Large-Scale Urban Multiple-Modal Transport Evacuation Model for Mass Gathering Events Considering Pedestrian and Public Transit System

Jincheng Jiang, Wei Tu, *Member, IEEE*, Hui Kong, Wei Zeng, *Member, IEEE*, Rui Zhang, and Milan Konecny

***Abstract*— Mass gathering events occur frequently in urban regions. Not only serious traffic jams, but also safety risks are consequently caused. Although many evacuation strategies have been proposed, the spatiotemporal coordination issue of multiple-modal transport tools is not solved well to deal with the efficiency and safety risk during the traditional evacuations. This study presented a large-scale multi-modal transport macro-optimization evacuation model for urban mass gathering events. By taking full advantages of each kind of public transit vehicles and optimizing their spatiotemporal cooperation with pedestrian evacuation, our models can greatly improve the global evacuation efficiency. Experiments on a realistic event was carried to validate the proposed model. The numerical results demonstrated that, under the premise of no increasing additional vehicle supply, the efficiency of proposed multi-modal transport evacuation can be improved by 49.7%, 46.5%, 118.7%, and 20.8%, compared with pure metro-, bus-, taxi- single-modal-transport evacuation, and simulated multi-modal transport evacuation without adequate optimization, respectively.**

***Index Terms*— Evacuation, multi-modal transport, multi-source spatiotemporal data, macro-optimization, path planning.**

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Jincheng Jiang is with the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China.

Wei Tu is with the Shenzhen Key Laboratory of Spatial Smart Sensing and Service, School of Architecture and Urban Planning, Smart City Research Institute, Shenzhen University, Shenzhen 518060, China (e-mail: tuwei@szu.edu.cn).

Hui Kong is with the School of Architecture and Civil Engineering, Xiamen University, Xiamen 361005, China.

Wei Zeng is with the Thrust of Computational Media and Arts and Thrust of Data Science and Analytics, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou, Guangdong 511400, China.

Rui Zhang is with the Shenzhen Institute of Beidou Applied Technology, Shenzhen 518055, China.

Milan Konecny is with the Laboratory on Geoinformatics and Cartography, Department of Geography, Faculty of Science, Masaryk University, 611 37 Brno, Czech Republic.

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I. Introduction

MASS gathering events, such as vocal concert, football match, light show, New Year's countdown, festival celebration, occur frequently in urban regions. Tens of thousands of people gather crowdedly. Potential safety risk and heavy traffic jam issues are triggered consequently, when population instantaneously rush out of venue after the ending of these events. For instance, the fangirl stampede in Shanghai bund on the last day of 2014 caused 35 deaths and 42 injuries [1]. When such mass gathering events occur, it is necessary to evacuate large crowds as soon as possible in a safe way. However, this goal is full of challenges due to the high population density, complex geographical and built environments, a wide range of influence scope, multi-modal transport vehicles, and so on.

Evacuation for urban mass gathering events involves both pedestrian and public vehicles. Generally, when a mass gathering event is over, pedestrian traffic with access to public transit systems travel to the pick-up points [2]. Pedestrian evacuations by walking on foot are appropriate for short-distance evacuations due to high utilization ratio of road resources, but the escape speeds are low. For another, public transit system is a leading means of intra-urban travel, which undertakes the major traffic demands in urban mass gathering events [3], as well as in daily life. For example, Gangi [4] used a mesoscopic approach to model evacuation operations, where, pedestrians are guided through emergency exits from buildings to a pick-up point of buses. Public vehicle evacuations have relatively fast escape speeds and they are easily controlled, resulting in they are appropriate for long-distance evacuations [5]. But available public vehicles within a time window are usually limited.

Effective integration of pedestrian and public transit system would be a good solution of evacuation for urban mass gathering events. However, present researches didn't develop effective pedestrian-vehicle switch strategies to concurrently take full respective advantages of walking on foot and diverse public vehicles. In order to achieve this goal, two tasks must be achieved: The first one is the dynamic operation states of public transit systems should be inferred and their potentiality for evacuations should be fully exploited. The other task is the spatiotemporal coordination of pedestrian and public transit system evacuations needs to be greatly improved.

In this study, a multi-modal transport hybrid evacuation model was proposed for large-scale urban gathering events to evacuate crowds as soon as possible in a safe way. Here, pedestrian evacuations are optimized integrally with multiple kinds of public transport vehicles in both spatial and time dimensions from a global perspective to improve the whole evacuation efficiency. The main contributions of this study lie in that:

- The spatiotemporal residual carrying capacities of public transit system are estimated using multi-source spatiotemporal data.
- An effective multi-modal transport macro-optimization evacuation model is proposed to evacuate large crowds safely and efficiently integrating both pedestrian evacuation and multi-modal public vehicle evacuation (i.e., metro, bus, and taxi). In this optimization model, different constraint ways of diverse transport tools are modelled in different ways.
- An evaluation framework including three indicators is presented to comprehensively evaluate the global evacuation time efficiency, physical output of pedestrians, and contribution ratios of diverse public transit resources. Using this evaluation framework with multiple indicators, not only the evacuation effects, but also the collaboration degrees of different modal transit tools can be revealed.

II. Literature Review

Regional outdoor evacuation models can be classified into pedestrian-, vehicle-, pedestrian-vehicle-, public transit-, and multi-modal transport-oriented evacuation models according to different oriented objects.

Pedestrian evacuation models usually focused on the microcosmic behavioral characteristics and macroscopic crowd dynamics during evacuation [6]. Many software (such as Simulex, Exodus, Bgraf, Exitt, etc.) and models (such as cellular automata models [7], lattice gas models [8], social force models [9], agent models [10], animal-based experimental path models [11], etc.) were proposed for pedestrian evacuation. These models have their respective advantages and disadvantages for specific problems. For instance, cellular automata models depicted evacuees' path choice, experience in emergency response, action capability, and crowding phenomena during the evacuation process at a microscopic level. But the parameters of behavior rules were not easy to be determined. For another example, agent models integrated individual microscopic behaviors and macroscopic features of the entire evacuation system, but they still cannot provide global optimal routes. A limited amount of optimization-based decision-making for outdoor pedestrian evacuation scheme usually used the shortest path directly for escape without considering the load-carrying capacity of road resources [12]. However, in an open setting, they lack of global optimal path planning under the constraints of road resources and effective linking with urban public traffic system, resulting in the requirements of large-scale long-distance evacuations in an urban outdoor environment cannot be satisfied.

Compared with pedestrian-oriented evacuation models, vehicle-oriented evacuation models have different traits, which were mainly investigated by simulation- and optimization-based models. Simulation-based models were usually used to analyze and evaluate the evacuation procedures [13]. While, optimization-based models aimed at devising vehicle evacuation solutions [14], [15]. The objectives of minimizing total evacuation times, minimizing clearance times, or maximizing the number of evacuees within a time window were optimized by developing the best traffic flow assignment under user equilibrium or system optimality principles in both static and dynamic configurations [16]. Even so, existing vehicle-oriented evacuation models are insufficient for our scenarios because they focused more on private cars. The functions of public transit system were usually ignored. Moreover, they did not consider the integration (or switch) of pedestrian and vehicle evacuations.

The requirements of large-scale outdoor evacuations for urban mass gathering events can be satisfied by integrating pedestrian and vehicle evacuations in a unified and coordinated way. There are also some pedestrian-vehicle mixed evacuation models were proposed. Simulation-based mixed evacuation models analyzed the variations of mixed flows [17], mixed traffic flow characteristics [18], mutual interaction between vehicle and pedestrian in crossroads [19], modeling pedestrian-vehicle mixed flows [20], or mixed behavior characteristics under traffic lights [21]. Optimization-based mixed evacuation models directly make evacuation plans to provide spatiotemporal decision supports for evacuations. Experimental results demonstrated that unified traffic controls [22], proper mixing ratio [23], contraflow lane reversal [24], and the combined use of pedestrians and buses [25], can significantly improve evacuation capacity. However, the typical characteristics of pedestrian-vehicle mixed flows are the conflicts of pedestrians and vehicles in shared roads [26]. Pedestrians look on vehicles as dynamic obstacles and conflicts with them, so that evacuation efficiencies decreased and safety risks increased, especially at interactions [27]. Thus, pedestrian and vehicle should be separated to improve evacuation safety by reducing the pedestrian-vehicle conflicts. Even though pedestrian-vehicle mixed evacuation models overcome some disadvantages of pure pedestrian or vehicle evacuation models, they still lack of global planning from a global macroscopic perspective in terms of the whole evacuation system.

Transit-oriented evacuation is an effective means to evacuate high-density population [28]. However, the requirements of large-scale regional evacuations for urban mass gathering events cannot be satisfied by existing transit-based evacuation models. Generally, merely single-modal transport (usually bus) in public transit system was treated as the principal objects utilized to evacuate crowds [29]. Their focuses were mainly on planning the bus routes [30], dispatching bus to coordinate with rails' operation [31], designing transit signal priority [32], allocating vehicles to evacuate evacuees from pick-up points to safer shelters [33], etc. Besides, the cooperation between vehicular traffic and mass-transit shuttle buses [34], and between subway and bus transit [35], were also considered to improve the evacuation efficiency. Even so, there's still plenty of room to improve the evacuation ability of public transit system, especially considering multi-modal public vehicles simultaneously.

Compared with single-modal evacuation models, multi-modal transport evacuations have advantages on efficiency. In the past literatures, both multi-modal evacuation simulation and optimization models were applicated. For example, the movements and interactions of pedestrians, private vehicles, and buses [36], the busses and other vehicles [37], or hybrid transport simulation [38] involved in the evacuation operation were simulated from different scales. Simulation-based multi-modal transport evacuation can analyze the impacts of various multimodal evacuation behaviors [39]; while optimization-based multi-modal transport evacuation can make evacuate plannings. Generally, multi-modal optimization evacuation models were adopted usually in large-scale extreme disaster (e.g., Hurricane) with different combinations of transport tools, such as pedestrian and transit bus [37]; auto, bus, and subway [40]; a combination of foot, public transit, coaches, and vans [41]; bi-objective passengers evacuation optimization with multiple travel modes in transit terminal [42]; multi-mode choice behavior after subway breakdown [43]; and so on. These multi-modal transport models were designed to offer customized services for evacuation by adopting dynamic traffic assignment or integrated contraflow strategy.

Despite above few literatures about multi-modal evacuations had been proposed, multi-modal evacuation planning for large-scale urban mass gathering events still face many challenges [41] and their authors also recommended the development of multi-modal evacuation models. The common issues include: firstly, under normal circumstances, public transit vehicles usually are not customized for evacuation; secondly, the spatiotemporal conditions of multi-modal transportation are not deeply understood with sufficient data; lastly, the pedestrian evacuation and multi-modal public vehicle evacuation for urban mass gathering events are not well integrated. More reviews on multi-modal evacuation can refer to literatures [44], in which they suggested the emphasis of future researches should be moved to the utilization of available modes for simultaneously optimizing the multimodal evacuation process.

For that, this study constructed a multi-modal transport hybrid evacuation model, in which the pedestrian evacuation and multi-modal public vehicle evacuation are highly integrated, to make evacuation plans for urban mass gathering events under normal circumstances where public transit system simultaneously service for daily commuting.

III. Methodology

This study aims at providing scientific response schemes including personalized escape paths and transport tools for individual evacuees to improve the evacuation efficiency and safety of the global evacuation system. The main research contents of this study include the following four modules:

A. Urban Multiple-Modal Transport System

Urban multiple-modal transport system involves pedestrian network for walking on foot, public bus system, taxi system, and metro system.

1) Pedestrian Network: The pedestrian network is a main carrier of whole evacuation system. It contains sideway, roadway, underpass, squares, footbridges, metro stations, bus stops, etc. Firstly, the topological structures of pedestrian network are constructed by bidirectionally connecting these spatially adjacent and walkable geographical units. The network arcs and nodes represent the walkable units and their intersections, respectively. Subsequently, the static attributes of pedestrian network contain the width W_{ij}, length L_{ij}, flatness of footways which can be inferred from measurable geographic data.

Lastly, the dynamic attributes mainly involve the road travel time $c_{ij}(t) = \frac{L_{ij}}{\upsilon(\rho(t))}$ and corresponding road capacities $U_{ij} = \max(F(\rho_{ij}) = \upsilon(\rho_{ij}) \times \rho_{ij})$, where $\upsilon(\rho_{ij})$ and $\rho_{ij}(t)$ are the moving speed and crowd density on the entrance of road (i, j), respectively. Generally, there exists an optimum crowd density ρ_O satisfying $\upsilon(\rho_{ij})$ is always close to that in free condition and $F(\rho_O)$ is nearly the maximum flows if $\rho_{ij} \leq \rho_O$. For convenience, the road capacity $U_{ij} = \upsilon(\rho_O) \times \rho_O$ and travel time $c_{ij}(t) = \frac{L_{ij}}{\upsilon(\rho_O)}$ in the following optimization model. Under this setting, the roads can be unblocked only if the crowd density into a road is required to be not more than optimum density ρ_O.

2) Metro System: Passengers use his/her smart cards to pay for their public transportation service. The terminal installed in metro station automatically generates the unique card number, trade time, trade position, and card type. With such information, the time and location for arbitrary passenger to get on/off a metro are captured. The capacity of a metro is set to be the maximum inflows in rush hours and the residual carrying capacity is the difference of maximum capacity and existing passenger volume for background traffic. According to these information, the maximum residual receivable evacuees $p_i^{\delta=1}(t)$ of metro station $i \in D^{\delta=1}$ at time moment t could be known.

3) Public Bus System: Spatiotemporal traffic data and transit smart card data can be utilized to mine the operation status of bus. Arbitrary bus travels in a fixed path and its visiting time to a bus stop is generally regular according to the preset path and time-table. Thus, we can estimate when and where a bus will reach a bus stop to pick up evacuees. Furthermore, the number of buses driving into the study area and the number of all available buses staying in event area can be counted. The carrying capacity and background traffic (i.e., existing passenger volume) of bus system can be inferred using similar method for metro system with the transit smart card data, bus path, time table, and field observation.

4) Taxi System: Trajectory data, containing instantaneous location, time, and occupancy state, can monitor the real-time position and operating status of a taxi. A passenger can use *DiDi* or other service platforms to online reserve a taxi within certain scope ζ (usually 2km). If there is an unoccupied taxi within such scope, it would be invoked and pick up the passenger after a time. If there is no available taxi within such scope, those taxis outside the scope travel as usual and will be reserved by evacuees once they driven into the effective scope. As the pick-up points P_d of taxi are spatially distributed in different distances from event sites (i.e., space region R_d), the available taxis for different groups of pick-up points are necessary to know. We can figure out the dynamic carrying capacity of taxis under different ζ according to the aforementioned reservation principle and real trajectory data of taxis.

B. Multiple-Modal Transport Evacuation Macro-Optimization Model

When a large-scale mass gathering event occurs in city, abundant evacuees gather around the event sites and serious congestion would be caused if there is no global optimization. In such case, on one hand, the global evacuation is very inefficient and unsafe from the perspective of whole evacuation system; on the other hand, considerable public transport resources which are a bit away from event sites are not utilized.

In this study, we focus on the multi-modal transport evacuation macro-optimization model to develop the optimal evacuation planning. The evacuations of diverse modal public transport vehicles are connected and collaborated via pedestrian evacuation on foot. The evacuees should walk to destinations (i.e., metro stations, bus stops, and taxi pick-up points) and take public transit vehicles away in the least possible time. While, our model is to obtain the optimal spatiotemporal pedestrian distribution considering the dynamic operating states of bus, metro, and taxi. Such spatiotemporal pedestrian distribution contains the optimal dynamic ratios of choosing different public transport vehicles, the best route planning for evacuees to walk from event sites to destinations, the balance between the time cost of walking on foot and accessible vehicle resources. With these strategies, multiple public transit vehicle resources are fully utilized, so that the global evacuation efficiency would be improved greatly.

The mathematical form of presented multi-modal evacuation macro-optimization model is defined as following:

Objectives:

$$\min \sum\nolimits_{t=0}^{T} \left(\sum\nolimits_{i\in S} \left(g_i(t) - f_i(t)\right) \times t + \sum\nolimits_{(i,j)\in A} f_{ij}(t)\right) \tag{1}$$

$s.t.$

$$\sum\nolimits_{i\in S} \sum\nolimits_{t=0}^{T} \left(f_i(t) - g_i(t)\right) = -F_S \tag{2}$$

$$\sum\nolimits_{i\in D} \sum\nolimits_{t=0}^{T} \left(f_i(t) - g_i(t)\right) = F_S \tag{3}$$

$$\sum\nolimits_{t=0}^{T} \left(f_i(t) - g_i(t)\right) = 0, \quad \forall i \in N - S - D \tag{4}$$

$$0 \le f_{ij}(t) \le \alpha U_{ij}(t), \forall (i,j) \in A \tag{5}$$

$$\sum\nolimits_{\tau=0}^{t} \left(f_i(\tau) - g_i(\tau)\right) \le \beta F_i, \forall i \in N, t \in [0,T] \tag{6}$$

$$f_i(t) - g_i(t) \le p_i^{\delta=1}(t), \forall i \in D^{\delta=1} \tag{7}$$

$$\sum\nolimits_{i\in P_\xi} \left(f_i\left(t_i^\xi\right) - g_i\left(t_i^\xi\right)\right) \le U_\xi, \xi \in \Upsilon, P_\xi \in D^{\delta=2} \tag{8}$$

$$\sum\nolimits_{\tau=0}^{t} \sum\nolimits_{i\in P_d} \left(f_i(\tau) - g_i(\tau)\right) \le \chi_d(t), \quad \forall t \in [0,T], d \in [d_1, d_1+d_2] \tag{9}$$

Related notations used in this paper can refer to Appendix-A of the supplementary material. As shown in Formula-1, the objective function is to minimize the integrated evacuation time, which contains two parts: the first part $\sum_{t=0}^{T}\sum_{i\in S}((g_i(t) - f_i(t))\times t)$ asks for the evacuees to leave event sites as early as possible; the second part $\sum_{t=0}^{T}\sum_{(i,j)\in A} f_{ij}(t)$ means the evacuees should take the least time walking on the pedestrian evacuation network and waiting for public vehicles. This objective function simultaneously maximizes the global evacuation efficiency and plans pedestrian evacuation path.

TABLE I
THE CONSTRAINT WAYS OF DIVERSE PUBLIC TRANSIT VEHICLES

	WAIT FOR EVACUEES	CONSTRAINT FOR SINK NODES
Metro	No	Each metro station maximally receives a dynamic number of evacuees at set intervals
Bus	No	The total capacity of a series of temporospatial sinks is less than a certain value
Taxi	Yes	The accumulated received evacuees in taxi sinks for a given geographic scope is less than a dynamic value which is changed with time window.

Formulas-2∼9 represent constraints 1-8, respectively. As general constraints, all affected population need to evacuated from event sites to destinations and taken away by public vehicles within designated time window, refer to constraint-1; Similarly, all evacuees have arrived in sink nodes (i.e., bus stops, metro stations, and pick-up points of taxi) and left by public transit system after evacuation terminates, refer to constraint-2, where $D = D^{\delta=1} \cup D^{\delta=2} \cup D^{\delta=3}$ and $F_S = |Q|$; while for intermediate transit points, the flow conservation requires no addition or reduction of evacuees during the whole evacuation period, refer to constraint-3. These three general constraints are to keep flow conservation and achieve evacuation tasks.

In our multi-modal evacuation model, four transport modes (i.e., pedestrian, bus, taxi, metro) are employed and their respective constraint ways in the optimization model are different, as shown in Table I.

Pedestrian evacuation is to assign spatiotemporal crowd flows to match well with public transit vehicle evacuation. Like conventional outdoor pedestrian evacuation model, our pedestrian evacuation by walking on foot is also mainly under the restrictions of road and intersection capacity. Constraint-4 is arc capacity constraint and it suggests the dynamic flows on a road cannot beyond its capacity; Constraint-5 is node constraint that the evacuees stranded in any node at arbitrary time moment are limited to the node capacity, where $f_i(t) = \sum_{(k,i)\in A} f_{ki}(t_0)$, $g_i(t) = \sum_{(i,j)\in A} f_{ij}(t)$, and $t_0 + c_{ij}(t_0) = t$. α and β are the parameters for adjusting the safety of crowds. Without loss of generality, $\alpha = 1$ and $\beta = 1$ in this study.

Metro evacuation plays its role in the sink nodes (i.e., metro station) by setting dynamic maximum receivable capacity. Refer to constraint-6, the reduced evacuees carried away by metro at destination (i.e., the metro station) cannot exceed its dynamic residual carrying capacity. This constraint describes the pedestrian-metro switch. One characteristic is that metros don't wait for evacuees and their carry capacity would be wasted if evacuees don't utilize them on time.

Buses travel along fixed path and pick up evacuees in designated bus stops. Each sink node (i.e., bus stop) receives evacuees only when a bus visits it at particular time moment.

Due to the limited capacity, the summation of evacuated evacuees on a bus cannot be greater than its residual capacity. Refer to constraint-7, the total received evacuees at all visited bus stops for an arbitrary available bus are less than its residual carrying capacity, where t_i^{ξ} is the time moment when bus ξ visits sink node i.

Taxi evacuation highlights the mutual competition of multiple sinks due to limited available vehicle resources. Different from bus and metro, taxi can be utilized once it is reserved. But the number of available taxis within a time window and within a certain geographic space is limited. Thus, the accumulated received evacuees in taxi pick-up points within a time window for a given geographic scope are limited to a value and this value is dynamic in different time windows, refer to constraint-8.

C. Optimization Solution

1) Network Configuration: Before solving the multi-modal macro-optimization evacuation model, we'd like to introduce the definition of time-expanded network. Given a transportation network $G(N, A)$ and time window $[0, T]$, the corresponding time-expanded network $G'(N', A')$ is constructed as following. N' is the T copies of N; node $i' \in N'$ has the same attributes as node $i \in N$, where $i' = i + t \times |N|$, $t \in [0, T]$; for arbitrary arc $(i, j) \in A$ and time moment t, a new arc (i', j') is generated, where $i' = i + t \times |N|$ and $j' = j + (c_{ij}(t) + t) \times |N|$. (i', j') is added to A' if $j' \leq T \times |N|$; $(i', j') \in A'$ has the same attributes as $(i, j) \in A$. Thus, it can be seen that all dynamic flows on original underlaying transportation network can be represented by static flows on corresponding time-expanded network.

The constructed multi-modal evacuation optimization model is a variant of network flow problem [45]. Three main differences from general quickest network flow model exist: Firstly, there are several egresses out of event sites. All metro stations, bus stops, and pick-up points of taxi are treated as sink nodes. Secondly, stay in source or sink nodes is allowed. Evacuees can reach sink nodes to wait for bus/metro/taxi. Thirdly, the maximum receivable capacities of sink nodes are dynamic and interplay.

In order to conveniently apply algorithmic techniques developed for static network flows [46] to solve our multi-modal evacuation optimization model, several general configurations on time-expanded networks are necessary:

Firstly, arbitrary dynamic flows in nodes or arcs are mapped to corresponding time-expanded network. That is, arbitrary node $i \in N$ at time moment t on original underlaying network has only one unique corresponding node $i + t \times |N|$ on G'. Similarly, arbitrary arc $(i, j) \in A$ at time moment t on original underlaying network has only one unique corresponding arc $(i + t \times |N|, j + (t + c_{ij}(t)) \times |N|) \in A'$, where $|N|$ is the total number of nodes on G.

Secondly, evacuees are allowed to stop at bus stops, metro stations, or pick-up points of taxis. In order to explicitly represent the stay process in our mathematical form, a special class of arcs $(i + t \times |N|, i + (t+1) \times |N|) \in A'$ is added to G', where its capacity is the maximum retention volume of node i. This arc means the evacuees stay at node i from time moment t to the next time moment $t + 1$.

Thirdly, public vehicles (i.e., bus, metro, taxi) pick up evacuees in a discrete way. The bus stops, metro stations, and pick-up points of taxi are treated as the sink nodes of pedestrian evacuation network.

2) Solution Algorithm: Based on time-expanded network technique and fundamental network configurations, this study utilizes two methods (i.e., linear programming algorithm and static minimum cost network flow algorithm) to solve our proposed multi-modal macro-optimization evacuation model.

On one hand, our multi-modal evacuation optimization model is a linear programming problem and the optimal solution exists because its objective function is convex. *Google OR-Tools* [47] is utilized in this study to solve our optimization problem and the spatiotemporal flows $f_{ij}(t)$ for each arc $(i, j) \in A$ can be directly acquired from time-expanded network.

On the other hand, the proposed multi-modal evacuation optimization model can be equivalent to a static minimum cost network flow model with additional specific network configurations, which were presented in Appendix-B of the supplementary material. Thus, the proposed evacuation optimization model can be also solved by classical network algorithm [45].

3) Evacuation Strategy Extraction and Path Planning: Based on the solved solution $f_{ij}(t)$, the detailed evacuation strategies and route planning can be further extracted.

Flow control: the inflows into the entrance of arbitrary road $(i, j) \in A$ at time moment t is set to $f_{ij}(t)$, which can be directly acquired from the solution of multi-modal macro-optimization evacuation model. With the known $f_{ij}(t)$, the optimal pedestrian flows into a node i naturally is $f_i(t) = \sum_{(k,i)\in A} f_{ki}(t_0)$ and the optimal pedestrian flows out of node i is $g_i(t) = \sum_{(i,j)\in A} f_{ij}(t)$, where $t_0 + c_{ij}(t_0) = t$. These variables guide the spatiotemporal pedestrian flow assignments on the pedestrian evacuation network.

Individual pedestrian evacuation path planning: in the context of optimal and fixed collective spatiotemporal pedestrian flows, the individual evacuation paths are extracted under "fair" principle. To extract equitable individual evacuation paths, the following steps are executed: firstly, the latest evacuee is selected to departure event site and his/her shortest path P_{last} to destination is figured out covering spatiotemporal pedestrian flows F; secondly, spatiotemporal pedestrian flows F is updated by reducing a flow along P_{last}; at last, these two steps are repeated till all evacuees have been assigned available paths.

Due to the flow conservation in constraint-3, temporal pedestrian flows F are the collection of all individual routes. After executing above steps, $F = \emptyset$ when all evacuees have been assigned available paths. The termination condition is satisfied. Moreover, the available shortest path P_{last} is figured out, so that each evacuee can be assigned an optimal route under the premise of ensuring global optimality.

Switch of pedestrian and public vehicles: after walking to the destinations (i.e., bus stops, metro stations, and pick-up points of taxi) of pedestrian evacuation network, evacuees switch to public transit system for further leaving. The number of carried evacuees in destination $i \in D$ at time moment t is $f_i(t) - g_i(t)$. If destination $i \in D^{\delta=1}$ is a metro station, then it is metros that take evacuees away; Similarly, if destination i is a bus stop (i.e., $i \in D^{\delta=2}$) or pick-up point of taxi (i.e., $i \in D^{\delta=3}$), then buses or taxis take evacuees away. Due to constraints-6∼8, the reduced people in the destinations (i.e., bus stops, metro stations, and pick-up points of taxi) can always take corresponding public transport vehicles to leave.

D. Evaluation of Evacuation Efficiency

This study presents an evaluation framework including clearance time, average walking distance, and contribution ratio to comprehensively evaluate the evacuation results from different perspectives. Using these multiple indicators, not only the evacuation efficiency, but also the collaboration degrees and potentials of different evacuation modes can be also revealed.

Clearance time τ_c is the earliest time when all evacuees have taken public transport vehicles to leave. If $t > \tau_c$, $L_S(t) = 0$; otherwise, $L_S(t) > 0$. It is an absolute evaluation indicator determined by comprehensive evacuation system. As common sense, the smaller τ_c is, the higher evacuation efficiency will be.

Average walking distance $\bar{d}$ is the average walking distance for all evacuees to walk from event site to the destinations where they take public vehicles. $\bar{d} = \frac{1}{F_S}\sum_{\kappa \in Q}|P_\kappa|$, where $|P_\kappa|$ denotes the length of path P_κ. Generally, the longer $\bar{d}$ is, the more chance an evacuee can get to take public vehicles, but more physical energy would be consumed. $\bar{d}$ measures the compromise of pedestrian and public vehicle evacuations.

Contribution ratio C_δ is the ratio of evacuees $\mathcal{F}_\delta = \sum_{i \in D^\delta}\sum_{t=0}^{T}(f_i(t) - g_i(t))$ carried by public transport mode δ within time window $[0, t]$ and the total evacuees F_S need to be evacuated. That is, $\mathrm{C}_\delta = \frac{F_\delta}{F_S}$. This indicator can be used to compare the contributions made by diverse transport vehicles.

IV. Case Study

A. Study Area and Data Source

In order to test our multimodal-transport collaborative evacuation model, numerous experiments are done for a major vocal concert event held in Shenzhen Bao'an Stadium. The pedestrian evacuation network G with 325 nodes and 565 arcs contains 94 crossroads, 4 exits from Shenzhen Bao'an Stadium (i.e., S), 8 footbridges, 56 bus stops (i.e., $D^{\delta=1}$), 56 pick-up points of taxi (i.e., $D^{\delta=2}$), 5 metro stations (i.e., $D^{\delta=3}$), and each metro station has 4 entrances. The evacuation conditions described in [70] are similar to our evacuation case for urban mass gathering events. Thus, their density-velocity relation (Appendix-C of the supplementary material) and fundamental diagram (Appendix-D of the supplementary material) provided by [48] are utilized in this study. As bolded in Appendix-C of the supplementary material, the optimum crowd density ρ_O is 1.25, 1.9, 1.9 person/m^2 for smooth roads, upstairs, and downstairs, respectively. The corresponding optimum moving speed $\upsilon(\rho_O)$ are 0.93, 0.44, and 0.5 m/s, respectively. Then, the road travel time $c_{ij} = \frac{L_{ij}}{\upsilon(\rho_O)}$ and road capacity $U_{ij} = \upsilon(\rho_O) \times \rho_O$ are figured out.

Inferred from transit smart card data, the dynamic passenger inflows and outflows of five metro stations are shown in Appendix-E of the supplementary material, where the time interval is 10 min. The carrying capacities of metros are set to be the maximum passenger inflows, that is, 528pph, 2100pph, 2868pph, 1884pph, 2274pph for *BaoAn*, *BaoAnZhongXin*, *FanShen*, *BaoTi*, and *BaoHua*, respectively. The dynamic residual carrying capacity at these stations are the difference of total carrying capacity and the existing dynamic passenger inflows.

Learned from transit smart card data and field observation, the maximum passenger capacity of a bus in Shenzhen is about 60 and the background busload is about 20 in the study area and study period. Thus, the residual carrying capacity U_ξ of a bus is approximately 40. Combining with buses' travel path and time table, the available buses and their residual carrying capacity at bus stops are further figured out, as can be seen in Appendix-F of the supplementary material.

We collected the trajectory data of all taxis in Shenzhen on 26, July, 2019 and calculated the accumulated residual capacity $\chi_d(t)$ for all taxis within different R_d from time moment 0 to t, as shown in Appendix-G of the supplementary material.

This study fused multi-source spatiotemporal data to infer the gathered crowds. Firstly, the maximum seating capacity is informed directly from official website. In our case, Shenzhen Bao'an Stadium contains maximumly 40,000 ordinary spectator seats. Secondly, social media data and official live broadcast (and ticket sales position) unfold the events. According to the information collected online, all tickets of the vocal concert held on 26, July, 2019 (from 19:30 to 21:30) were sold out and about 28028 people were gathered to attend this event, which means $F_S = |Q| = 28028$.

B. Experimental Results

Fig. 1 demonstrates the spatial distribution of pedestrians, buses, and taxis during different evacuation stages under our hybrid evacuation strategy. At the initial stages of evacuation, pedestrians gradually spread out in space to access public transport resources as much as possible; As time went by, the spatial distribution of pedestrians reaches the peak of dispersed states at about 30∼40$^{\text{th}}$ min; Evacuees gradually evanished at a later stage and evacuation process ends at about the 84$^{\text{th}}$ min.

Different from pedestrians, after using up the relatively large inventory, taxis picked up evacuees in event area with a slowly-decreasing amount during the whole evacuation process due to their persistent supply. While, the number of buses in the event area remains relatively stable, which is also because the bus supply is persistent.

As shown in Fig. 2a and Table-II, the experimental results demonstrated the evacuation performance using our optimized multi-modal public transport vehicles is significantly better than that using single-modal or non-optimized multi-modal public transit tools.

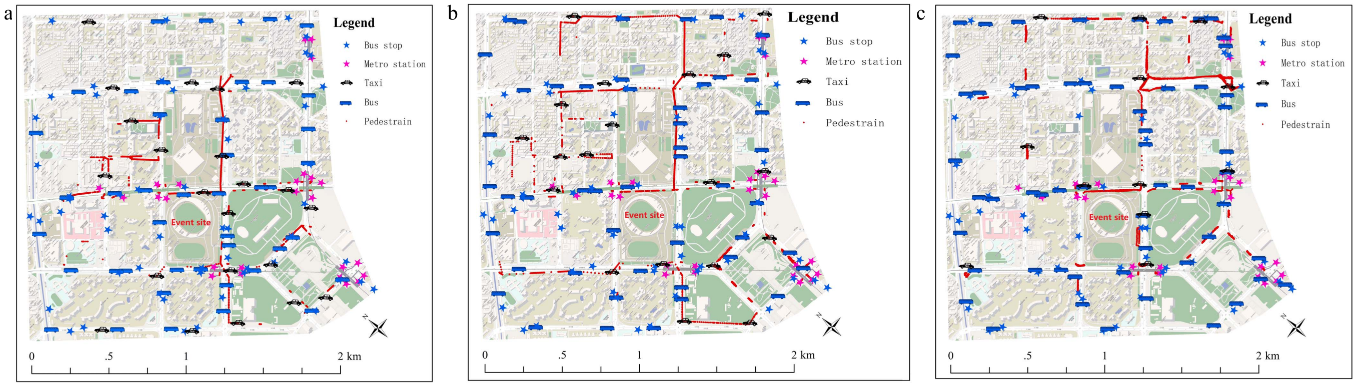

Fig. 1. The spatial distribution of pedestrian, bus, and taxi during evacuation process: (a) the 10^{th} min; (b) the 30^{th} min; (c) the 60^{th} min.

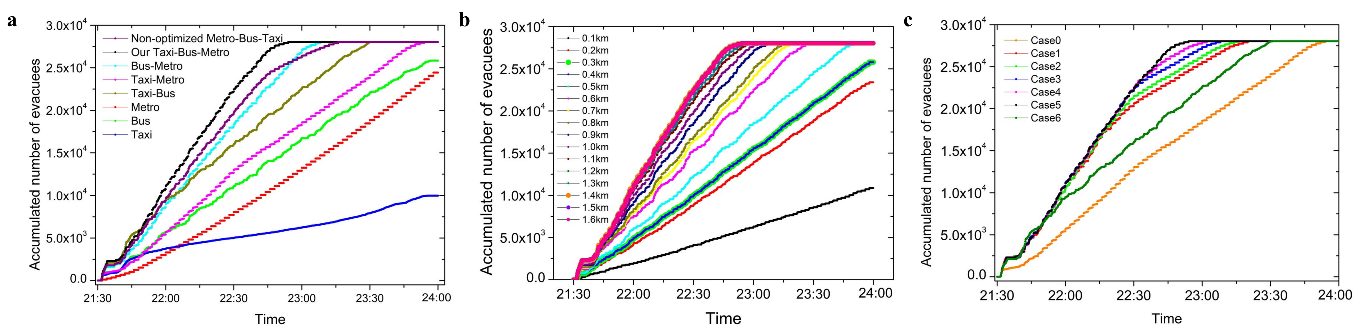

Fig. 2. Evacuation results: (a) The accumulated number of evacuees who have taken different kinds of (or groups of) public transit vehicles to leave event area; (b) The accumulated number of evacuees when the walking distances of pedestrian evacuation are limited; (c) The accumulated number of evacuees considering different proportion of evacuees choosing different transport tools.

TABLE II
THE EVACUATION RESULTS USING DIFFERENT KINDS OF (OR GROUPS OF) PUBLIC TRANSIT VEHICLES

Transport mode	τ_c (min)	C_δ	C_1	C_2	C_3	$\bar{d}$ (km)	$\mho$
Metro	148	0.871	0.871	-	-	0.855	0.898
Bus	147	0.922	-	0.922	-	0.402	0.911
Taxi	145.5	0.356	-	-	0.356	0.327	1
Metro-Bus	98	1	0.431	0.569	-	0.459	0.502
Metro-Taxi	144	1	0.705	-	0.295	0.620	0.754
Bus-Taxi	122	1	-	0.724	0.276	0.381	0.727
Non-optimized Metro-Bus-Taxi	106	1	0.379	0.423	0.198	0.490	0.426
Optimized Metro-Bus-Taxi	**84**	**1**	**0.349**	**0.466**	**0.185**	**0.494**	**0.426**

1) Single-Modal Public Transit Evacuation: In terms of a single kind of public transit vehicle, no matter metro, bus, or taxi cannot evacuate all evacuees within 2.5 hours, but they do their evacuation job till the end of time window (that is, τ_c is close to 150min). From the experimental results, we can observe that the evacuation capability of bus is larger than metro, and much larger than taxi, because the contribution ratios $C_{\delta=1} = 0.871$, $C_{\delta=2} = 0.922$, and $C_{\delta=3} = 0.356$, respectively.

The required average walking distances for metro evacuation, bus evacuations, and taxi evacuation, are 0.855, 0.402, and 0.327km, respectively. The reason why taxi evacuation requires the shortest walking distance is that taxis can drive to evacuees once they are reserved, and the purpose of walking on foot is to broaden the search area for reserving more taxis. The bus stops are evenly distributed in space and their average distance from event sites is shorter than metro stations, resulting in shorter required walking distance.

Thus, it can be seen that each kind of public transit vehicles has their respective characteristics. For example, the total carrying capacity of bus is maximum, and the required walking distances are moderate; taxi has a shortest average walking distance, but lowest carrying capacity; the carrying capacity of metro is considerable, but at the cost of longest average walking distance. In general, bus is the optimum evacuation tool.

2) Our Multi-Modal Evacuation: When multiple kinds of public transit vehicles are collaborated in our optimized strategy, all evacuees can be evacuated out of event area within 2.5 hours. Without doubt, the collaboration of all metro, bus, and taxi can achieve the best evacuation performance at the minimum clearance time. τ_c is reduced to 84min. Besides, the clearance time of metro-bus hybrid evacuation is reduced greatly compared with single metro or bus evacuation. The same thing is also observed in the metro-taxi and bus-taxi hybrid evacuations, but their improvements of clearance times are not significant as metro-bus hybrid evacuation.

In the aspect of contribution ratio, buses always play a key role in fulfilling the evacuation task, metros follow closely, and taxis assist further. This depends on the different evacuation capacities of bus, metro, and taxi. On the whole, bus, metro, and taxi make 46.6%, 34.9%, and 18.5% contributions of evacuation tasks, respectively.

A general finding is that the average walking distance $\bar{d}$ of multi-modal evacuation is the compromise between the walking distances of corresponding single-modal evacuations. For instance, the average walking distance $\bar{d} = 0.620$km of metro-taxi hybrid evacuation is between 0.855km and 0.327km, which are the average walking distances of single metro- and taxi-evacuations, respectively.

Here, we define the improvement of evacuation efficiency comparing multi- and single-modal transport evacuation is $\Psi = \frac{\tau_c - \tau_c'}{\tau_c} \times \frac{C_\delta'}{C_\delta}$, where τ_c and τ_c' are the clearance times under single- and multi-modal transport evacuations; C_δ and C_δ' are the global contribution ratios under single- and multi-modal evacuations, respectively. Compared with pure metro-, bus-, or taxi-single-modal evacuation, the evacuation efficiency of our metro-bus-taxi hybrid multi-modal transport evacuation can be improved by 49.7%, 46.5%, and 118.7%, respectively.

From Fig. 2a, we can further conclude that: Firstly, metro and bus pick up evacuees at set intervals and the accumulated number of evacuated evacuees are increasing linearly in general. This is because of the relatively equal intervals of departure time-table. Moreover, the curve of accumulated evacuees carried by bus fluctuated more frequently than by metro. Secondly, taxi have strong power of evacuating evacuees at the early stage, because sufficient unoccupied taxis can be utilized; however, this situation changes in the later stage and only a few taxis are available when they drive to event area. Thirdly, when multiple kinds of public transit vehicles evacuate evacuees together, the performance curves are more like single bus- or metro-evacuation, because they play a dominant role.

3) Simulated Multi-Modal Evacuation Without Global Optimization: People would choose multiple modal transport tools for their evacuations in reality, but their choices are not optimized systematically. To simulate real-world situation, we set that the longest walking distance of pedestrian is 1km, taxis are utilized as much as possible, and the proportions of evacuees choosing metros and buses are comparable. As shown in Table II and the purple line in Fig. 2a, the simulated multi-modal transport evacuation without adequate optimization can finish evacuation task within 106 min. When the proportions of evacuees choosing metros and buses we set in the simulated situation are close to the optimal values, the contribution ratios of different transport tools and average walking distances are similar with our optimal evacuation strategy. Even under such conservative settings, the evacuation efficiency of our optimal multi-modal transport evacuation is improved by about 20.8%, compared with non-optimized multi-modal evacuation in a simulated situation.

C. Influence of Pedestrians' Walking Distance on Evacuation Efficiency

The essence of our proposed multi-modal hybrid evacuation model is to schedule pedestrian evacuations to maximum the utilization of surrounding multiple kinds of public vehicles. Excellent spatiotemporal coordination of pedestrian evacuation and public vehicle evacuations play a decisive role to the success of a high evacuation efficiency. From the perspective of pedestrian evacuation, the walking distance is an important, but adjustable factor that affects the spatiotemporal coordination, which further influence global evacuation efficiency.

Longer walking distance of evacuees, on one hand, can undoubtedly improve the probability of accessing more available public vehicles; on the other hand, may reduce the utilization of nearby vehicles and increase the physical burden of evacuees, especially for elders, children, and disabled people; vice versa. Proper walking distance of evacuees is important for pedestrian-vehicle hybrid evacuation. The following experiments are conducted to investigate how different walking distance affects the multi-modal transport evacuation efficiency.

Let d_{max} be the longest walking distance, and d_{max} are about 2km in above experiments (Section IV-B). All interchange stations (i.e., bus stops, metro stations, and pick-up points of taxi) are unavailable in the following experiments if they are more than d_{max} away from the event sites.

From the experimental results in Fig. 2b, we can observe the influences of allowable longest walking distance on the evacuation efficiency of proposed multi-modal transport evacuation model. Firstly, the evacuation tasks cannot be fulfilled within the given time window when the allowable longest walking distances d_{max} are less than 0.5km. This is because the available public transport tools are not enough within such spatial range and time window. Secondly, the global evacuation efficiency is continually improved when d_{max} increases from 0.5 to 1.4km. This is because the increased available vehicles efficiently lessen the latency time of evacuation. Thirdly, when $d_{max} > 1.4$km, the evacuation results remain unchanged even if d_{max} increases. This is because the cooperation of pedestrian evacuation and public vehicle evacuations has attained the maximum efficiency at $d_{max} = 1.4$km. The accessibility to more available vehicles cannot compensate the time cost of walking more distances, resulting in no need of walking more than 1.4km. Fourthly, the approximately linear accumulated number of evacuees indicate the steady evacuation rates when multiple kinds of transport tools are considered.

Similar phenomena are also observed in Table III: Firstly, with the increasing d_{max}, the clearance time τ_c decreases to a steady state. Secondly, when d_{max} is less than 0.5km, the global contribution ratio C_δ is less than 100%, which indicates the evacuation tasks are not finished; vice versa. Thirdly, the contribution ratio C_3 of taxi persistently grows with the increasing d_{max}, because more available taxies are accessible and they are easy to be fully utilized. While, the contribution ratios C_1 and C_2 of metro and bus change with only a little fluctuation.

Thus, an appropriately allowable longest walking distance d_{max} is important to the collaboration of pedestrian and public vehicle evacuations, because too small d_{max} may results in unfinished tasks or low evacuation efficiencies; while too large d_{max} makes the payoff of accessing more vehicles cannot compensate the time cost of walking more distances. In this case, 1.4km is the optimal allowable longest walking distance and is also affordable for evacuees' physical burdens.

TABLE III
THE EVACUATION RESULTS WITH DIFFERENT LIMITED MAXIMUM WALKING DISTANCES

$\bar{d}_{max}$ (km)	τ_c (min)	C_δ	C_1	C_2	C_3	$\bar{d}$ (km)	$\mho$
0.1	148	0.388	0.357	0.031	0	0.012	0.172
0.2	148	0.835	0.357	0.478	0	0.105	0.356
0.3	148	0.920	0.357	0.508	0.055	0.224	0.394
0.4	148	0.920	0.357	0.508	0.055	0.224	0.394
0.5	142	1	0.439	0.450	0.111	0.352	0.426
0.6	118	1	0.355	0.554	0.091	0.484	0.426
0.7	110	1	0.325	0.522	0.153	0.472	0.426
0.8	106	1	0.314	0.539	0.147	0.432	0.426
0.9	98	1	0.286	0.528	0.186	0.421	0.426
1.0	94	1	0.324	0.494	0.182	0.481	0.426
1.1	88	1	0.343	0.476	0.181	0.481	0.426
1.2	86	1	0.332	0.490	0.178	0.474	0.426
1.3	86	1	0.332	0.490	0.178	0.474	0.426
1.4	84	1	0.347	0.469	0.184	0.490	0.426
1.5	84	1	0.349	0.466	0.185	0.494	0.426
1.6	84	1	0.349	0.466	0.185	0.494	0.426

TABLE IV
THE EVACUATION RESULTS WITH DIFFERENT PROPORTION OF CHOOSING VARIOUS TRANSPORT TOOLS

	τ_c (min)	C_δ	C_1	C_2	C_3	$\bar{d}$ (km)	$\mho$
Case0	144	1	0.705	0	0.295	0.620	0.754
Case1	110	1	0.496	0.285	0.219	0.533	0.426
Case2	106	1	0.470	0.317	0.213	0.522	0.426
Case3	98	1	0.431	0.365	0.204	0.508	0.426
Case4	92	1	0.394	0.410	0.196	0.501	0.426
Case5	84	1	0.349	0.466	0.185	0.494	0.426
Case6	122	1	0	0.724	0.276	0.381	0.727

Our proposed multi-modal transport hybrid evacuation model can automatically use the best walking distance to achieve the optimal evacuation efficiency as long as the presupposed d_{max} is longer than the best one.

D. Influence of Proportion of Choosing Different Transport Tools on Evacuation Efficiency

In reality, pedestrians would choose all bus, taxi, and metro for evacuation, but the proportions may not be optimal. This section is to test how different proportions of pedestrian choosing different transport tools influence the evacuation efficiency. The experiments are set as following: taxis are utilized by evacuees as much as possible based on the fact that taxis are easily not enough during actual evacuations for mass gathering events due to the priority and small total number of taxis; the proportions of pedestrian choosing bus is from 0 to 0.724 in Cases-1∼6, and the rest of pedestrian choose metro.

From the experimental results in Fig. 2c and Table IV, several general phenomena are observed: Cases-0, -5, and -6 are three boundary states. That is, Case-5 (i.e., our proposed multi-modal hybrid evacuation strategy) is the optimum state; while Cases-0 and -6 are two extreme states without using buses or metros, respectively. Starting from Case-0 where no bus is utilized, the global evacuation efficiency is gradually improved to the optimum efficiency when the proportion of pedestrians choosing bus increases from 0 to 0.466. If the proportion of pedestrians choosing bus is greater than the optimal value (i.e., 0.466), the global evacuation efficiency decreases conversely, as Case-6.

Moreover, when we limit the total proportion of pedestrians choosing specified transport tools, their effects work only in the later period, while the evacuation progresses in the early phase are highly similar with the optimal strategy. These phenomena are congenial with our common sense that we would fully utilize available vehicle resources as much as possible in the early phase.

From above, appropriate assignments of evacuees to different transport tools also play an important role to global evacuation efficiency and our hybrid evacuation model can plan the optimal assignments.

V. CONCLUSION AND FUTURE WORK

Evacuation for urban mass gathering events has important application significance. The achievements of this study, on one hand, fulfilled the gap of pedestrian-based and public transit system-based evacuations; on the other hand, achieved the spatiotemporal cooperation of evacuations using different kinds of public transit vehicles. Experimental results demonstrated that each kind of single-modal public transit vehicle has its own evacuation characteristics, but any of them cannot finish evacuation tasks solely. Moreover, the cooperation of multiple kinds of public transit vehicles can greatly improve the evacuation efficiency by 49.7%, 46.5%, 118.7%, and 20.8% compared with pure metro, bus, taxi single-modals transport evacuation, and simulated multi-modal transport evacuation without adequate optimization, respectively. More experiments considering different gathered population and carrying capacity are carried out, and all experimental results demonstrate the superiority of our proposed multi-modal transport hybrid macro-optimization evacuation model (Appendix-H and -I of the supplementary material).

In this study, we utilized multiple-source spatiotemporal data to mine the evacuation capacity of existing public transit system, optimized the pedestrian evacuation strategies and path planning to appeal to the operations of public transit system. To some extent, these research achievements overcome the space-time coordination of multi-modal transport tools, which can promote the developments of theory and methodology for urban safety response. In the future, we will further optimize both pedestrian evacuation strategies and public transit scheduling (such as, increasing the public transport supply) to achieve more efficient evacuation for mass gathering events.

Conflict of Interest: On behalf of all authors, the corresponding author states that there is no conflict of interests.

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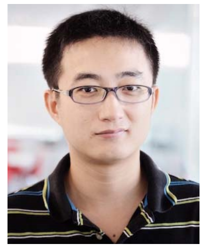
Jincheng Jiang received the Ph.D. degree in geographic information science from Beijing Normal University in 2016. He is currently an Associate Research Professor with the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen, Guangdong, China. He has published over 30 papers and hosted multiple scientific research projects, such as NSFC, the Natural Science Foundation of Guangdong Province, and the Shenzhen Special Science and Technology Project. His major research interests include emergency evacuation, spatiotemporal data analysis, mobile monitoring, sustainable development, and big data for disaster.

Wei Tu (Member, IEEE) received the B.S. and Ph.D. degrees from Wuhan University, Wuhan, China, in 2007 and 2013, respectively. He is currently an Associate Professor with the Department of Urban Informatics and the Guangdong Key Laboratory of Urban Informatics, Shenzhen University, Shenzhen, China. He has published more than 60 SCI-indexed articles. His research interests include spatiotemporal data modeling, spatiotemporal data analysis, and spatiotemporal data mining. He was a recipient of four scientific and technology awards.

Hui Kong received the Ph.D. degree from The Ohio State University in 2018. She worked as a Post-Doctoral Associate at the Massachusetts Institute of Technology, Cambridge, MA, USA, from 2018 to 2020. She was also an Assistant Professor at the Humphrey School of Public Affairs, University of Minnesota. She is currently an Associate Professor at the School of Architecture and Civil Engineering, Xiamen University. Being a broadly trained researcher in urban planning, geography, and transportation, she leverages GIS, spatial big data analytics, and statistical models to advance the efficiency and equity of shared mobility and multimodal urban transportation. Her work has been published on leading academic journals, including *Nature Sustainability*, *Transportation Research Part A: Policy and Practice*, *Transportation Research Part D: Transport and Environment*, and *Journal of Transport Geography*.



Wei Zeng (Member, IEEE) received the Ph.D. degree in computer science from Nanyang Technological University. He worked as a Senior Researcher at the Future Cities Laboratory, ETH Zurich, and an Associate Researcher at the Shenzhen Institute of Advanced Technology, Chinese Academy of Sciences. He is currently an Assistant Professor with The Hong Kong University of Science and Technology (Guangzhou). His recent research interests include visualization and visual analytics, AR/VR, and urban computing.

Rui Zhang received the Ph.D. degree in management science and engineering from the Huazhong University of Science and Technology (HUST) in 2011. He is currently the President of Shenzhen Beidou Applied Technology Research Institute Company Ltd., Shenzhen, Guangdong, China. He has published over ten papers, obtained ten invention patents, and hosts more than 20 scientific research projects. The projects he presided over have won many awards, such as the Third Prize of Science and Technology Award of China Intelligent Transportation Association in 2019. He is mainly engaged in research and development in the fields of big data, intelligent transportation, and smart city.

Milan Konecny is currently a Professor of cartography and geoinformatics at Masaryk University, Brno, Czech Republic. He was/is a Guest Professor of The Chinese University of Hong Kong; Henan University, Kaifeng; Shenzhen University, China; Vienna University, Austria; and Constantine the Philosopher University. From 2003 to 2007, he was the President of the International Cartographic Association (ICA). He founded and served as the Chairman of ICA Commission on cartography on early warning and crises management and from July 2019 continues as its Vice-Chair. He was an Acting President and the Vice-President of the International Society for Digital Earth. He is an Academician and the Vice-President of the International Eurasian Academy of Science.