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Spatial fluctuations of pedestrian velocities in bidirectional streams: Exploring the effects of self-organization

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HIGHLIGHTS

- Measuring pedestrian's velocity distribution in bi-directional streams.
- Measuring pedestrians' velocity profile in bi-directional streams.
- Comparison of stable separated lanes versus dynamic multi lanes.
- Observing the significance of the self-organization phenomena.

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ABSTRACT

Individual pedestrian velocities vary over time and space depending on the crowd size, location of individuals' within the crowd, and formation of self-organized lanes. We use empirical data to explore the spatial fluctuations of pedestrian velocities in bidirectional streams. We find that, unlike ordinary fluids, the velocity profile in bidirectional pedestrian streams does not necessarily follow a hyperbolic form. Rather, the shape of the velocity profile is highly dependent on the formation of self-organized lanes. We also show that the spatial fluctuations of pedestrian velocities along and transverse to the flow direction are widely distributed and can be modeled by a sum of Gaussian distributions. Results suggest that the effect of self-organization phenomenon is strong enough that for the same crowd size, the velocity distribution does not significantly change when pedestrians are highly mixed compared to when separate lanes are formed.

1. Introduction

Crossing an intersection on a busy crosswalk, pacing in a narrow corridor in a train station, and walking in a shopping mall are all familiar examples of bidirectional and multidirectional pedestrian streams. Such flows, when having sufficiently high density, exhibit dynamic self-organization that maintains the stability of the stream in both directions despite the apparently random movements. Various models have been developed in the past two decades to simulate and reproduce dynamics of pedestrian crowds. Fluid based models [1–3], cellular automata based models [4,5], social force model [6], continuum macroscopic models [7–11], agent-based models [12–14], and more recently area/network-wide models [15,16] are among the most commonly known ones.

Extending a study by Henderson [1], Helbing [2] developed a fluid based pedestrian model that is based on pedestrian interactions and intentions using the concept of viscosity. Helbing [2] suggested that the velocity profile in unidirectional

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pedestrian flows follow a hyperbolic form with lower values on the boundaries and higher values in the middle. A recent study by Saberi and Mahmassani [16] suggested that the velocity profile in bidirectional pedestrian streams is also hyperbolic but with higher values on the boundaries and lower values in the middle, in opposite of the velocity profile of ordinary fluids. In this paper, we further explore the viscosity concept in pedestrian flows using a larger empirical dataset. We show that the velocity profile in bidirectional streams, unlike findings in previous studies, do not always follow a specific form; rather, it is mostly dependent on the formation and configuration of the self-organized pedestrian lanes.

Despite the growing body of literature on pedestrian crowds in bidirectional and multi-directional flows [8,13,17–27], our understanding of dynamics of such streams is still limited. Several of the previous studies proposed theoretical and simulation-based models with limited attention to calibration and validation. Also, the previous empirical studies were mostly focused on the shape of the fundamental diagram and headway distribution of pedestrian flows as key measurements. The observed variations in the shape of the fundamental diagram in bidirectional versus unidirectional streams in previous studies have not been thoroughly investigated to understand why and how such variations exist. The main objective of this paper is to use empirical data to explore the spatial fluctuations of pedestrian velocities in bidirectional streams to further understand the effects of self-organization on some of the observed collective patterns in pedestrian crowds. This study builds upon the previous studies and extends the analysis of bidirectional pedestrian streams to model such fluctuations using statistical empirical distributions. Results of this study can be used to calibrate and validate existing pedestrian models. Any model of bidirectional pedestrian streams should be able to reproduce similar patterns to the empirically observed ones. Further research is still required to develop a calibration and validation framework using velocity distributions and other measures.

The remainder of this paper is organized as follows. In the next section, we provide a brief background on previous theoretical, simulation-based, and empirical studies on bidirectional and multidirectional pedestrian streams. Section 3 provides a description of the data and methodology used in the study. In Section 4, velocity profile in bidirectional streams are discussed compared to ordinary fluids. Section 5 presents a visual qualitative methodology to identify stable self-organized lanes and its effect on velocity variations. In Section 6, spatial fluctuation of pedestrian velocities are explored and modeled. The last section concludes the paper and suggests directions for future research.

2. Background

The literature on bidirectional pedestrian flows is not vast and includes a few theoretical, simulated-based, and empirical studies with limited effort made for calibration and validation of the models.

2.1. Theoretical and simulation-based studies

A study by Al-Gadhi and Mahmassani [7] provided a numerical solution to a finite-difference form of a first-order bidirectional continuum model of crowd flow using a calibrated equilibrium bidirectional speed–density relation based on real-world observations [8]. Blue and Adler [17,18] developed a microsimulation model for a bidirectional and four-directional pedestrian walkways. They mainly used the relationships between speed, density, and flow to characterize different bidirectional streams. Hoogendoorn and Bovy [9] proposed a gas-kinetic based model and presented a comparison between speed–density relationship in unidirectional and bidirectional flows. Later in another study, Hoogendoorn and Bovy [19] presented a model based on differential games in which pedestrians try to minimize their walking cost.

Tian et al. [25] extended a hydrodynamic model of traffic to bidirectional pedestrian flows. In another study, Xue et al. [26] explored jamming transitions and density waves in bidirectional streams using a hydrodynamic based model considering pedestrian path change. Wong et al. [27] developed a model of bidirectional streams with oblique intersecting angle based on Drake's model of traffic flow. More recently, Moussaid et al. [28,29] proposed a cognitive based model to predict individuals' trajectories and collective patterns in pedestrian crowds for bidirectional streams. Also, a theoretical study by Hoogendoorn et al. [30] presented a continuum modeling framework that captures pedestrian path choice behavior. For a more comprehensive background, refer to Refs. [31–33].

2.2. Empirical studies

Lam et al. [20] empirically investigated the speed–flow relationship of a bidirectional flow at a signalized crosswalk. Helbing et al. [21] studied the effect of self-organization on headway distributions in unidirectional and bidirectional streams before and after a bottleneck. Using empirical data from a set of controlled experiments, they found that the average time gap between pedestrians in bidirectional flows is smaller compared to unidirectional flows. Hoogendoorn and Daamen [22,23] studied lane formation and crossing strip formation in bidirectional streams using a clustering method. They observed a relationship between the average number of clusters and density and applied a composite headway model to pedestrian flows at bottlenecks. Lee and Lam [24] studied the variation of speeds in unidirectional versus bidirectional stairways, mainly looking at the relationship between average speed, standard deviation of speed, and average flow.

More recently, Zhang et al. [34] and Zhang and Seyfried [35] used the Voronoi method to study empirical characteristics of bidirectional pedestrian streams versus unidirectional. They observed that the maximum flow in the fundamental diagram of a bidirectional stream is significantly smaller than the maximum flow of a unidirectional stream. However, their studies were