Multimodal-Transport Collaborative Evacuation Strategies for Urban Serious Emergency Incidents Based on Multi-Sources Spatiotemporal Data

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Abstract

When serious emergency events happen in metropolitan cities where pedestrians and vehicles are in high-density, single modal-transport cannot meet the requirements of quick evacuations. Existing mixed modes of transportation lacks spatiotemporal collaborative ability, which cannot work together to accomplish evacuation tasks in a safe and efficient way. It is of great scientific significance and application value for emergency response to adopt multimodal-transport evacuations and improve their spatial-temporal collaboration ability. However, multimodal-transport evacuation strategies for urban serious emergency event are great challenge to be solved. The reasons lie in that: (1) large-scale urban emergency environment are extremely complicated involving many geographical elements (e.g., road, buildings, over-pass, square, hydrographic net, etc.); (2) Evacuated objects are dynamic and hard to be predicted. (3) the distributions of pedestrians and vehicles are unknown. To such issues, this paper reveals both collaborative and competitive mechanisms of multimodal-transport, and further makes global optimal evacuation strategies from the macro-optimization perspective. Considering detailed geographical environment, pedestrian, vehicle and urban rail transit, a multi-objective multi-dynamic-constraints optimization model for multimodal-transport collaborative emergency evacuation is constructed. Take crowd incidents in Shenzhen as example, empirical experiments with real-world data are conducted to evaluate the evacuation strategies and path planning. It is expected to obtain innovative research achievements on theory and method of urban emergency evacuation in serious emergency events. Moreover, this research results provide spatial-temporal decision support for urban emergency response, which is benefit to constructing smart and safe cities.

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1 Introduction

Serious emergency events mainly refer to major natural disasters, fire disaster, explosive outbreaks, production safety accident, terrorist attack, explosion events, and so on. Tens of thousands of people died in such disasters every year. These events cause serious damages to personal and property safety, and they are principal threat to urban security. The top priority task after serious emergency events is to evacuate the crowd from the sites of accident [3]. As an important core of response plan for emergency management, emergency evacuation for serious sudden events has become a hot topic in our society [9], and it is very benefit to construct safety cities.

Emergency evacuation for serious sudden events in bustling city has its own characteristics: (1) High population density. The density of population in city is very high and the aggregation effect works during evacuation process. For example, over 300 thousands people gathered in Shanghai's Bund area for the arrival of the new year and caused stampede event in 2014. (2) Pedestrian take occupation of vehicular road. As a result, regular traffic rules don't work anymore. (3) Wide spreading. As large-scale crowd-gathering, the traffic congestion spreads out and the evacuation distance generally reaches several kilometers. (3) Evacuated objects may change their modes of transportation. (4) The evacuation statuses are highly dynamical [7]. Under this scenario, if there is no scientific and reasonable unified guidance, the crowd must be mingled with the traffic vehicles and the evacuation efficiency is very low. Thus, single modal-transport cannot meet the requirements of quick evacuations under serious sudden events [11]. A new theory is in urgent need to efficiently and synergistically invoke various transportation tools [8]. So that, the pedestrian and vehicles can be scheduled in a scientific and reasonable way to ensure the high-efficiency, safe, ordered emergency evacuation system. Undoubtedly, multimodal-transport evacuation strategies for urban serious emergency event are very meaningful and urgent required, but also full of great challenges.

Existing multimodal-transport evacuations generally indicate the pedestrian-vehicle mixture evacuation [10] [1], [5], [4]. They focused on analyzing the behavior characteristics under mixed statuses, but lack of spatiotemporal collaborative capacity. In general, the challenges of developing the efficient multimodal-transport evacuations come from two aspects: (1) For dynamic distributed people and vehicles, all walk, road vehicle and rail transit are used to evacuate the pedestrian and traffic flows in a collaborative way; (2) Under time-geography environment, multimodal-transport evacuations are constrained by the limited road resource and dynamic conditions. Traffic control, road resource allocation and route planning should be considered to minimize obstructions, maximize evacuation efficiency, minimize traffic conflicts between vehicle and pedestrian and ensure safety. These two challenges become the development bottleneck of urban emergency evacuation. With spatiotemporal dynamic evacuation task and time geography-constrained environment, multimodal-transport collaborative evacuation strategies are a difficult issue to be resolved for emergency response in serious incidents.

This paper focuses on the multimodal-transport collaborative evacuation strategies considering walk, road vehicle and rail transit under dynamic distributions of people and vehicles and time geography constraints. The research achievements could improve the spatiotemporal collaborative capacity for various transportation tools, provide space-time decision supports for emergency response in serious sudden incidents.

2 Research framework

This paper aims at constructing an effective multimodal-transport collaborative evacuation optimization model under space-time evacuated objects and time geography-constrained environment for urban serious sudden incidents. This optimization model should satisfy two requirements: in global scale, the entire evacuation system must be operated in a high-efficiency and safe way under scientific guidance; in local scale, personalized escape path and transportation modes should be provided for individuals. For this goal, we propose a research framework in which Four main parts are contained:

- Modeling the emergency environment;
- Constructing multimodal-transport collaborative evacuation optimization model;
- Solving the model and separating evacuation strategies;
- Experimental testing and assessing. More detailed contents embed in each part and their association among them are shown Fig. 1.

Generally speaking, this paper utilizes multi-source spatiotemporal data to construct static and dynamic emergency, uses multi-commodity network flow model to build multi-objectives multi-constrained emergency evacuation optimization model considering multi transport modals. Moreover, our solution contains multiple strategies, such as routing planning [6], [2], road resources distribution, dynamic flow control and transportation tool conversion, etc. As considering relative comprehensive factors, this proposed model is expected to achieve satisfactory effects and this will be tested by empirical data.

3 Study area and data source

Our study area is an entertainment Center, which is located in Shenzhen, one of the biggest cities in China. Many large-scale public events, such as concerts, sports, exhibition, were held here. Large crowds gather, and the large traffic jam ultimately emerges and last a long time. Furthermore, complex geographical environment involves 2 metro stations, 7 bus stops, four main routes and lots of bypass, squares, bridges, and so on. Thus, this study is of representativeness in metropolis. Multi-source spatiotemporal data used in this paper mainly includes:

- Foundational geographic data. This dataset can accurately static 3D geographic model including buildings, roads, overpasses, underground passages, hydrographic net, vegetation-covered area, metro stations, and so on.
- Phone cellular signaling data. For the goal in this paper, this data is mainly used to estimate dynamic population distribution.
- GPS data of bus and taxi. With the real position information of bus, we can infer how many available buses at arbitrary time moment. Massive amounts of taxi's GPS are widely used to calculate traffic congestion status by many software. Besides of traffic congestion status, this paper attempt to further figure out dynamic traffic flows.
- Smart card records for buses and subways. Smart cards record the location and time of passengers to get on and off the bus or subway. From these, we can know the maximum passenger capacity and residual available capacity.

4 Methodology

With above known emergency evacuation environment, an effective multi-objective multi-dynamic-constraints optimization model for multimodal-transport collaborative emergency evacuation is constructed in this section. As the core of the entire framework, the objective functions and constraint conditions in this model are analyzed from macro-perspective.

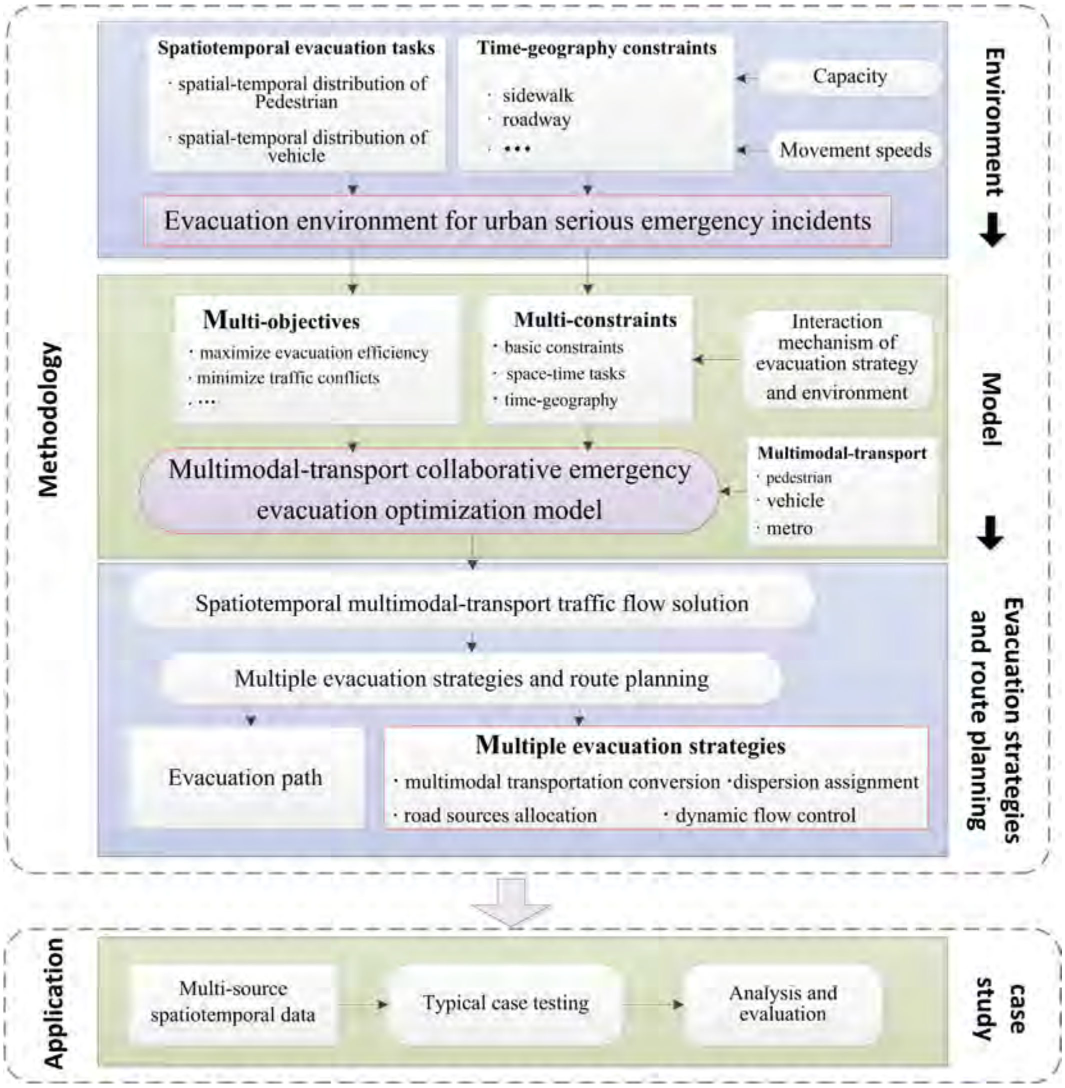

Figure 1 The framework to study multimodal-transport collaborative evacuation strategies

Objective functions. All evacuation efficiency, security, evacuation distance for various transportation tools and many other objectives should be optimized in an integrated way.

- As the basic requirements for emergency response, the evacuation efficiency is the primary goal.
- The mixture of pedestrian and vehicles would cause chaos. It is very necessary to separate pedestrian and vehicle flows and minimize vehicle-pedestrian conflicts.
- In order to make full use of the advantages of various transportation modes, the conversion among different transportation modes should be considered. So that, short-, moderate-, and long-distance evacuations are assumed respectively by walk, road transport and rail transit. In such way, a kind of spatial-layered evacuation phenomenon emerges.
- Besides, more other objectives should also be considered, and different objectives play various roles or even contradict each other.

Figure 2 The study area: an entertainment center in Shenzhen, China.

Constraint conditions. Numerous constraint conditions can be classified into three major categories:

- Basic constraints. Evacuation strategy and status (or environment) influence each other. Their interaction mechanisms can be described in mathematical forms, which is treated as a kind of constraint. These constraints include limited flow capacity of pedestrian, vehicle and metro, and the conservation of total population.
- Constraints from space-time evacuated tasks. At the scene of an accident, dynamic evacuation tasks are assigned to walk, car, bus and metro, etc. in real time, so that stranded population at arbitrary time and site is always less than a threshold; in transit, under the conservation of total population, conversion of various transportation modes is allowed to control traffic and pedestrian flows. This reflects the task-cooperation relations among multimodal transportations.
- Constraints from time-geography. The movement speeds of escapers are affected by surrounding environment, which is a kind of constraints. The capacity of a metro station is limited to receive people within a specific time interval. On the sidewalks and motorways, pedestrian and vehicle flows are not allowed to exceed their respective capacities. But, pedestrian can occupy motorways in such emergency scenario and this requires to reasonably allocate the road resources. Constraints from time-geography implies the resource competition relations among multimodal transportations.

Model Solution. Above multi-objective multi-dynamic-constraints optimization model simultaneously optimize numerous factors. As a result, lots of evacuation strategies are hided in the solution of aforementioned emergency evacuation optimization model. Two main steps are needed to be executed to obtain the finial evacuation strategies:

- Spatiotemporal multimodal-transport traffic flow solution

  Pedestrian and vehicle can respectively occupy different lanes in the same road, but not allowed to be mixed up in a same lane. Due to the limited capacity of road, the flows of

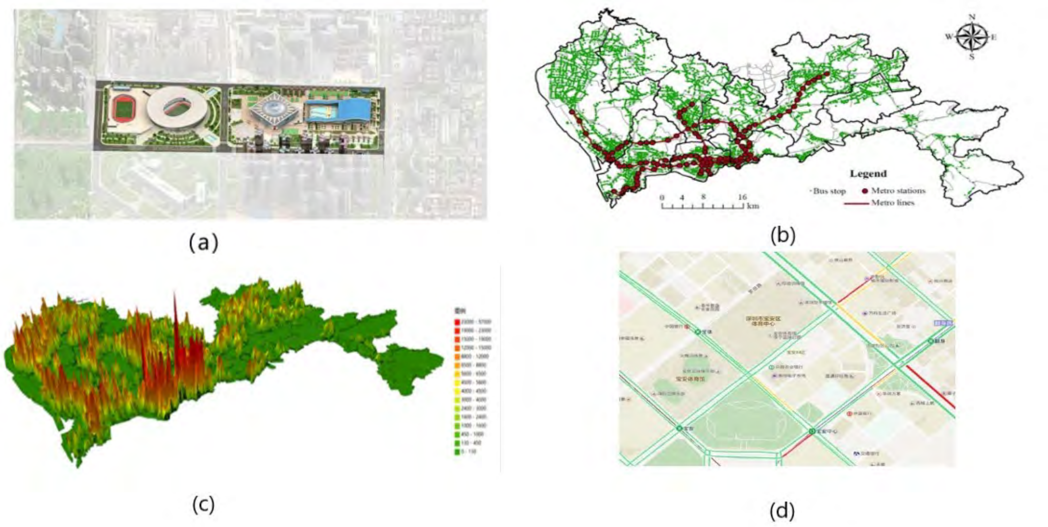

Figure 3 Emergency environment modeling from multi-source spatiotemporal data: (a) 3D emergency scenario model; (b) Spatial configuration of bus stops and the metro system; (c) population distribution; (d) dynamic traffic states.

pedestrian and vehicle are complementary:

$$f^p_{i,j}(t) \leq C^p_{i,j}(t) \times u_{i,j}(t) \tag{1}$$

$$f^v_{i,j}(t) \leq C^v_{i,j}(t) \times [1 - u_{i,j}(t)] \tag{2}$$

Where $f^p_{i,j}(t)$ and $f^v_{i,j}(t)$ are respectively dynamic pedestrian and vehicle flows; $C^p_{i,j}(t)$ and $C^v_{i,j}(t)$ are the road capacity for pedestrian and vehicle; $u_{i,j}(t)$ the percentages of lane occupied by pedestrian, which suggest road resource allocation. As for rail transit, it is an independent system, but share small number of nodes with sidewalks.

If pedestrian, vehicles and metros are respectively treated as three kinds of commodity flows with different behavior characteristics, then multi-commodity network flow model can be used to solve above multi-objective multi-dynamic-constraints optimization model. After these endeavors, the optimized spatiotemporal flow of pedestrian, vehicles and metros would be obtained.

- Multiple evacuation strategies and route planning In order to consider the interaction mechanism of evacuation strategy and evacuation environment, above model simultaneously optimize multiple strategies and their solutions are mixed together. These strategies mainly include road sources allocation, dynamic flow control and route planning for pedestrian and vehicles, orbital traffic scheduling, multimodal transportation conversion, dispersion assignment in intersection, and so on. In order to make evacuation strategies is more clear and available for managers to operate, it is necessary to extract them as shown in Fig. 4.

5 Conclusion

Multimodal-transport collaborative evacuation system for urban serious emergency incidents is a complex dynamic system: on one hand, the pedestrian and vehicles from large-scale public places, building, parking lots, etc. are dynamic. In order to reduce threats of sudden incidents, the pedestrian and vehicles in the site of incident should be evacuated in a quickest time; on other hand, emergency evacuation is carried out in special place and time. Restricted by the

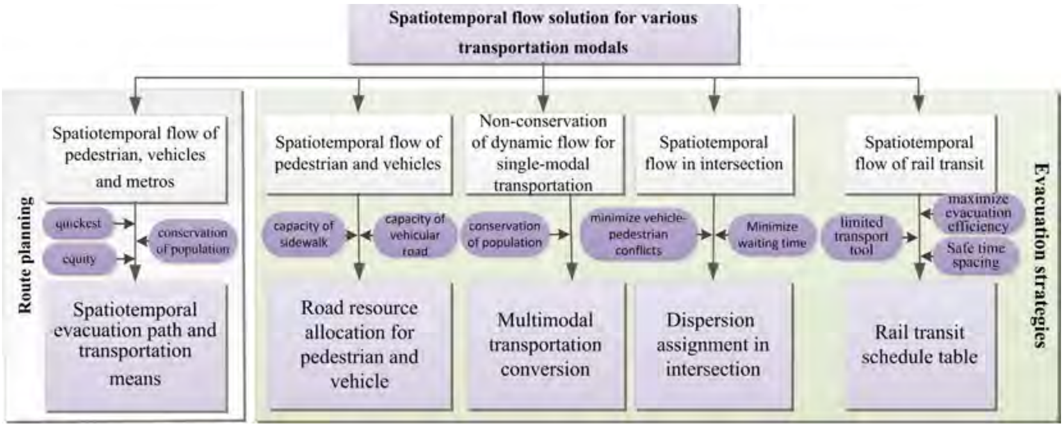

Figure 4 Multiple evacuation strategies and route planning.

limited road resources, superabundant pedestrian or vehicles could cause congestion and low efficiency of emergency evacuation. For management departments, it is necessary to figure out the optimized task allocation for multimodal transportation, road resources distribution and other evacuation strategies under both dynamic tasks and time geography constraints. The aim of improving the spatiotemporal cooperative capability of multimodal transportation is to minimize the safety risk of evacuated objects and maximize the evacuation efficiency. Thus, multimodal-transport collaborative evacuation mechanism considering dynamic tasks and time geography constraints is a key scientific issue. This paper comprehensively takes into account the external environmental impacts and interactions of internal multiple evacuation strategies to solve above issue.

For evacuated individuals, they all want to escape from dangerous places along shortest path and in a quickest way. If everyone does this, some areas could be heavily-crowded and the evacuation efficiency must be very low; while global optimal paths would sacrifice the interests of some individuals and increase their safety risks. It is necessary to find a balance point between global and individual optimum. This paper firstly figures out the global optimal spatiotemporal flows based on optimization theory, and then the individual escape path is obtained following the principle of risk-sharing.

Above two key scientific issues are respectively to ensure the efficiency, safety and equity. This paper aims at solving the challenge of spatiotemporal collaborative capacity for multimodal transportations. Its achievement can improve the theory and method of emergency response for urban serious incidents, and safety of smart city.

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