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A conflict–congestion model for pedestrian–vehicle mixed evacuation based on discrete particle swarm optimization algorithm

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ABSTRACT

A simulation model based on temporal–spatial conflict and congestion for pedestrian–vehicle mixed evacuation has been investigated. Assuming certain spatial behaviors of individuals during emergency evacuation, a discrete particle swarm optimization with neighborhood learning factor algorithm has been proposed to solve this problem. The proposed algorithm introduces a neighborhood learning factor to simulate the sub-group phenomenon among evacuees and to accelerate the evacuation process. The approach proposed here is compared with methods from the literatures, and simulation results indicate that the proposed algorithm achieves better evacuation efficiency while maintaining lower pedestrian–vehicle conflict levels.

1. Introduction

Pedestrian–vehicle mixed evacuation is an important and urgent issue which is confronted frequently by modern transportation, earth observation, geography, artificial intelligence, computer science, modern communications, and public health and security. In some types of large public areas, a huge number of pedestrians and vehicles are highly crowded together. Once catastrophic events such as hurricanes, fire, or terrorist attacks occur, pedestrians and vehicles crowd and congest together, which may lead to serious results for human beings. Recently, modeling and simulation of emergency evacuation have been attracting widespread attention from researchers [1,2].

However, the existing evacuation studies do not address the demands of mixed evacuation of pedestrians and vehicles. Currently, most evacuation models have focused on pedestrian evacuation from inside buildings [3] or vehicle evacuation over road networks [4]. Research on mixed evacuation of pedestrians and vehicles [5,6] is a more changeable and open issue in emergency management, particularly in the areas which integrate both building and roads.

On the other hand, only a few researches on evacuation modeling have been studied by using optimization algorithms. Existing optimization models involve optimizing only one objective for a single transportation mode or converting multiple objectives into a single-objective optimization problem for which the single optimal solution cannot offer decision support on multiple objectives.

The main difficulty in modeling and simulating pedestrian–vehicle mixed evacuation lies in the simulation of evacuation movements and the interaction behavior between pedestrians and vehicles. In this paper, pedestrian–vehicle temporal–spatial conflict and temporal–spatial congestion are defined. An evacuation model for mixed traffic flow based on temporal–spatial conflict and congestion is presented. In addition, a novel discrete particle swarm optimization with neighborhood learning factor (DPSONLF) algorithm is proposed to solve this mixed evacuation problem.

This paper is organized as follows. Section 2 discusses previous work related to simulation and modeling for evacuation. Section 3 presents a mixed evacuation model based on temporal–spatial conflict and temporal–spatial congestion. Section 4 introduces a DPSONLF algorithm based on discrete particle swarm optimization (DPSO) to simulate and optimize the evacuation process with mixed traffic flow. Section 5 analyzes and compares the simulation results using different optimization approaches. Finally, Section 6 draws conclusions and discusses directions for future research.

2. Related work

Current studies on mixed traffic flow usually focus on simulation [7,8]. Meng et al. [9] proposed a single-lane cellular automaton model to simulate mixed traffic with motorcycles. In the model, density-flow relations and the "lane-changing" behavior of motorcycles were investigated to find the relationship between the maximum flow

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and motorcycle density. Si et al. [5] presented link resistance functions based on travel demand for different roads in an urban mixed traffic network and analyzed the characteristics of different traffic modes including cars, buses, and bicycles. Xie et al. [6] proposed a two-dimensional car-following model to depict the features of mixed traffic flow consisting of motorized and non-motorized vehicles. Characteristics of mixed traffic flow were studied by investigating the interaction between left-turning non-motorized vehicle flow and straight-ahead motorized vehicle flow at a typical unsignalized intersection. However, the researchers modeled mixed traffic flow under normal conditions, which is somewhat inappropriate for emergency situations. As for evacuation modeling, some studies have been done for the problem inside buildings [10] or in road networks [11]. For example, Chen et al. [12] presented a force-driving cellular automaton model considering the social forces on cell movement, such as the desire of a pedestrian to exit, the repulsive interaction among or between pedestrians, and the effect of obstacles, to investigate the evacuation behaviors of pedestrians at a T-shaped intersection. The model studied the pedestrian evacuation problem from the microscopic point of view, but neglected attraction forces to simulate the conformity phenomenon. Guo et al. [13] investigated the route choice in pedestrian evacuation under conditions of both good and zero visibilities. They presented a microscopic evacuation model with discrete space representation to simulate the behavior of pedestrians. As for vehicle evacuation, Tanaka et al. [14] studied the mixing of vehicles on a two-lane highway in hurricane evacuation and proposed a deterministic model of two-lane traffic in which vehicles changed lanes using a deterministic rule. Bretschneider and Kimms [15] proposed a two-stage heuristic solution approach for a pattern-based mixed integer dynamic network flow model that restructured the traffic routing for the case of an evacuation. In their model, the time-expanded network and a relaxation-based heuristic were used to minimize the evacuation-time while prohibiting conflicts within intersections.

These models for either pedestrian or vehicle evacuation mainly focused on the microscopic evacuation behavior of pedestrians or vehicles. But the real evacuation scenarios usually involves the area integrated both building and roads around. Therefore, pedestrians inside a building and vehicles on the roads around need to be considered as evacuees simultaneously. And the interaction among and between pedestrians and vehicles during evacuation process should be analyzed. Recently, some researchers studied modeling and simulation of mixed evacuation problem. For example, Jin et al. [16] developed a mixed traffic evacuation model to study the influence of different transport modes. These simulations focused on the evacuation time for various combinations of people, bicycles, and motor vehicles. Zong et al. [17] studied the mixed evacuation problem and proposed model considering the factors such as congestion and the interaction between pedestrians and vehicles, but the model has not taken the potential conflict between pedestrians and vehicles into account, which is crucial to evacuation efficiency.

Currently, multi-objective optimization algorithms and swarm intelligence have been used to simulate and solve evacuation problems for making evacuation plans which satisfy more than one objective [18–20]. A number of optimization algorithms or techniques, including the ant colony optimization algorithm [21,22], the particle swarm optimization algorithm [23,24], game theory [25], agent theory [26,27], non-dominated sorting genetic algorithm [28], and genetic algorithm [29] in general, have been used to solve evacuation problems. For example, Izquierdo et al. [23] used particle swarm optimization to simulate and forecast evacuation time. The model took minimizing distance from an exit as the optimization objective. Zheng et al. [24] also presented a PSO-based heterogeneous evacuation model. In the model, the distance from a particle to the nearest exit was taken as the fitness function and the pedestrian's velocity was impacted by the local pedestrian's density. The model simulated the pedestrian's psychology of rapid evacuation and investigated the relationship between velocity and density, but the tendency of going with the crowd was not considered. Xie et al. [30] proposed a method to solve a lane-based evacuation network optimization problem. The objective of the approach was to minimize the number of crossing points at the given intersection and an integrated Lagrangian relaxation and tabu search solution method were developed. Most of these evacuation models considered one aspect as optimization objective. However, several factors need to be taken into account simultaneously, especially for such complex optimization problems, to make effective evacuation plans.

Stepanov and Smith [31] generated an evacuation plan with objectives including minimization of total clearance time, minimization of total distance traveled, and the avoidance of blocking. Saadatseresht et al. [28] used multi-objective evolutionary algorithms and a geographical information system for evacuation planning. In their model, maximizing the capacity of safe areas and minimizing distance were defined as two optimization objectives, and the NSGA-II algorithm was used to determine the distribution of evacuees into safe areas in a GIS environment. Tzeng et al. [32] constructed a multi-objective model for delivering commodities to demand points in an emergency situation using fuzzy multi-objective programming. Lim et al. [33] presented a capacity constrained network flow optimization approach for finding shortest evacuation paths with maximum evacuees. Dijkstra's algorithm was used to find the evacuation paths first and then a greedy algorithm for finding the maximum flow of each path. These evacuation models optimized more than one objective in evacuation process. But the interaction between evacuees and the congestion level at each time interval were not studied. And most of these multi-objective models converted several objectives into a single objective. Few studies have optimized the evacuation process considering multiple objectives simultaneously, especially both in temporal and spatial aspects.

Recently, Fang et al. [34] proposed and demonstrated a space–time use efficiency model on the basis of trajectories in the case of mixed vehicle and pedestrian flows in intersections. A two-tier hybrid multi-objective optimization algorithm was presented to plan vehicle and pedestrian turning movement directions, and three objectives: average evacuation time, the overall length traveled, and space–time use efficiency of network were optimized. But the space–time objectives of conflict and congestion caused by the interaction between pedestrians and vehicles were not considered.

From a review of evacuation models, two challenges are evident. The first challenge is modeling the evacuation process not only for a single traffic mode, but also for pedestrians and vehicles mixed together. The second challenge is solving the mixed evacuation problem using multi-objective optimization algorithms.

In this research, the evacuation problem with mixed traffic flow has been solved with the help of a new temporal–spatial evacuation model using a new discrete particle swarm optimization approach with a neighborhood learning factor algorithm. Different optimization methods available in the literatures are also evaluated and compared. The proposed approach may help the decision makers make temporal–spatial evacuation plans more rationally and develop feasible strategies.

3. Evacuation model based on temporal–spatial conflict and congestion

3.1. Mixed evacuation problem

Mixed pedestrian–vehicle evacuation as studied in this paper refers to the problem that in an emergency situation, people in public