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Simulation of spatial and temporal separation of pedestrian counter flow through bottleneck

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HIGHLIGHTS

- Model pedestrian counter flow through bottleneck.
- Propose two rules to formulate spatial and temporal separation of pedestrian flow.
- Reproduce four classes of self-organizing movement of pedestrians.

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ABSTRACT

We propose a revised social force model to simulate the pedestrian counter flow through a bottleneck. Spatial and temporal separation rules are involved in this model so as to reproduce these self-organizing movement patterns of pedestrians, including oscillatory flow and three classes of lane formations. Moreover, by scenario simulations, we show that, by reasonably adjusting the parameters in these separation rules, the pedestrian efficiency of passing the bottleneck can be improved. The study is helpful for designing and planning pedestrian facilities involving pedestrian counter flow through the bottleneck and for evaluating the pedestrian efficiency of passing a bottleneck.

1. Introduction

It is well-known that metro or light rail transportation, as a mode of public transit, can be tuned to reduce traffic jam. In the mode of transportation, one of critical parameters affecting the system performance and service quality is the waiting time of the train sitting at station, which is defined as the time elapsed between the door opening and the door closing. The waiting time represents a significant fraction of the total travel time along serviced transit line, and hence affects the travel time and system capacity. According to the user equilibrium theory [1], if the travel time of metro or light rail transportation enhances or the capacity of metro or light rail transportation reduces, more travelers will select other modes of transportation and the passenger volume of other modes of transportation will increase. As a result, the performance of the whole urban transportation system is affected and the urban traffic jam is likely to be increased.

The waiting time is devoted to the loading and unloading processes of a train, along with door opening and closing processes. Passenger alighting and boarding at stations are likely the most significant factors causing the variation of the waiting time. Effectively organizing and orderly conducting the process of passenger alighting and boarding can lead to significant savings in train loading and unloading times, which are two main components of the waiting time. Therefore, how to organize and conduct the process of passenger alighting and boarding is a problem deserving of study. The study of the passenger alighting and boarding behaviors would lay the groundwork for devising passenger alighting and boarding schemes and

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designing internal layouts in the metro station. This is also helpful for saving the travel time of metro or light rail transportation and for improving the system capacity, as a result, reducing traffic jam of the whole urban transportation system. The passenger alighting and boarding at stations is a movement of pedestrian counter flow through the bottleneck.

The counter flow through the bottleneck also occurs in the situations, where two groups of pedestrians in opposite directions pass through a door or exit of a building. As the number of pedestrians in all the two groups is larger and the density of pedestrians around the door is higher, fluctuating and uncontrollable patterns of motion among pedestrians, i.e., crowd turbulence, becomes dominant due to more conflictions and stronger physical interactions among pedestrians in different Q5 groups. This would result in a crowd stampede [2,3]. Thus, studying the counter flow is helpful for the organization and management of crowds and the design of doors in the situations to avert the stampede. In this paper, we will investigate the counter flow through the bottleneck utilizing the modeling and simulation method.

Of course, there are a number of existing studies of modeling and simulating pedestrian and crowd dynamics. However, these studies mainly involve the following three topics: Counter flow [4–9], bottleneck flow [10–14], and route choice [15–20]. Sometimes, pedestrian dynamics is associated with specific scenarios, for example, mixed flows [21,22], aircraft boarding [23,24], and space acquisition [25]. Existing studies of pedestrian counter flow through the bottleneck mainly focus on two self-organizing movement patterns of pedestrians. i.e., oscillatory flow and lane formation [26]. Self-organization means that these movement patterns are not externally planned, prescribed, or organized, but emerge through the nonlinear interactions of pedestrians.

Empirical observations have shown that, when two groups of pedestrians try to pass a narrow bottleneck into opposite directions, once a pedestrian has passed the bottleneck, other pedestrians in the same group tend to follow him or her. However, the pedestrian stream arising in this way is stopped by the pressure of the opposing group after some time. Subsequently, the bottleneck is captured by pedestrians in the counter group. This change of the process occurs several times. This class of self-organizing movement is called oscillatory flow. Moreover, some individuals in each group walk in a line or side by side, and form a lane. In this way, these individuals in the front or at the edge of the lane protect the pedestrians at the rear or on the inside, who are thus less affected by surrounding pedestrians in the other group. This class of self-organizing movement is called lane formation. Helbing and Molnár [27] and Helbing et al. [28,29] reproduced the oscillatory flow and lane formation using the social force model. Subsequently, Zhang et al. [30] and Dai et al. [31] also modeled the two classes of self-organization movement patterns respectively utilizing a cellular automata model and a microscopic model with continuous space representation.

In this paper, we focus on another problem of the counter flow through the bottleneck, i.e., how to organize the movement of the two groups of pedestrians so that they can efficiently pass the bottleneck in opposite directions. For this purpose, spatial and temporal separation rules of counter flow are considered to relieve the interaction between the two groups of pedestrians as soon as possible. In this case, we categorize the lane formations into three classes. In Section 2, we revised the social force model to simulate the pedestrian counter flow through the bottleneck. In Section 3, we show the revised model can reproduce not only the oscillatory flow and a class of lane formation, which have been reproduced by existing models, but also the other two classes of lane formations. Moreover, we illustrate the effect of the spatial and temporal separation rules on the pedestrian efficiency of passing the bottleneck in this section. Section 4 concludes the paper.

2. Scenario and model

2.1. Scenario description

Fig. 1 shows the alighting and boarding process of passengers on the platform near the door of a train in a metro station. The platform area near the door is divided into three regions. i.e., two waiting regions respectively located in the west and east sides of the platform area and an alighting region located in the middle of the platform area. In spatial dimension, boarding passengers stand in the two waiting regions and these passengers on the train get off through the alighting region. In temporal dimension, the rule of 'alighting first and boarding second' is implemented. In other words, these passengers in the two waiting regions begin to get on, after these passengers on the train have got off. In this case, the flow pattern can be regarded as a particular oscillatory flow and the direction of flow passing through the bottleneck undergoes only a change. Moreover, the alighting and boarding passengers respectively form a lane due to temporal separation. We refer to this class of lane formation as unidirectional lane formation.

Of course, to get on the train as quick as possible, some boarding passengers probably do not comply with the rule and they begin to move towards the door as there are still alighting passengers. Alighting and boarding passengers simultaneously pass the bottleneck. In this case, oscillatory flow and lane formation can be observed. Moreover, there exists competition or cooperation movement mode. For competition mode, the two groups of passengers compete for passing through the bottleneck and they become mixed together. As a result, these lanes also become mixed together. We refer to this class of lane formation as mixed lane formation. For cooperation mode, alighting and boarding passengers are separated. Alighting passengers tend to pass through the middle of the bottleneck and boarding passengers tend to pass near two sides of the bottleneck. In this way, the two groups of passengers interfere less with each other. We refer to this class of lane formation as separate lane formation.

In a word, we divide the lane formations into three classes, i.e., unidirectional, mixed, and separate ones. Helbing and Molnár [27], Helbing et al. [28,29], Zhang et al. [30], and Dai et al. [31] have reproduced the mixed lane formation by