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Lane formation in pedestrian counterflows driven by a potential field considering following and avoidance behaviours

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HIGHLIGHTS

- A potential field considering the velocity distribution and density distribution is proposed.
- The proposed potential field CA model can be used as an improved floor field model.
- Avoidance behaviour is more relevant to lane formation than following behaviour.

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ABSTRACT

Lane formation in pedestrian counterflows is an interesting self-organization phenomenon. It is believed to be caused by the following or avoidance behaviours of pedestrians. In this paper, a potential field CA model that considers the velocity and density distributions of a crowd and their subjective consciousness is proposed to study the effects of the two behaviours on lane formation in the case of a pedestrian counterflow in a corridor with a periodic boundary. An indexing system is introduced to distinguish the three different patterns observed in the counterflow, and a smoothness index is introduced to measure the smoothness of the counterflow. It is found that avoidance behaviour is more relevant to lane formation than following behaviour. Some differences between the two behaviours are also presented.

1. Introduction

Self-organization in pedestrian counterflows (i.e., two groups of people moving in opposite directions) has always captured the interests of scholars. In a counterflow, the motion of the pedestrians tends to self-organize in such a way that dynamically varying lanes are formed where people move in the same direction. This effect is termed lane formation, which is a type of spontaneous symmetry breaking. In this way, strong interactions with oncoming pedestrians are reduced, and a higher walking speed is possible. However, the mechanism that leads to lane formation and its associated factors are not fully understood. Studying lane formation is conducive to describe the evolution of crowd behaviour and significant to the design of safe evacuation routes.

Many models have shown different ways to reproduce the lane formation phenomenon in pedestrian counterflows; the lattice-gas model is the most widely used one of these. In general, there are two approaches that segregate pedestrians:

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left-hand/right-hand movement [1–4] and considering the surrounding environment [5–8]. The former assumes that people prefer to walk on the left or right side of the road; thus, this model generally simulates two-lane formation. Considering the surrounding environment can be divided into two types: following the persons ahead that are moving in the same direction [5–7] and avoiding the persons ahead that are moving in the opposite direction [5,8]. The effect of the latter is thought to be weaker than that of the former [5]. In the cellular automaton (CA) model, following and avoidance behaviours are also used to explain pattern formation in pedestrian counterflows. In the floor field (FF) model, following behaviour can be simulated with the dynamic floor field (DFF) [9], and avoidance behaviour can be simulated with the anticipation floor field (AFF) [10,11]. By introducing the swapping and politeness factors into the FF model that contains DFF and AFF, the results of simulation coincided well with experimental data [12]. It is found that counterflows can form lanes more easily due to AFF than DFF, which is not compatible with the view of Ref. [5]. DFF seems to mimic the pheromone traces left by ants, which are weak interactions, while AFF is based on classification of pedestrians that are moving in the opposite direction. The CA model with a cost potential field [13] can simulate avoidance behaviour; however, the model ignores the influence of crowd velocity on individuals due to the limitation of cell size. With the social force model, which is used widely to study pedestrian dynamics, lane formation is described as the related decrease in the frequency of necessary deceleration and avoidance manoeuvres [14]. The process that pedestrians in a counterflow segregate into distinct lanes is thought to be a symmetry breaking via noise induction, which brings the system from a symmetric but disorderly state into one or more definite states [14–16]. The shear stress in the crowd is also considered to be a critical factor [17]; however, it is not necessary for lane formation if the crowd density is low. In this case, lanes could also form if pedestrians follow or avoid others based on their own initiative. As mentioned above, following and avoidance behaviours are considered to be important factors.

Conversely, experiments with pedestrian counterflow could help make simulation models more accurate. Lam et al. [18,19] investigated the pedestrian counterflow effects and the relationships between walking speed and pedestrian flow under various flow conditions at signalized crosswalks and at indoor walkways in Hong Kong. Isobe et al. [6] compared the relationships between the arrival time and density of pedestrians in an experiment and in a lattice-gas model considering following behaviour and found that jamming transition did not occur in the experiment because of the finite size effect. Kretz et al. [20] studied the relationship of passing times, walking speed and fluxes to group size of counterflows in a corridor. In the experiment, lane formation was present, and it was found that the participants would use space more efficiently to compensate for the existence of a counterflow; therefore, the intellectual power of pedestrians should be considered in the simulation models. Moussaid et al. [21] found that structural instabilities in counterflows were significantly associated with the speed variability among individuals, which had been found in previous modelling work. In this experiment, lanes formed and evolved into jams when people walking faster overtook others in front of them. This illustrates that the subjective consciousness of pedestrians plays an important role. Guo et al. [22] found that the velocity of pedestrians was negatively correlated with not only the densities of the opposite-direction and the identical-direction pedestrians around them but also the densities of the same-direction pedestrians ahead of them. This work indicated that the so-called look-ahead behaviour, which refers to how pedestrians assess the traffic conditions ahead and accordingly adjust their velocities, indeed existed among the pedestrians. Zhang et al. [23] studied the order of counterflows and its influence on the fundamental process. In their experiment, no significant differences among density-flow relationships were found in the observed density range for various forms of ordering, and jamming transitions occurred when ordering not pronounced. Combining the above experimental results, it is also important to consider the subjectivity of pedestrians as well as their speed and density.

This paper establishes a potential field to estimate the travel cost of pedestrians, which considers the velocity and density distributions of the crowd. Pedestrians tend to move in the negative gradient direction of potential and thus exhibit following and avoidance behaviours. The effects of these two behaviours on lane formation are studied in the case of a pedestrian counterflow in a corridor with a periodic boundary; the smoothness of pedestrian movement is also discussed.

2. Potential field CA model

The potential discussed in this paper is defined as the minimum cost for traveling from one position to a destination and is directly related to the continuum model of pedestrian flow [24]. If $\tau(x, y)$ describes the travel cost distribution for a pedestrian at position (x, y), and the travel cost required is nonnegative, then the potential $\phi(x, y)$, which represents the cost of traveling along the path L: $x = x(s), y = y(s)$, with $\mathrm{d}s = \sqrt{\mathrm{d}x^2 + \mathrm{d}y^2}$, is associated with the cost distribution $\tau(x, y)$ such that

$$\begin{aligned}\phi(x, y) &= \int_L \tau(x, y)\,\mathrm{d}s \\ &= \int_{(x,y)}^{(x_0,y_0)} \left(\tau(x, y)\, x'(s)\,\mathrm{d}x + \tau(x, y)\, y'(s)\,\mathrm{d}y\right), \qquad (1)\end{aligned}$$

where the unit vector $\left(x'(s), y'(s)\right)$ points to the integral direction. To ensure a one-valued function $\phi(x, y)$, it is necessary to assume that the integral is path independent

$$\phi_x(x, y) = -\tau(x, y)\, x'(s), \qquad \phi_y(x, y) = -\tau(x, y)\, y'(s). \qquad (2)$$