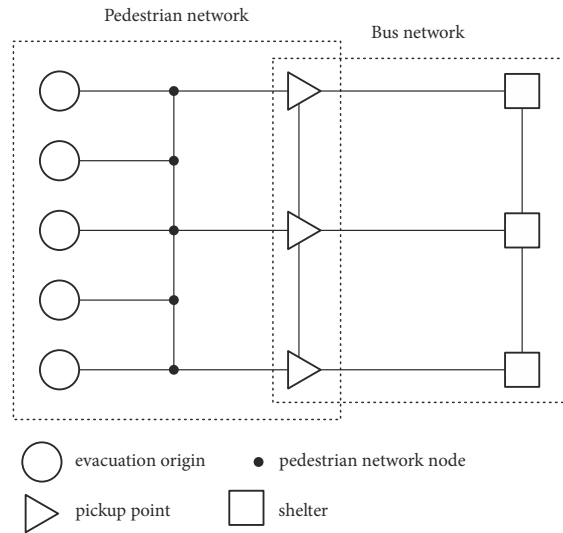


Figure 1. Sketch map of evacuation network

Table 1. Comparison of key elements in recently related evacuated model

Objective function	Optimization type	Pedestrian characteristic	Publication
MOBEBS	bus stop location	–	Kaisar <i>et al.</i> (2012)
MTET	bus route	–	He <i>et al.</i> (2009)
MTNE	vehicle assignment	pedestrian–vehicle mixed flows	Zhang, Chang (2014)
MED	pickup location	–	Swamy <i>et al.</i> (2017)
METD	evacuee assignment	uniform pedestrian flow and non-constraint	Liu, Yu (2012)
MTNE	bus route	–	Li <i>et al.</i> (2014)
MET/MTET	bus route	–	Bish (2011)
MTET	pickup location; pedestrian and bus route	uniform pedestrian flow and non-constraint	Heydar <i>et al.</i> (2016)
MET	pickup location; pedestrian and bus route	mixed pedestrian flow; bus resource constraint	Current paper

Notes:

MED – minimizing evacuation distance; MET – minimizing evacuation time; METD – minimizing the total distance; MOBEBS – maximizing the overall benefit of evacuation bus stops; MTET – minimizing total evacuation time; MTNE – maximizing the total number of evacuees.

*Assumption (1) – at each pickup node, after all evacuees leaving for this node are assembled, then assigned buses begin to transport them.* In view of this, how many the waiting evacuees can get on buses in each bus trip depends on the capacity of assigned buses whether they arrive early or late. Some pedestrian flows from different evacuation origin nodes are mixed at a selected pickup node, and therefore the bus use time/bus during time that the evacuee group of the different flows cost to their shelter is regarded to be equal.

*Assumption (2) – the buses can arrive at the pickup node on time, and the travel time to the shelters is not affected by traffic congestion.* For an effective evacuation, we think that the government arranges limited buses to participate in the event, and gives some priorities and traffic management strategies to keep bus lanes clear and unblocked. In addition, the shortest paths from any pickup nodes to any shelters are calculated in advance.

*Assumption (3) – round trip mode.* Based on limited bus transportation capacity, if the assembled evacuees on a pickup node are too many to transport to a shelter once by assigned buses, these buses can transport the evacuees by multiple trips. In addition, transfer time is not considered.

*Assumption (4) – one-one-one evacuation.* This paper proposes a model for the evacuation from one origin node to one pickup node, and to one shelter (one-one-one evacuation), which is similar to the work by Li *et al.* (2014). There are two reasons: (1) the evacuees are hard to be assigned to different routes quantitatively in realistic operation, so that we see the evacuees from an origin node as whole; (2) once a pickup node is determined, the bus from this node will leave for the closest shelter.

### 3. Model formulation

#### 3.1. Coupling constraints between pedestrian routes and pickup nodes

To characterize the connection between pedestrian routes and pickup nodes, we introduce inequality (Equation (1)) to express the relationship between the location selection of a pickup node and potential pedestrian routes (Tong *et al.* 2015):

$$k_{o,m} \leq y_m, \forall o \in O, m \in M. \quad (1)$$

In addition, to guarantee at least one potential pickup node, inequality (Equation (2)) is used:

$$\sum_{m \in M} y_m \geq 1. \quad (2)$$

#### 3.2. Pedestrian flow balance constraints

In a pedestrian route, each pedestrian link flow corresponds to a single evacuation origin  $o$ , and pickup node  $m$ . To generate a route, a set of flow balance constraints are formulated as follows. It is worth noting that  $k_{o,m}$  is a binary variable. If  $k_{o,m}$  is equal to 0, it means pickup node  $m$  is not used, and there is no available pedestrian flow for

pickup node  $m$ . If  $k_{o,m}$  is equal to 1, a route will be generated (Liu, Zhou, 2016).

$$\begin{aligned} \sum_{j \in N} x_{i,j,o,m} - \sum_{j \in N} x_{j,i,o,m} = & \\ \begin{cases} k_{o,m}, & i = o, (i, j) \in E; \\ -k_{o,m}, & i = m, (i, j) \in E; \\ 0, & i \neq o, i \neq m, (i, j) \in E, \end{cases} & (3) \\ \forall o \in O, m \in M. & \end{aligned}$$

#### 3.3. One-one-one evacuation constraints

According to the Assumption 4, for any one of evacuation origins, only one pickup node is corresponding to it. In addition, for any one of pickup nodes, there is only one destination shelter. Equation (4) ensures the evacuation from one origin node to one pickup node in a pedestrian network. Equation (5) ensures the evacuation from one pickup node to one shelter in a bus network.

$$\sum_{m \in M} k_{o,m} = 1, \forall o \in O; \quad (4)$$

$$\sum_{d \in D} b_{m,d} = y_m, \forall m \in M. \quad (5)$$

#### 3.4. Bus quantity constraints and bus using trips

Equation (6) ensures that the total number of buses assigned to the pickup nodes is a fixed value. Inequality (Equation (7)) is used to ensure that all evacuees at pickup node  $m$  are transported to a safety shelter, and the buses are fully loaded as possible, where  $\sum_{o \in O} k_{o,m} \cdot p_o$  is the total number of evacuees at pickup node  $m$ . Equation (8) is used to calculate the time it takes to transport all evacuees from pickup node  $m$  to shelter  $d$  by  $n_m$  buses with capacitated passengers under round trip mode.

$$\sum_{m \in M} y_m \cdot n_m = bn; \quad (6)$$

$$tt_m \cdot n_m \cdot bc \geq \sum_{o \in O} k_{o,m} \cdot p_o, \quad tt_m \cdot n_m \cdot bc \geq \sum_{o \in O} k_{o,m} \cdot p_o; \quad (7)$$

$$cb_{m,d} = (2 \cdot tt_m - 1) \cdot tb_{m,d}, \quad \forall m \in M, d \in D. \quad (8)$$

#### 3.5. Upper bound of evacuation time for each evacuation origin and model objective function

As shown in Equation (9), for evacuees at any one of the evacuation origin nodes, when they arrive at a shelter, the evacuation time is made up of two parts: travel time spent on pedestrian roads and bus using time. Constraint (Equation (10)) requires *upper* being greater or equalling to the maximum evacuation time of flows starting at evacuation origin nodes, which is then minimized by the objective function (Equation (11)). Apparently, constraint (Equation (9)) and constraint (Equation (10)) can be integrated as one constraint (Feng, Miller-Hooks 2014).



Table 2. Demand values at each demand node

Demand nodes	1	2	3	4	5	6	7	8	9	10	11	12	16	17	18	Total demand
Evacuees	60	42	40	46	38	50	34	44	44	52	48	40	36	26	30	630

Table 3. The bus information under Scenarios 1 and 2

The number of available buses under Scenario 1 [veh]	21
The number of available buses under Scenario 2 [veh]	14
Bus capacity [pas/veh]	30

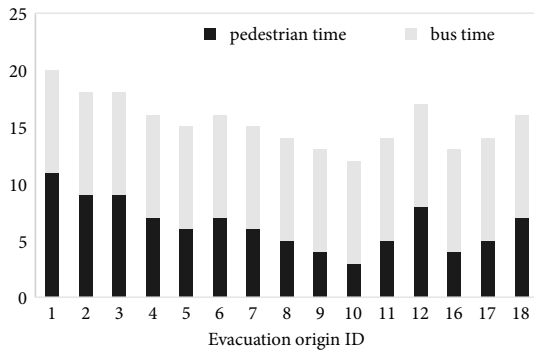


Figure 3. Evacuation during time for each evacuation origin under Scenario 1

However, cost time due to either bus scheduling or bus queuing can be easily added into the proposed model when necessary. For example, the bus travel time can integrate both actual travel time and average bus delay.

Also, in order to explain and clarify the result that the shortest evacuation duration time is 20 time units as GAMS software runs, the random experiments are designed by using MATLAB 2014 (<https://www.mathworks.com/products/matlab.html>), where 1000 random evacuation schemes satisfying all constraint conditions are produced. In each evacuation scheme, evacuation origin nodes, pickup nodes to shelters, and selected shelters are randomly allocated. What’s more, evacuation duration time is the time that the longest pedestrian–bus route costs. To satisfy constraint condition (Equation (3)) quickly and easily, Dijkstra’s algorithm is used to calculate the route between any two nodes. The experiments results are illustrated in Figure 4a. It is not hard to see that the variation of evacuation duration time is volatile. When evacuation duration time ranks in descending order in Figure 4b, an obvious feature shows that all evacuation duration time is no less than 20 time units, which proves that the optimized result by GAMS is reasonable, and the proposed model in this paper can be used to minimize the upper bound of evacuation duration time. It is worth noting that there may be other evacuation routes except the routes in Table 4 when evacuation duration time is optimal. If their existence does not have an effect on optimal/maximal evacuation duration time, they will also be feasible routes.

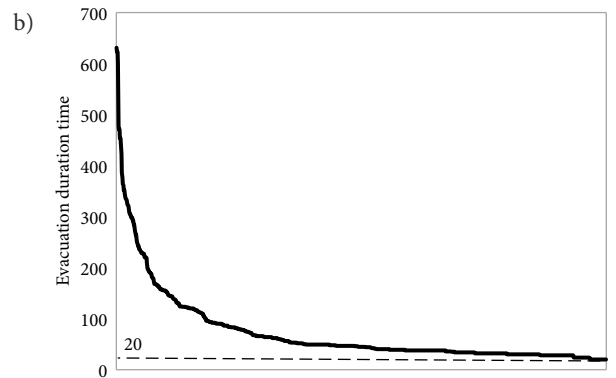
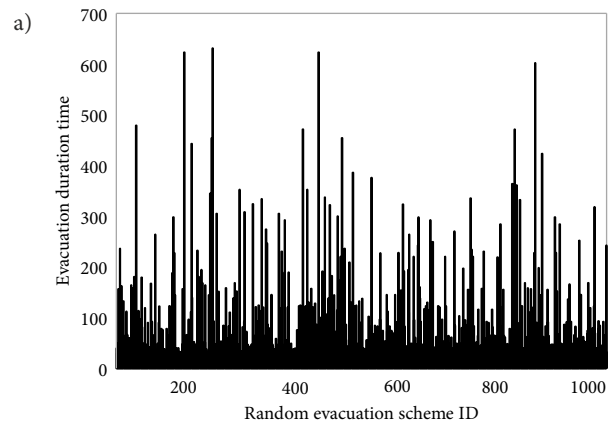


Figure 4. Results of random experiments: a – the evacuation duration time of random experiments; b – ranked evacuation duration time in descending order

Table 4. Optimal results under Scenario 1

Evacuation origin ID	Pickup location	Pedestrian route	Bus route
1	15	1–3–4–11–10–15	15–22
2		2–6–5–9–10–15	
3		3–4–11–10–15	
4		4–11–10–15	
5		5–9–10–15	
6		6–5–9–10–15	
7		7–8–9–10–15	
8		8–9–10–15	
9		9–10–15	
10		10–15	
11		11–10–15	
12		12–11–10–15	
16		16–10–15	
17		17–16–10–15	
18		18–16–10–15	

4.2. Scenario 2

In this scenario, the total number of buses is 14. In order to make bus assignment more balanced, the bus travel time of the bidirectional links from node 12 to node 13, from node 19 to node 20, and from node 18 to node 20 are changed to 10, 11 and 12 time units respectively. The set of possible pickup nodes are updated as node 12, node 18, node 19, node 22 and node 23, where node 12 and node 18 are not evacuation demand nodes anymore. The set of shelters are updated as node 13, node 20, node 21 and node 24.

Because the passenger capacity of all 14 buses is less than the total evacuation demand, the optimization of bus transport trips has a more important effect on evacuation duration time. The results solved by GAMS are shown in Table 5 and Figure 5, and the running time is 10.23 s. Compared with Scenario 1, the number of evacuation routes and pickup nodes increase obviously in Scenario 2, which attributes to the travel time modification in some links and insufficient bus resource. As shown as Figure 5, the evacuation duration time is 34 time units, longer than that under Scenario 1. Especially, in Table 5, we can further find the evacuation routes going through nodes 9, 10 and 11 are the most, which means that the evacuation efficiency will decrease deeply if the nodes are disturbed. These nodes should be paid more attention and implemented traffic management strategies for keeping node capacity and efficiency.

The results of bus assignment and transport trips under Scenario 2 are shown in Figure 6, and the bus assignment at pickup node 19 is maximum. Analysing this phenomenon, the reason is that the pickup nodes, linked by those longer pedestrian routes, may be allocated to more buses to reduce bus transport trips. In addition, the pickup nodes linked by the shorter bus lane to the shelters may be allocated to fewer buses to increase bus transport trips, saving the number of buses for other pickup nodes and this may reduce the integral evacuation duration time throughout the pedestrian–bus network.

Table 5. Optimal results under Scenario 2

Evacuation origin ID	Pickup location	Pedestrian route	Bus route
1	12	1–3–12	12–13
3	12	3–12	12–13
16	12	16–10–11–12	12–13
17	12	17–10–11–12	12–13
2	18	2–6–8–16–18	18–20
7	18	7–18	18–20
9	18	9–10–16–18	18–20
4	19	4–11–10–17–19	19–20
5	19	5–9–10–17–19	19–20
6	19	6–8–16–17–19	19–20
10	22	10–15–22	22–20
8	23	8–9–10–11–14–23	23–24
11	23	11–14–23	23–24

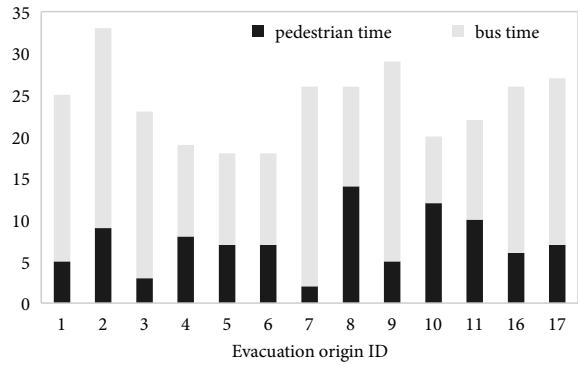


Figure 5. Evacuation duration time for each evacuation origin under Scenario 2

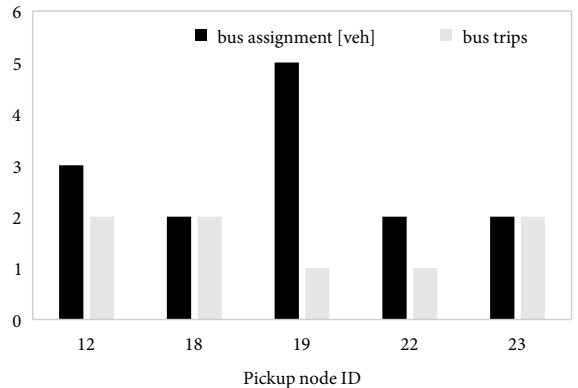


Figure 6. Results of bus assignment and transport trips under Scenario 2

Conclusions

The paper differs from its closest relatives in two important aspects: (1) the objective function, which is to minimize the duration of an evacuation, that is, how long it takes to transport evacuees from origins to shelters in the pedestrian–bus network; (2) bus transport trips, bus assignments and bus routes can be optimized simultaneously in this model. Aiming to minimize the evacuation duration time, this paper presents an approach to determine the location of pickup nodes for evacuees to assemble in a pedestrian–bus network. Moreover, this method is considered to be applied under a long/short-notice evacuation, especially when the bus resource is constrained. Through experimental tests in the Sioux Falls street network from North Dakota (United States), the proposed model is verified as reasonable for optimizing the assignment of bus resources to evacuate pedestrians. GAMS software is used to solve the model under two designed scenarios. The results show that: (1) in the condition of current network size, the high-quality solution for the proposed model can be attained by GAMS; (2) when the bus capacity is limited, the optimized bus schedule tends to allocate more buses to pickup nodes with larger demand and longer evacuation routes, and assign less buses with more transit round trips to pickup nodes with shorter evacuation routes.

Although we have provided mathematical programming formulations for the pedestrian–bus route and pickup location optimization with bus resource constraints

under evacuation circumstances, due to its computational complexity, a heuristic technique is required for realistic size problems, which will be our next research goal. There are still two challenges for the study in the future. First, to provide an effective and accurate evacuation plan, the dynamic delay in pedestrian–bus transfer process should be considered. For this challenge, it may be a suitable solution to abstract important activities (such as pickup, walk, drop off) as pedestrian–state–time vertexes to construct pedestrian–state–time networks and then to solve the multidimensional problem. Second, the time dependent effect is not considered in this model. If the time dependent effect is included, a dynamic bus dispatch plan would be proposed.

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### Author contributions

The authors confirm contribution to the paper as follows:

- »» study conception and design: *Weike Lu*;
- »» data collection: *Feng Wang*;
- »» analysis and interpretation of results: *Weike Lu, Lan Liu*;
- »» draft manuscript preparation: *Guojing Hu, Jianan Mao*.

All authors reviewed the results and approved the final version of the manuscript.

### Disclosure statement

There are no conflicts of interest.

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