This is an electronic reprint of the original article.
This reprint may differ from the original in pagination and typographic detail.

Zhang, Dawei; Zhu, Haitao; Hostikka, Simo; Qiu, Shi

Pedestrian dynamics in a heterogeneous bidirectional flow : Overtaking behaviour and lane formation

Published in:
Physica A: Statistical Mechanics and its Applications

DOI:
[10.1016/j.physa.2019.03.032](https://doi.org/10.1016/j.physa.2019.03.032)

Published: 01/07/2019

Document Version
Peer reviewed version

Published under the following license:
CC BY-NC-ND

Please cite the original version:
Zhang, D., Zhu, H., Hostikka, S., & Qiu, S. (2019). Pedestrian dynamics in a heterogeneous bidirectional flow : Overtaking behaviour and lane formation. *Physica A: Statistical Mechanics and its Applications*, 525, 72-84.
<https://doi.org/10.1016/j.physa.2019.03.032>

Accepted Manuscript

Pedestrian dynamics in a heterogeneous bidirectional flow: Overtaking behaviour and lane formation

Dawei Zhang, Haitao Zhu, Simo Hostikka, Shi Qiu

PII: S0378-4371(19)30259-6
DOI: <https://doi.org/10.1016/j.physa.2019.03.032>
Reference: PHYSA 20667

To appear in: *Physica A*

Received date : 1 September 2018

Revised date : 30 January 2019

Please cite this article as: D. Zhang, H. Zhu, S. Hostikka et al., Pedestrian dynamics in a heterogeneous bidirectional flow: Overtaking behaviour and lane formation, *Physica A* (2019), <https://doi.org/10.1016/j.physa.2019.03.032>

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

- A model was proposed to investigate the pedestrian lane formation and overtaking behavior
- The proposed model was validated by comparing with the pedestrian flow patterns recorded
- The fundamental diagram of heterogeneous pedestrian counter-flow was studied
- The effect of the right-hand traffic norm on the lane formation was analyzed
- The effect of the lane formation on overtaking behavior was also investigated

Pedestrian Dynamics in a Heterogeneous Bidirectional Flow: Overtaking Behaviour and Lane Formation

Dawei Zhang^a, Haitao Zhu^{b,*}, Simo Hostikka^c, Shi Cao^d

^aCollege of Mechanical and Electrical Engineering, Harbin Engineering University, 150001 Harbin, China

^bCollege of Shipbuilding Engineering, Harbin Engineering University, 150001 Harbin, China

^cDepartment of Civil Engineering, School of Engineering, Aalto University, 02150 Espoo, Finland

^dNo.703 Research Institute of China Shipbuilding Industry Corporation, 150001, China

Abstract

We propose an optimization-based counterflow model to simultaneously investigate the pedestrian lane formation and overtaking behaviour in a heterogeneous bidirectional pedestrian flow. A comparison of pedestrian flow patterns in bidirectional flows with overtaking behaviour between the proposed model and a counterflow-based active decision model is performed with real collected data. Furthermore, the fundamental diagram of heterogeneous pedestrian counterflows with different corridor widths is compared with the experimental data. The effects of personal preferences regarding evading behaviour, going straight ahead and the right-hand traffic norm on lane formation are also studied for different corridor geometries with various pedestrian densities. The numerical results show that both overtaking behaviour in sparse bidirectional crowds and personal preference for the right-hand traffic norm in a wide corridor may reduce the specific flow of a pedestrian counterflow. Simultaneously, a strong personal preference for the right-hand traffic norm can determine lane formation in a counterflow scenario regardless of differences in corridor widths, pedestrian densities or other personal preferences. Additionally, lane formation may enhance not only the traffic efficiency of the whole counterflow but also the mobility of fast pedestrians in a heterogeneous bidirectional pedestrian flow.

Keywords: Counterflow model, lane formation, overtaking behaviour, right-hand traffic norm

1. INTRODUCTION

To identify evacuation strategies for pedestrian facilities and to serve as a reference for facility design, numerous models of pedestrian dynamics have been proposed to investigate the mechanisms that drive individual pedestrian behavior and the formation of collective patterns.

Overtaking behavior is widely encountered in reality because pedestrians commonly walk at different velocities. Pedestrians with a higher walking velocity are accustomed to overtaking others to maintain their own mobility [1]. To decide whether to evade on the left-hand side or the right-hand side, a side preference [2] is required, which can be determined by a ‘social norm’ [3] or as a result of an effective force applied by the surrounding pedestrians and boundaries [1].

*Corresponding author

Email address: zhuhaitao@hrbeu.edu.cn (Haitao Zhu)

10 Additionally, the variation in walking speed has been further extended in a cellular automata
model [4] to account for the overtaking behavior observed in crowds of pedestrians. In a more
general approach, i.e., the cognitive heuristics model [5], each pedestrian chooses the direction
that provides the most direct path to the target. Although the studies discussed above were con-
ducted to simulate overtaking behaviour, no attention was paid to investigating the overtaking
15 mechanism in a bidirectional pedestrian flow. Real-world observations show that pedestrians
within a uniform pedestrian lane experience spatial separation, aggregation and re-separation
during their interactions with the occupants of the counterflow in a heterogeneous bidirectional
pedestrian flow. This means that overtaking behaviour commonly occurs before and after en-
gagement with counterflow traffic in heterogeneous crowds.

20 Spontaneous lane formation by pedestrians is an interesting phenomenon in bidirectional
flows whereby pedestrians share the available space by forming lanes of uniform walking direc-
tions [6, 7, 8, 9, 10, 11]. The apparent ‘highways of pedestrians’ that form in such counterflows
constitute a decentralized collective organization that enhances traffic efficiency by reducing the
need for avoidance maneuvers among individuals [12]. Various numerical simulations and empiri-
cal studies [13, 14, 15, 16, 17, 18] have been conducted to analyze the related self-organization
25 phenomena and their synchronization [19], such as the formation of lanes [20] and the jam-
ming transition at sufficiently high densities [21], while considering emotion propagation [22],
psychological tension [23], subconscious behavior [24], and following behavior [25], among
other factors. The occurrence of lane formation does not require a preference for moving to
one side. It also occurs in situations without a left or right preference. However, cultural dif-
ferences with regard to the preferred side have been observed. Although this preference is not
essential for the phenomenon itself, it has an influence on the kinds of lanes that form and their
order [26]. Generally, simulations using approaches that consider a left-hand/right-hand prefer-
ence [27, 28, 29, 30, 31, 32] tend to result in two-lane formation. However, the effect of a side
30 preference on lane formation in corridors with different widths and pedestrian densities is still not
well understood. For instance, it is unknown how the personal side preference impacts the fun-
damental diagram in corridors with different widths or how it results in different lane formation
behaviours in a counterflow scenario. Furthermore, the phase changes observed in actual pedes-
trian lanes before and after their interaction with a counterflow, particularly the phase changes in
40 lane formation with overtaking behaviour, have attracted no attention.

To simultaneously investigate the overtaking behavior and pedestrian lane formation in a het-
erogeneous pedestrian counterflow as well as the effect of the right-hand traffic norm on pedes-
trian traffic under different conditions, we propose an optimization-based counterflow model to
simulate the movement of pedestrian crowds in a heterogeneous bidirectional flow. In this work,
45 we first consider a corridor in a real-world situation with a bidirectional pedestrian flow. The
performance of the proposed model is compared with the pedestrian flow patterns recorded by
a camera in a real situation and with the simulation results obtained using the *FDS + Evac*
model [33]. Then, the fundamental diagram of heterogeneous pedestrian counterflows is investi-
gated in comparison with the experimental data. The results show that the proposed counterflow
50 model can simultaneously reproduce the lane formation phenomenon and overtaking behaviour
observed in reality. It is found that a strong personal preference for the right-hand traffic norm
will always lead to the formation of two lanes in a heterogeneous pedestrian counterflow sce-
nario, regardless of different corridor widths, pedestrian densities and other behavioural pref-
erences. Moreover, evading behaviour may result in more lanes than straight-ahead movement
55 does, up to the lane capacity of the corridor, under the condition of a weak personal preference for
the right-hand traffic norm in the crowd. Additionally, with a moderate proportion of opposing

pedestrians, lane formation can not only enhance the traffic efficiency of the bidirectional flow but also improve the mobility of fast pedestrians by providing more opportunities to reallocate the walking space shared by occupants in the subsequent unidirectional pedestrian flow.

The rest of the paper is organized as follows: In Section 2, the force-based movement model is first briefly reviewed, and then the optimization-based counterflow model is introduced in detail. Section 3 presents the model validation, simulation results and analysis. Conclusions are given in Section 4.

2. MODEL

2.1. Movement model

The counterflow model proposed in this work is a modification of the counterflow-based active decision model that has been implemented in the *FDS + Evac* platform [34]. For convenience, the proposed model is referred to as the *MEvac* model. The body of each pedestrian agent is represented by an elliptical cross-sectional shape, and the pedestrian agents experience physical contact and social and motive forces as well as the corresponding moments. As in the original *FDS + Evac* model, the extended version of the initial social force model [35] used in *FDS + Evac* [34] is adopted to describe the movement of pedestrian agents. In this paper, henceforth, this modified social force model is referred to as the *MSF* model. The movement of each pedestrian agent evolves depending on the equation of motion:

$$m_i \frac{d^2 \vec{x}_i(t)}{dt^2} = \vec{f}_i^m + \sum_{j \neq i} \vec{f}_{ij} + \sum_w \vec{f}_{iw} + \vec{\xi}_i(t), \quad (1)$$

where $\vec{x}_i(t)$ is the position of pedestrian i . The velocity of pedestrian i at time t is given by $\vec{v}_i(t) = d\vec{x}_i(t)/dt$. m_i is the mass of pedestrian i . Each pedestrian's internal motivation to walk toward his target at his desired walking speed $v_i^0 = |\vec{v}_i^0|$ is reflected by the motive force $\vec{f}_i^m$:

$$\vec{f}_i^m = \frac{m_i}{\tau_i} (\vec{v}_i^0 - \vec{v}_i). \quad (2)$$

The relaxation time parameter τ_i determines the strength of the motive force. The repulsive forces $\vec{f}_{ij}$ and $\vec{f}_{iw}$ in Eq. (1) describe the effects of interactions with other pedestrians and obstacles, respectively. $\vec{\xi}_i(t)$ is a small random fluctuation force. The elliptical shape of each agent's body is approximated by three cross-sectional circles, and each pedestrian has his own rotational equation of motion. Thus, the agents can change their body angles in response to the repulsive forces in Eq. (1). For simplicity, these equations are not given in this paper. More details regarding the interaction forces and the corresponding moments can be found in Refs. [34, 36].

2.2. Counterflow model: MEvac model

The original *FDS + Evac* model is designed to enable realistic simulations of dense crowds moving in different directions. A short-range area is incorporated for the detection of each agent's surroundings, and each pedestrian agent reacts only to other agents that are within this short range in front of him. The area in front of agent i is divided into three overlapping sectors, S_1 , S_2 , and S_3 (see Fig. 1), each covering a 2θ -wide sector around the desired walking direction. The set of corresponding vectorial directions is $\{\vec{u}_i^{-\theta}, \vec{u}_i^0, \vec{u}_i^{+\theta}\}$, pointing to the left side, straight ahead, and to the right side, respectively. Straight ahead always corresponds to the direction of the preferred

Figure 1: Definition of the visual area in front of the current pedestrian i . The pedestrian evaluates the utility values of all three sectors and chooses the optimal walking direction.

90 velocity $\vec{v}_i^0$ in the *MSF* model. Each pedestrian agent can receive information concerning his neighbouring pedestrian agents within the short-range area ahead and react by choosing one of three options: dodging to the left, moving straight on, or dodging to the right. The basic idea of the *FDS + Evac* counterflow model is to choose the sector with the lowest counterflow. This is formulated as an optimization problem:

$$\vec{u}_i^* = \underset{\vec{u}_i^0}{\operatorname{argmax}}(P). \quad (3)$$

If the sector directly in front of agent i is not empty, this agent selects the movement direction $\vec{u}_i^*$ with the highest score $P = P_I + P_{rl} + P_{sa} + P_{nc}$ from among the directions corresponding to the three sectors, $\{\vec{u}_i^{-\theta}, \vec{u}_i^0, \vec{u}_i^{+\theta}\}$, 10 times per second on average. P_I is the score of sector I , where $I = \{1, 2, 3\}$, and reflects the utility or space availability of that sector based on its occupants:

$$P_I = P_{df} - P_{cf}, \quad (4)$$

where P_{df} is a score that depends on the location and velocity of each occupant moving in the same direction,

$$P_{df} = \sum_{j \in S_{I, \uparrow}} \frac{d_{df} \langle \vec{v}_j - \vec{v}_i, \vec{u}_i^0 \rangle + c_{df}}{\max(0.2, D_{ij})}, \quad (5)$$

and P_{cf} is an analogous score corresponding to each pedestrian agent moving in the opposite direction,

$$P_{cf} = \sum_{j \in S_{I, \downarrow}} \frac{c_{cf} - d_{cf} \langle \vec{v}_j, \vec{u}_i^0 \rangle}{\max(0.2, D_{ij})}. \quad (6)$$

95 Here, $\vec{v}_j$ is the velocity of pedestrian j . $\vec{u}_i^0$ is the vectorial direction of the desired velocity $\vec{v}_i^0$ in the *MSF* model. Each pair of angle brackets denotes the inner product of the arguments, and c_{df} , d_{df} , c_{cf} and d_{cf} are constants. D_{ij} is the skin-skin distance between agents i and j . $\max(0.2, D_{ij})$ is used in the denominator to avoid an undefined value. The maximization problem given above in Eq. (3) also includes two terms, P_{rl} and P_{sa} , that represent the preferences for moving to the right side and for moving straight ahead, respectively, over moving to the left side to produce the observed right-handed traffic:

$$P_{rl} = c_{v0}(\delta_{\theta>0} - \delta_{\theta<0}), \quad (7)$$

and

$$P_{sa} = |c_{v0}|v_i\delta_{\theta=0}, \quad (8)$$

where c_{v0} is a parameter. The symbol $\delta_{\theta>0}$ represents a binary variable that is equal to one if $\theta = 0$ and to zero otherwise, and the other δ symbols are defined similarly. P_{ncf} is the additional score for straight-ahead movement when there is no counterflow:

$$P_{ncf} = N_0(c_{ncf} + d_{v0}v_i)\delta_{\theta=0}\delta_{N_0^{cf}=0}, \quad (9)$$

where c_{ncf} and d_{v0} are constants and N_0 is the number of agents in the sector directly ahead.

The pedestrian agents in the *FDS + Evac* counterflow model prefer to follow other agents moving in the same direction to reduce the need for avoidance maneuvers among the individuals in a uniform flow. However, it is found that avoidance maneuvers for evading obstructions ahead moving in the same direction are nevertheless required when there is sufficient walking space available in the crowd before and after interaction with the counterflow, particularly when fast pedestrians engage in overtaking behavior in a heterogeneous crowd. Overtaking behavior is widely encountered in reality because pedestrians commonly walk at different velocities. Pedestrians who are being obstructed by other, slower pedestrians will evade these slow pedestrians to continue moving at their desired walking velocities [1]. A previous controlled overtaking experiment [4] found that the actual overtaking action is executed when consecutive spaces are available perpendicularly to the side and diagonally in front. In an individual-level experiment [2], a ‘decision zone’ was treated as necessary for pedestrians to decide whether to evade collision by moving to the left-hand side or the right-hand side. Given these features of pedestrian dynamics, the short-range area illustrated in Fig. 1 is used as the ‘visual area’ of each pedestrian agent to allow the pedestrian agents to receive visual information [37] regarding neighbouring pedestrian agents within their ‘visual areas’ ahead and to react by choosing the optimal walking direction from among three options: dodging to the left, moving straight on, or dodging to the right.

Although the same *MSF* movement model for the agents and the same short-range area are employed in the proposed *MEvac* model, the pedestrian agents’ decision-making procedures and their responses to the other occupants in the same unidirectional flow have been greatly changed. Extensive modifications have been performed with a focus on the calculation of the score P . For the score that depends on the location and velocity of each occupant moving in the same direction, the score P'_{df} is obtained by modifying P_{df} as follows, and similar modifications are applied for the other scores:

$$P'_{df} = \sum_{j \in S_1} \frac{d_{df}(v_i/v_{ref})^h |\langle \vec{v}_j - \vec{v}_i, \vec{u}_i^0 \rangle| + c_{df}}{\max(0.2, d_{ij} - r_{ij})}, \quad (10)$$

where the constants d_{df} and c_{df} are negative, as opposed to the positive constants used in the *FDS + Evac* model. Consequently, the current pedestrian agent prefers to evade other occupants in the same uniform flow rather than following them closely, particularly when there are large differences in walking speed and direction between the current agent and the other occupants. The absolute value of the inner products is used to ensure the influence of this preference in each unidirectional pedestrian flow. Note that overtaking cannot be a commonly used strategy in crowds because only fast pedestrians need to maintain their high mobility by avoiding and overtaking obstructions in front of them. The factor $(v_i/v_{ref})^h$ is introduced into Eq. (10) to describe the pedestrians’ sensitivity to the space availability in each sector. v_i is the walking speed of pedestrian i , and h is the sensitivity degree parameter, which satisfies $h > 1$. The

non-dimension item (v_i/v_{ref}) is achieved by a reference velocity v_{ref} with $v_{ref} = 1.0 m/s$. For example, given the same space availability (i.e., the same distribution of pedestrian agents) in a certain sector, the negative score for a pedestrian agent i with a high walking speed (e.g., higher than $1.0 m/s$) will be further depressed by multiplication by a positive and exponentially increasing $(v_i/v_{ref})^h$, i.e., $(v_i/v_{ref})^h > 1$. In other words, a fast pedestrian agent will react more strongly to other occupants in the same lane and evade those in front of him more actively. By contrast, for a pedestrian agent i with a low walking speed (e.g., lower than $1.0 m/s$), the impact of other occupants on the score will tend to be made negligible by multiplication by a rather small $(v_i/v_{ref})^h$, i.e., $(v_i/v_{ref})^h < 1$. Thus, the heterogeneity of various pedestrians can be made manifest not only by the differences in their velocities but also by their differences in perception and decision-making. Consequently, only pedestrians with high velocities will actively react to the dynamic changes in the space availability in each sector and will effectively overtake obstructions ahead of them, while slow pedestrians will prefer to move straight ahead without much detour.

Pedestrian agents will certainly wish to avoid other agents moving in the opposite direction; thus, there is no change to the score P_{cf} except for the values of the relevant constants, while the modifications to the scores related to the preferences for moving straight ahead and to the right side are as follows:

$$P'_{sa} = a_{sa} v_i \delta_{c < 0}, \quad (11)$$

where a_{sa} is a constant, and

$$P'_{rl} = (c_{rl} - v_i)(v_{ref} - \delta_{\theta < 0}), \quad (12)$$

where c_{rl} is a parameter used to assign the side preferences of the pedestrians. For example, $(c_{rl} - v_i) > 0$ holds for pedestrians who prefer the right-hand side, and the opposite is true for a left-hand side preference. Thus, the preferences of pedestrian agents for these binary directions (i.e., the left and right sides) depend on velocity. P_{ncf} , defined in Eq. (9), is removed since it was employed to amend the strong following strategy, which is eliminated in the present *MEvac* model. Depending on the combination of the utility in each sector and the sector scores based on the direction preferences, the optimal walking direction with the highest total score $P' = w_l(P'_{df} - P_{cf}) + w_{sa}P'_{sa} + w_{rl}P'_{rl}$ will be selected from among the three directions $\{\vec{u}_i^{-\theta}, \vec{u}_i^0, \vec{u}_i^{+\theta}\}$, where w_l , w_{sa} and w_{rl} are used to weight the trade-off among the three evaluation criteria and satisfy $w_l + w_{sa} + w_{rl} = 1$.

3. SIMULATIONS AND RESULTS

3.1. Overtaking behaviour in a heterogeneous bidirectional pedestrian flow

This section describes our attempt to validate the proposed *MEvac* model. The results of the proposed *MEvac* model are compared with the pedestrian flow patterns recorded in a real situation as well as the simulation results obtained using the *FDS + Evac* model [34]. Fig. 2(b) shows the pedestrian lane formation phenomenon and the overtaking behaviour of pedestrians in a real bidirectional flow. The data were collected with a 'GoProHERO5 Black' camera (firmware version 'HD5.0.01.50.00'). The measurement area recorded in the video is a $12 m \times 3 m$ corridor in a shopping mall in China.

We specified the parameters of the proposed model as follows. Since the intention of the *FDS + Evac* decision-based counterflow model was not to change the flows and movement of

Figure 2: (Color online) Snapshots of simulations using two counterflow models. (a) A simulation using the proposed *MEvac* model. (b) The images captured of the corresponding pedestrian flow pattern in the video. (c) A simulation using the *FDS + Evac* model. The blue arrows in subfigures (a), (b) and (c) indicate the walking directions. The lines in subfigures (a) and (c) depict the walking trajectories. A pedestrian who was not relevant to the counterflow interaction is covered with mosaics in subfigure (b). The times T that are superimposed in subfigure (b) show the time elapsed in the video from the starting state, i.e., the state selected for the initialization of the simulations.

crowds under *MSF* model when all the agents were mainly going towards the same direction [33, 34] and the results made sense, the values of parameters in the *MSF* model [34] were also adopted in this work. For the *MEvac* model, parameters $d_{df} = -1.0$, $c_{df} = -1.25$, $h = 4.0$, $d_{sa} = 3.0$ and the set of weighting parameters $w_l = 0.3$, $w_{sa} = 0.4$, $w_{rl} = 0.3$ were already tested in our previous work [38] by reproducing the experimentally overtaking behaviour in heterogeneous unidirectional flows. The values of other parameters were found by trial-and-error to avoid unrealistic movement in the heterogeneous counterflow recorded in reality. The parameter $c_{rl} = 9.0$ was employed to determine pedestrians' preferences for the binary directions. $d_{cf} = 1.0$ and $c_{cf} = 5.0$ were used to calculate the utility of each sector depending on pedestrian agents moving in the opposite direction. The ranges of the sectors in the 'visual area' were taken to maximally extend to $3m$ ahead of each pedestrian agent and to $1.5m$ on the sides. If the speed of the agent is low when the speed approaches zero, the maximal range straight ahead approaches $1.5m$, and the sectors form a semicircle as the angle of the sectors, θ , increases from 40 degrees to 45 degrees. The 'Elderly' and 'Adult' pedestrian agent types [34] were chosen for the slow and fast agent populations, respectively. For robustness and calibration, identical values of the model parameters mentioned above were assigned to all pedestrians.

Based on the given model and the assumptions of the relevant parameters, we simulated the lane formation phenomenon and the overtaking behaviour in a bidirectional pedestrian flow within a $12m \times 2m$ corridor. The simulation results were compared to the pedestrian flow patterns observed in reality and the results of the *FDS + Evac* counterflow model; see Fig. 2. The two models were initialized with the geometry and initial positions of the pedestrians and their individual walking velocities as captured by the video camera. The walking velocities of the pedestrians were determined by dividing the distance travelled along a straight line trajectory in the corridor by the time taken. The fast pedestrian velocity was $1.25m/s$, and the slow pedestrian velocity was $0.87m/s$, which was the average speed over all slow pedestrians.

The results in Fig. 2 show that the pedestrian lane formation observed in the real counterflow,

Figure 3: Schematic illustration of the bidirectional pedestrian flow in a corridor with length L and width w . Group 1 and group 2 represent two pedestrian crowds moving in opposite directions. The rectangle A in the middle of the corridor is the measurement area for analysis. The red dash-dotted line along the midsection of rectangle A is considered as the location of the counter for recording the number of pedestrians.

as shown in Fig. 2(b), could be reproduced using both the *MEvac* model and the *FDS + Evac* model; see Fig. 2(a) and Fig. 2(c), respectively. However, the pedestrian flow pattern of lane formation after the counterflow interaction that was predicted by the *MEvac* model agreed better than the pattern predicted by the *FDS + Evac* model with that recorded in reality. In particular, the fast pedestrian walking rightward in Fig. 2(a) (marked in black) began to evade and overtake the slow pedestrian agents ahead after encountering the counterflow traffic. By contrast, in the *FDS + Evac* simulation, all pedestrians preferred to follow other agents travelling in the same direction and thus formed a single-file line. This can be following behaviour of the fast pedestrian led to unrealistic collisions under sparse heterogeneous crowd conditions, i.e., frequent pushing behaviour with a high walking speed even when there was sufficient walking space available.

Additionally, as shown in Fig. 2, the absolute errors on the predicted times resulting from the simulation of each real pedestrian formation in panels 1, 2, 3 and 4 of Fig. 4(b) under the *MEvac* model were 0.6 s, 1.37 s, 1.37 s and 1.87 s, respectively, all of which are less than 2 s. The errors may have resulted from the fact that the consecutive movement of the pedestrian group in reality was disrupted by the inactive initial status of the pedestrians in the simulation. Moreover, interactions with the counterflow may lead to some complex situations.

The results for both pedestrian flow patterns and the corresponding predicted times show that the proposed *MEvac* counterflow model can reproduce a realistic simulation of pedestrian lane formation in a heterogeneous counterflow, particularly the simultaneous overtaking behaviour of a fast pedestrian in a heterogeneous crowd.

3.2. Fundamental diagram of heterogeneous pedestrian counterflows

The fundamental diagram describes the empirical relation between the density ρ and the flow J (or the specific flow per unit width, $J_s = J/w$), and in general, it is assumed that the fundamental diagram for facilities of the same type but different widths w merge into one diagram for the specific flow J_s [4, 39, 40]. In addition to its importance for the dimensioning of pedestrian facilities, the fundamental diagram is associated with every qualitative self-organization phenomenon, such as the formation of lanes or the occurrence of congestion [40]. This section presents our attempts to further validate the proposed *MEvac* counterflow model by investigating the fundamental diagram of heterogeneous pedestrian counterflows in a long corridor. The simulation results are compared with the experimental data.

All the parameters of the *MEvac* model and the properties of the pedestrian agents were chosen to correspond to those in the previous section, i.e., section A. Based on the given model and the assumptions of the relevant parameters, we investigated the fundamental diagram of the

bidirectional pedestrian counterflows in a corridor with a length of $L = 50\text{ m}$; see Fig. 3. The corridor widths considered in the simulations were $w = 3\text{ m}$, $w = 5\text{ m}$ and $w = 7\text{ m}$. The pedestrians in group 2, walking leftward through the corridor, were a homogeneous crowd consisting only of fast pedestrians. By contrast, those in group 1, walking rightward, formed a heterogeneous crowd consisting of both fast and slow pedestrians. The flow proportions of the two opposing pedestrian groups, i.e., group 1 and group 2, were the same, and the proportions of fast and slow pedestrians in groups 1 were also the same.

For the analysis, a rectangle A with a length of 10 m and a width equal to the width of the corridor was chosen as the measurement area for the pedestrian counterflows; see Fig. 3. Since the average speed of pedestrian group 1 was lower than that of group 2, an imaginary line along the midsection of the rectangle was considered rather than the center line of the corridor. The numbers of pedestrians who crossed this line over time from both directions were recorded. The reference location x of the imaginary line in the corridor was considered to investigate the actual time Δt taken by $N_{\Delta t}$ pedestrians to pass this location. Thus, the specific flow J_s over time Δt could be calculated as

$$J_s = \frac{N_{\Delta t}}{w\Delta t}, \quad (13)$$

where w is the width of the corridor and the density ρ is defined as the number N of pedestrian divided by the area of the measurement section A :

$$\rho = \frac{N}{wL_A}, \quad (14)$$

where L_A is the length of the measurement section. According to a previous experimental study [14], the specific flow concept of a unidirectional flow is also applicable to bidirectional streams, and the velocity of a bidirectional crowd can be calculated using the hydrodynamic relation

$$v = \frac{J_s}{\rho}. \quad (15)$$

Based on the measurement and calculation methods described above, the data for heterogeneous bidirectional pedestrian flows in corridors with widths of $w = 3\text{ m}$, $w = 5\text{ m}$ and $w = 7\text{ m}$ were simulated and compared with the experimental data, as shown in Fig. 4. The simulation results were averaged over 20 runs, and the experimental data used to construct the fundamental diagram for bidirectional pedestrian flows were taken from Navin and Wheeler [41], Older [42] and Weidmann [43] and were obtained from the website of the University of Wuppertal [44]. The findings show that the fundamental diagrams of heterogeneous pedestrian counterflows for corridor facilities of the same type but different widths w converge to one diagram when plotted in terms of the specific flow, which is consistent with previously reported results [14, 39, 40]. Moreover, the simulation results obtained with the proposed *MEvac* counterflow model are in good agreement with the experimental data. These results imply that the proposed *MEvac* model can realistically emulate the pedestrian counterflows observed in the real world.

Since Weidmann's data are drawn from an idealized fundamental diagram obtained by collecting and fitting data from 25 other experiments, these data were used as the reference data for analysis. Fig. 4(a) shows that the fundamental diagrams for the simulation data obtained for different corridors agree well with Weidmann's data in the density range of $\rho < 0.8\text{ m}^{-2}$. The specific flow J_s increases as the density ρ increases, implying that the bidirectional pedestrian flow is in an uncongested state. However, the predicted specific flows for heterogeneous pedestrian counterflows are slightly lower than Weidmann's data, at least for densities of $\rho < 0.5\text{ m}^{-2}$.

Figure 4: (Color online) Comparison of the fundamental diagram of heterogeneous pedestrian counterflows for different corridor widths with the experimental data. $MEvac_{(w=3m)}$ denotes that the simulations were conducted with the $MEvac$ model for a 3 m wide corridor, and the notations $MEvac_{(w=5m)}$ and $MEvac_{(w=7m)}$ are defined similarly.

One possible reason is that the locations of the heterogeneous pedestrians in group 1 at a low pedestrian density were more discrete than those in the homogeneous group, i.e., group 2. Fast pedestrians could evade and overtake slow ones when there was sufficient walking space available in the uniform rightward-going flow before encountering the counterflow, and the resulting displacement between the fast and slow pedestrians remained in the subsequent counterflow traffic, causing the specified $N_{\Delta t}$ pedestrians to take a long time Δt to cross the counter line. Fig. 4(b) shows that the velocities of the heterogeneous pedestrian counterflows are lower than Weidmann's data for densities of $\rho < 0.5 m^{-2}$, which may have directly resulted from the presence of the slow pedestrians, with their lower walking speed, in the crowd. Then, it was exactly this difference in velocity between the fast and slow pedestrians that resulted in overtaking in group 1 before the counterflow interaction and the lower specific flow of the heterogeneous pedestrian counterflow under sparse crowd conditions.

As the pedestrian density in the corridor increased, the heterogeneous pedestrian group 1 became more continuous and to following behaviour since there was not sufficient space for the fast pedestrians to evade and overtake the slow ones in the higher-density crowd, even in the unidirectional flow before the counterflow interaction. Furthermore, the lane formation behaviour of these more continuous uniform groups (see Fig. 5) reduced the strength of the interactions with oncoming pedestrians, allowing the specific flow to increase and resulting in higher walking speeds. The results show that for different corridor widths, the maximum specific flow was always obtained at a density of approximately $\rho = 1.5 m^{-2}$. After that, a capacity drop occurred due to the congestion in high-density crowds. It is also found that the predicted specific flows for heterogeneous counterflows are generally lower than Weidmann's data when $\rho > 2.0 m^{-2}$, which might be a result of the high impact of the slow pedestrians on the mobility of the fast pedestrians in a heterogeneous counterflow.

Differences in the fundamental diagrams of the simulation data for different corridors can be observed for densities of $\rho > 1.0 m^{-2}$. The results in Fig. 4(a) and Fig. 4(b) show that the predicted specific flow J_s and the velocity V of the pedestrian counterflow in the 3 m wide corridor are higher than Weidmann's data in the density range of $1 m^{-2} < \rho < 2 m^{-2}$. This is because the

Figure 5: (Color online) Snapshots of counterflow simulations of heterogeneous bidirectional pedestrian flows in corridors of different widths. The pedestrians marked in black (blue) are fast pedestrians walking rightward (leftward), and those marked in red are slow pedestrians walking rightward. Three types of lane formation can be observed in these simulations: two stably separated lanes, as seen in panel 1; two dynamically separated lanes, as seen in panel 2; and multiple dynamically flowing lanes, as seen in panel 3. The green dashed lines denote the imaginary partition lines between the separated lanes in the different corridors.

clear influence of the right-hand traffic norm considered in the *MEvac* model led to the formation of two stably separated lanes in the bidirectional flow; see panel 1 in Fig. 5. This rapidly forming pedestrian counterflow pattern effectively minimized conflicts between individuals moving in opposite directions. Interestingly, even with the same preference for the right-hand traffic norm, the predicted J_s and v values of the bidirectional pedestrian flows in the corridors with widths of 5 m and 7 m are, by contrast, generally lower than Weidmann's data. The reason may lie in the different pedestrian counterflow patterns formed in corridors of different widths.

The results revealed three types of lane formation in total in these counterflow simulations (see Fig. 5): two stably separated lanes, two dynamically separated lanes and multiple dynamically flowing lanes. Surprisingly, the number of lanes in the dynamic multi-lane flow case was always 4. The proportion of instances with different numbers of lanes in the corridors of different widths are shown in Fig. 6(a); across all three corridor geometries, the dynamic multi-lane flow case arose in only 17% of all instances. Simultaneously, we assumed that the conclusion reported in a previous experimental study [14], namely, that the fundamental diagrams of the case of two stably separated lanes and the dynamic multi-lane case for bidirectional flows are consistent, at least for densities of $\rho < 2.0 m^{-2}$, is actually fairly convincing. Thus, the differences in the pedestrian counterflow patterns between the case of two stably separated lanes in a narrow corridor and the case of two dynamically separated lanes in a wider corridor may offer some insight into the cause of the lower specific flows in the corridors with widths of 5 m and 7 m, at least for densities of $\rho < 2.0 m^{-2}$.

Fig. 5 shows the two types of imaginary partition lines between the two separated lanes in 3 m and 5 m corridors. It is found that the partition line in a narrow corridor is almost hori-

Figure 6: (Color online) Proportions of different counterflow types in corridors of various widths. n is the number of pedestrian lanes. The range of the pedestrian density ρ is used to specify the sample size.

horizontal, whereas the partition line in a wider corridor is oblique. These findings imply that the pedestrians in the wider corridor who adhere to the right-hand traffic norm must walk a longer lateral distance (perpendicular to the wall) to form stably separated pedestrian lanes, especially for pedestrians in group 1 (group 2) walking along the upper (lower) wall of the corridor before the counterflow interaction (see panel 2 in Fig. 5), which may cause the specified $N_{\Delta t}$ pedestrians to take a long time Δt to cross the counter line in the horizontal direction. Moreover, the outflow of the subsequent uniform pedestrian flows from the counterflow is limited to some extent due to the impact of the wide tail of the opposite pedestrian procession, i.e., the tail of the triangular formation, in the corridor. Although the two dynamically separated lanes of pedestrians that form in a wide corridor due to the personal preference for the right-hand traffic norm will evolve into two stable lanes over time in simulations of continuous bidirectional pedestrian flows, the consideration of the impact of the dynamic state is meaningful for practical applications in real complex and dynamic walking environments.

In addition, the results shown in Fig. 6(a) seem to indicate that the proportion of two-lane counterflows decreases as the corridor width increases, while the proportion of multi-lane counterflows increases, with no dependence on the pedestrian density, according to Fig. 6(b), Fig. 6(c) and Fig. 6(d). In other words, the maximum number of lanes in the corridor increases with the width of the corridor in the present model.

3.3. Effects of personal preferences on lane formation

It was found that under the proposed *MEvac* model with a weight parameter of $w_I = 0.3$ for evading behavior within the personal ‘visual area’, $w_{sa} = 0.4$ for the preference for going straight ahead and $w_{rl} = 0.3$ for the preference for right-hand traffic, the bidirectional streams tend to form two separated lanes that occupy proportional shares of $3m$ and $5m$ corridors; see Fig. 5 and Fig. 6. It was supposed that the personal preference for the right-hand traffic norm was the main reason for the frequent formation of two lanes in such counterflows. Subsequently, the different impacts of the three distinct personal preferences on the maximum number of lanes formed in heterogeneous pedestrian counterflows were tested by considering different sets of weight parameters such that $w_I + w_{sa} + w_{rl} = 1$. Simulations were conducted in long corridors (see Fig. 3) with a length of $L = 50m$ and different widths of $w = 4m$, $w = 6m$, $w = 8m$ and $w = 10m$. The flow proportions of the two opposing pedestrian groups, i.e., group 1 and group 2, were the same, and the proportions of fast and slow pedestrians in group 1 were also the same. The density of pedestrians in the corridors of different widths was fixed to $\rho = 1.0m^{-2}$. The properties of the pedestrian agents were chosen to correspond to those in the above sections, i.e., sections A and B. The parameters of the *MEvac* model were also kept the same, except for the weight parameters w_I , w_{sa} and w_{rl} .

The results for the maximum number of pedestrian lanes among 20 runs of counterflow simulations for each situation are shown in Fig. 7. The simulation results presented in Fig. 7(a) and Fig. 7(b) were obtained by assigning the same value to one parameter ($w_I = 0.2$ and $w_{sa} = 0.2$, respectively) and varying the others. For further comparisons, the simulation results presented in Fig. 7(c) and Fig. 7(d) were obtained by assigning the pedestrians a strong ($w_{rl} = 0.7$) or moderate ($w_{rl} = 0.4$) preference for the right-hand direction and a weak right-hand preference ($w_{rl} = 0.1$ or $w_{rl} = 0.2$), respectively, and varying the values of w_I and w_{sa} .

The results in Fig. 7(a), Fig. 7(b) and Fig. 7(c) show that the patterns that emerge in pedestrian counterflows with a strong preference for the right-hand traffic norm ($w_{rl} = 0.7$) all consist of two lanes, regardless of the corridor width or the values of the weight parameters w_{sa} and w_{rl} . For $w_{rl} = 0.4$, two lanes still form in the counterflows for corridors with widths of $w \leq 8m$, whereas four pedestrian lanes emerge in the $10m$ corridor, again without an apparent direct dependence on the values of the weight parameters w_{sa} and w_{rl} .

However, the variation in the personal preferences for evading behaviour (w_I) and going straight ahead (w_{sa}) begin to show an obvious impact on lane formation when the personal preference for the right-hand traffic norm is weak, e.g., $w_{rl} = 0.1$. The results in subfigure (a) show that the maximum number n_{max} of lanes increases from 2 to 6 as the corridor width increases from $4m$ to $8m$ when pedestrians prefer going straight ahead ($w_{sa} = 0.7$) over evading behaviour ($w_I = 0.2$). By contrast, the results in subfigure (b) show that the maximum number n_{max} of lanes increases from 4 immediately to 6 as the corridor width increases from $4m$ to $6m$ when pedestrians prefer evading behaviour ($w_I = 0.7$) over going straight ahead ($w_{sa} = 0.2$). Let us suppose that the lane capacity of a corridor is the maximum number of lanes that can form in that corridor. For instance, Fig. 7 shows that the lane capacity of the $4m$ wide corridor is 4 and that the $6m$, $8m$ and $10m$ wide corridors all have a lane capacity of 6. Then, the results seem to indicate that a strong preference for evading behaviour and a weak preference for the right-hand traffic norm generally lead to the formation of more lanes in the counterflow, up to the lane capacity of the corridor.

Comparisons of these results seem to indicate that in corridors with the same pedestrian density, a strong personal preference for the right-hand traffic norm, e.g., $w_{rl} = 0.7$, will always

Figure 7: (Color online) The maximum numbers of pedestrian lanes in corridors of different widths under the proposed *MEvac* model with different sets of weight parameters.

lead to the formation of two lanes in heterogeneous pedestrian counterflows, regardless of the corridor width and other preferences. As the personal preference for the right-hand traffic norm decreases, a moderate preference for the right-hand direction will lead to the formation of more lanes in a wide corridor, but the maximum number of lanes formed might not reach the lane capacity of the corridor. On the other hand, the preferences for evading behaviour and going straight ahead start to affect the maximum number of lanes formed when the personal preference for the right-hand traffic norm is weak. In this case, a preference for evading behaviour may result in more lanes than a preference for going straight ahead does, up to the lane capacity of the corridor.

Additionally, we tested the effects of the personal preferences on lane formation in heterogeneous counterflows with different pedestrian densities. Simulations of pedestrian counterflows with different densities were conducted in the 6 m wide corridor described above, since it was found that various numbers of lanes (i.e., 2, 4 and 6) could form in this corridor with different sets of weight parameters, as shown in Fig. 7. The average numbers of pedestrian lanes over 20 runs for each situation were obtained, and these average lane number results are listed in Table 1. Although the relationship between the number of pedestrian lanes and the pedestrian density is difficult to specify for each set of weight parameters in the *MEvac* model, the results in the table show that a strong personal preference for the right-hand traffic norm, i.e., $w_{rl} \geq 0.4$, again leads to two separated lanes in the 6 m wide corridor with no dependence on the pedestrian density. On the other hand, the number of pedestrian lanes increases as the right-hand traffic preference decreases, and evading behaviour may result in the formation of more lanes, up to the lane capacity of the corridor, again with no dependence on the density of pedestrians.

Table 1: The average numbers n of pedestrian lanes formed in heterogeneous pedestrian counterflows in the $80\text{ m} \times 6\text{ m}$ corridor with different densities of pedestrians. n_{w721} denotes the number of lanes formed under the model with weight parameters of $w_l = 0.7$, $w_{sa} = 0.2$, and $w_{rl} = 0.1$, and similar notations are used for other sets of parameter values. The maximum number n_{max} of lanes formed in the counterflow simulations for each situation is given in parentheses for cases in which the maximum number n_{max} was not 2.

	$n_{(w721)}$	$n_{(w271)}$	$n_{(w343)}$	$n_{(w154)}$	$n_{(w514)}$	$n_{(w217)}$	$n_{(w127)}$
$\rho = 0.2\text{ m}^{-2}$	4(4)	4(4)	2	2	2	2	2
$\rho = 0.5\text{ m}^{-2}$	4(6)	3(4)	2	2	2	2	2
$\rho = 1.0\text{ m}^{-2}$	3(6)	3(4)	3(4)	2	2	2	2
$\rho = 1.5\text{ m}^{-2}$	3(4)	3(4)	2	2	2	2	2
$\rho = 2.0\text{ m}^{-2}$	4(4)	4(4)	2	2	2	2	2

3.4. Effects of counterflow conditions on pedestrians' overtaking behaviour

An interesting finding is the possibility that lane formation might provide more opportunities for fast pedestrians to overtake slow ones in a dense heterogeneous bidirectional pedestrian flow. Simulations were carried out with the proposed *MEvac* model in a $50\text{ m} \times 3\text{ m}$ corridor with different flow ratios between the two opposing pedestrian groups; see Fig. 8. All parameters of the *MEvac* model and the properties of the pedestrian agents were chosen to be the same as those in sections A and B. There were 50 heterogeneous pedestrians in pedestrian group 1, located at the left end of the corridor; for realistic application purposes, 40 fast pedestrian agents were initially located behind 10 slow pedestrian agents. The walking direction of group 1 was from left to right. Meanwhile, the fast pedestrians walking leftward in homogeneous pedestrian group

Figure 8: Schematic illustration of the bidirectional pedestrian flow in the 50 m corridor.

2 were initially located in a rectangle with a width of 3 m between the longitudinal positions of $x = 20\text{ m}$ and $x = 30\text{ m}$ in the middle of the corridor. The number N of pedestrians in group 2 ranged from $N = 0$ to $N = 50$.

The predicted exit times of the heterogeneous group, i.e., pedestrian group 1, were obtained, as shown in Fig. 9. The results in Fig. 9(a) show the time required for the whole heterogeneous pedestrian group (group 1) to reach the exit when walking rightward through the corridor. Generally, pedestrians in a unidirectional flow, i.e., $N = 0$, spend less time going through the corridor than those in a bidirectional flow, and the exit time increases as the number N of opposing pedestrians increases from $N = 0$ to $N = 50$. That is, although the formation of lanes in the counterflow can reduce head-on conflicts [34], the presence of pedestrians moving in the opposite direction nevertheless results in conflict and a reduction in velocity. Furthermore, the limited capacity of the corridor and the increasing density of pedestrians also lead to congestion and, thus, a reduction in velocity.

Figure 9: (Color online) The time required to leave plotted against the number of heterogeneous pedestrians walking rightward. Sub-figure (a) showed the time against the number of the whole pedestrian group; Sub-figure (b) showed the time against the number of the fast pedestrians who leaving the corridor in top-ten list.

Interestingly, however, it is found that some fast pedestrians require less time to evacuate with the occurrence of counterflow interactions than is required in the unidirectional flow case. For example, the results in Fig. 9(a) show that even though the total exit time required by all of group 1 in the no counterflow case, i.e., $N = 0$, was less than that required in the case of $N = 10$, the first 5 pedestrians to leave in the $N = 0$ case took longer to do so than they did in the $N = 10$ case. This is because the fast pedestrians in heterogeneous pedestrian group 1 were initially located

behind 10 slow pedestrians, and in the $N = 0$ case, they could not find consecutive walking spaces perpendicularly and diagonally, as required for the overtaking action, when obstructed by the slow pedestrian group in front of them in the corridor. Thus, the fast pedestrians were strongly obstructed by the slow pedestrians spread over the width of the corridor. On the other hand, in the $N = 10$ case, the fast pedestrian agents experienced the re-separation of the pedestrian lanes after the aggregation of their group when interacting with the counterflow and thus had the opportunity to find available walking space to evade and overtake the slow pedestrians ahead of them. Some of the fast pedestrians in group 1 began to overtake the slow pedestrians on the left side of the lane formed along the right corridor boundary, where the area was not occupied by slow pedestrians once the counterflow interaction came to an end. Therefore, the fast pedestrian agents who succeeded in overtaking the slow pedestrian group could maintain their own high mobility and thus spend less time in the corridor. Fig. 9(b) shows the exit times of the fast pedestrians who were the first ten to leave the corridor for different flow ratios between the two opposing pedestrian groups. The first pedestrians to leave the corridor in all counterflow scenarios were fast pedestrians. Thus, fast pedestrians who experience lane formation under counterflow conditions might have a greater chance of maintaining their high mobility by overtaking the obstructions ahead of them. Notably, the fast pedestrians who overtook the slow pedestrian group spent less time in the corridor in the $N = 10$ case than in the other cases.

The above simulation results show that even though pedestrian lane formation enhances traffic efficiency by reducing the interactions among individuals travelling in opposing directions in a counterflow, counterflow conditions nevertheless result in conflicts and a reduction in pedestrian velocity. However, a moderate proportion of an opposing pedestrian flow may help fast pedestrians who experience lane formation in the counterflow traffic to find more opportunities to maintain their high mobility by engaging in overtaking behaviour.

4. Conclusions

Pedestrian lane formation in counterflows and overtaking behaviour by fast pedestrians are commonly observed simultaneously in real heterogeneous bidirectional pedestrian flows. Inspired by these observations, we proposed an optimization-based counterflow model called *MEvac* to simulate the movement of pedestrians in a heterogeneous pedestrian counterflow. Quantitative and qualitative analyses were performed. The proposed model was validated by reproducing the pedestrian flow patterns recorded in a real heterogeneous bidirectional flow, and the fundamental diagram of heterogeneous pedestrian counterflows was investigated in comparison with the experimental data.

The results showed that both the overtaking behaviour of fast pedestrians in sparse heterogeneous crowds and, surprisingly, the personal preference for the right-hand traffic norm in a wide corridor might lead to a lower specific flow in a sparse heterogeneous pedestrian counterflow. In addition, a strong personal preference for the right-hand traffic norm will always lead to the formation of two lanes in a heterogeneous pedestrian counterflow, regardless of the corridor width, pedestrian density and other personal preferences. On the other hand, a preference for evading behaviour may result in the formation of more lanes than a preference for going straight ahead does, up to the lane capacity of the corridor, under the condition of a weak personal preference for the right-hand traffic norm in the crowd. Additionally, it was found that with a moderate proportion of opposing pedestrians, lane formation can not only enhance the traffic efficiency of the bidirectional flow but also improve the mobility of fast pedestrians by providing more op-

portunities for the reallocation of the walking space shared by the occupants in the subsequent unidirectional pedestrian flow.

The work presented in this paper may improve the overall prediction of crowd movement in heterogeneous bidirectional flow scenarios. Future work will investigate the effect of social groups in heterogeneous pedestrian counterflows.

Acknowledgements

This work was partially supported by a special project of the Ministry of Industry and Information Technology of China (Grant No. KY10100170137) and the China Scholarship Council (Grant No. 201606680037). We are also grateful to the Fire Safety Engineering research group at Aalto University and Dr. Timo Korhonen of the VTT Technical Research Centre of Finland Ltd for their useful remarks and expertise.

References

- [1] J. Yuen, E. Lee, The effect of overtaking behavior on unidirectional pedestrian flow, *Safety science* 50 (8) (2012) 1704–1714.
- [2] M. Moussaïd, D. Helbing, S. Garnier, A. Johansson, M. Comolli, G. Theraulaz, Experimental study of the behavioural mechanisms underlying self-organization in human crowds, *Proceedings of the Royal Society of London B: Biological Sciences* 276 (1668) (2009) 2755–2762.
- [3] F. Zanlungo, T. Ikeda, T. Kanda, A microscopic social norm model to obtain realistic macroscopic velocity and density pedestrian distributions, *PloS one* 7 (12) (2012) e50720.
- [4] K. Shimura, K. Ohtsuka, G. Vizzari, K. Nishinari, S. Kandori, Mobility analysis of the aged pedestrians by experiment and simulation, *Pattern Recognition Letters* 26 (4) 58–63.
- [5] M. Moussaïd, D. Helbing, G. Theraulaz, How simple rules determine pedestrian behavior and crowd disasters, *Proceedings of the National Academy of Sciences* 108 (17) (2011) 6884–6888.
- [6] T. Kretz, A. Grünebohm, M. Schreckenberg, Experimental study of pedestrian flow through a bottleneck, *Journal of Statistical Mechanics: Theory and Experiment* 2006 (10) (2006) P10014.
- [7] M. Moussaïd, E. G. Guillot, M. Moreau, J. Fehrenbach, O. Chabiron, S. Lemerrier, J. Pettré, C. Appert-Rolland, P. Degond, G. Theraulaz, Traffic instabilities in self-organized pedestrian crowds, *PLoS computational biology* 8 (3) (2012) e1002442.
- [8] M. Isobe, T. Adachi, T. Nagatani, Experiment and simulation of pedestrian counter flow, *Physica A: Statistical Mechanics and its Applications* 331 (3-4) (2004) 638–650.
- [9] L. Jian, Y. Lizhong, Z. Daofang, Simulation of bi-direction pedestrian movement in corridor, *Physica A: Statistical Mechanics and its Applications* 354 (2005) 619–628.
- [10] W. Weng, T. Chen, H. Yuan, W. Fan, Cellular automaton simulation of pedestrian counter flow with different walk velocities, *Physical Review E* 74 (3) (2006) 036102.
- [11] Y. Yu, W. Song, Cellular automaton simulation of pedestrian counter flow considering the surrounding environment, *Physical Review E* 76 (4) (2007) 046112.
- [12] M. Moussaïd, J. J. Nelson, Simple heuristics and the modelling of crowd behaviours, in: *Pedestrian and Evacuation Dynamics 2017*, Springer, 2014, pp. 75–90.
- [13] J. Wei, H. Zhang, X. Guo, M. Gu, Experiment of bi-direction pedestrian flow with three-dimensional cellular automata, *Physica Scripta* 379 (16-17) (2015) 1081–1086.
- [14] J. Zhang, M. Klingsch, A. Schadschneider, A. Seyfried, Ordering in bidirectional pedestrian flows and its influence on the fundamental diagram, *Journal of Statistical Mechanics: Theory and Experiment* 2012 (02) (2012) P02002.
- [15] J. Zhang, A. Seyfried, Comparison of intersecting pedestrian flows based on experiments, *Physica A: Statistical Mechanics and its Applications* 405 (2014) 316–325.
- [16] M. Jaberi, F. Aghabayk, A. Sobhani, Spatial fluctuations of pedestrian velocities in bidirectional streams: Exploring the effects of self-organization, *Physica A: Statistical Mechanics and its Applications* 434 (2015) 120–128.
- [17] G. Petersö, J. Lämmel, Bidirectional pedestrian fundamental diagram, *Transportation research part B: methodological* 71 (2015) 194–212.
- [18] C. Petersö, K. Nishinari, Empirical analysis of the lane formation process in bidirectional pedestrian flow, *Physical Review E* 94 (3) (2016) 032304.

- [19] D. Helbing, L. Buzna, A. Johansson, T. Werner, Self-organized pedestrian crowd dynamics: Experiments, simulations, and design solutions, *Transportation science* 39 (1) (2005) 1–24.
- 515 [20] Y.-Q. Jiang, B.-K. Chen, B.-H. Wang, W.-F. Wong, B.-Y. Cao, Extended social force model with a dynamic navigation field for bidirectional pedestrian flow, *Frontiers of Physics* 12 (5) (2017) 124502.
- [21] S. Nowak, A. Schadschneider, Quantitative analysis of pedestrian counterflow in a cellular automaton model, *Physical Review E* 85 (6) (2012) 066128.
- 520 [22] L. Fu, W. Song, W. Lv, S. Lo, Simulation of emotional contagion using modified social model in cellular automaton approach, *Physica A: Statistical Mechanics and its Applications* 405 (2014) 380–392.
- [23] X. Li, F. Guo, H. Kuang, H. Zhou, Effect of psychological tension on pedestrian counterflow via an extended cost potential field cellular automaton model, *Physica A: Statistical Mechanics and its Applications* 487 (2017) 47–57.
- [24] K. Hua, S. Tao, L. Xing-Li, D. Shi-Qiang, Subconscious effect on pedestrian counterflow, *Chinese Physics Letters* 25 (4) (2008) 1498.
- 525 [25] J. Lee, T. Kim, J.-H. Chung, J. Kim, Modeling lane formation in pedestrian counterflow and its effect on capacity, *KSCE Journal of Civil Engineering* 20 (3) (2016) 1099–1108.
- [26] A. Schadschneider, W. Klingsch, H. Klüpfel, T. Kretz, C. Rogsch, A. Seyfried, Evacuation dynamics: Empirical results, modeling and applications, in: *Encyclopedia of complexity and systems science*, Springer, 2009, pp. 3142–3176.
- 530 [27] K. Takimoto, Y. Tajima, T. Nagatani, Effect of partition line on jamming transition in pedestrian counterflow, *Physica A: Statistical Mechanics and Its Applications* 308 (1-4) (2002) 460–470.
- [28] F. Weifeng, Y. Lizhong, F. Weicheng, Simulation of bi-directional pedestrian movement using a cellular automata model, *Physica A: Statistical Mechanics and its Applications* 321 (3-4) (2003) 633–640.
- [29] H. Kuang, X. Li, T. Song, S. Dai, Analysis of pedestrian dynamics in counterflow via an extended lattice gas model, *Physical Review E* 78 (6) (2008) 066117.
- 535 [30] Y. Yu, W. Song, Effect of traffic rule breaking behavior on pedestrian counterflow in a channel with a partition line, *Physical Review E* 76 (2) (2007) 026102.
- [31] L. Yang, J. Li, S. Liu, Simulation of pedestrian counterflow with right-moving preference, *Physica A: Statistical Mechanics and its Applications* 387 (13) (2008) 3281–3289.
- 540 [32] C. Feliciani, K. Nishinari, An improved cellular automata model to simulate the behavior of high density crowd and validation by experimental data, *Physica A: Statistical Mechanics and its Applications* 451 (2016) 135–148.
- [33] S. Heliövaara, T. Korhonen, S. Hostikka, H. Ohtani, Counterflow model for agent-based simulation of crowd dynamics, *Building and Environment* 48 (2012) 89–100.
- [34] T. Korhonen, S. Hostikka, Fire dynamics simulator with evacuation: Fds+ evac, Technical Reference and Users Guide. VTT Technical Research Centre of Finland.
- 545 [35] D. Helbing, P. Molnar, Social force model for pedestrian dynamics, *Physical review E* 51 (5) (1995) 4282.
- [36] D. Helbing, I. Farkas, T. Vicsek, Simulating dynamical features of escape panic, *Nature* 407 (6803) (2000) 487–490.
- [37] M. Batty, Predicting where we walk, *Nature* 388 (6637) (1997) 19–20.
- 550 [38] D. Zhang, H. Zhu, L. Du, S. Hostikka, An optimization-based overtaking model for unidirectional pedestrian flow, *Physics Letters A* 382 (44) (2018) 5172–5180.
- [39] A. Seyfried, A. Schadschneider, Fundamental diagram and validation of crowd models, in: *International Conference on Cellular Automata*, Springer, 2008, pp. 563–566.
- [40] A. Seyfried, M. Boltes, J. Kähler, W. Klingsch, A. Portz, T. Rupperecht, A. Schadschneider, B. Steffen, A. Winkens, Enhanced empirical data for the fundamental diagram and the flow through bottlenecks, in: *Pedestrian and Evacuation Dynamics 2008*, Springer, 2010, pp. 145–156.
- 555 [41] F. P. Navin, R. J. Whelan, Pedestrian flow characteristics, *Traffic Engineering, Inst Traffic Engr* 39.
- [42] S. Older, Movement of pedestrians on footways in shopping streets, *Traffic engineering & control* 10 (4).
- [43] U. Weidmann, J. der Fußgänger, *Transporttechnische eigenschaften des fussgängerverkehrs (literaturauswertung)* (1993).
- 560 [44] <http://www.asim.uni-wuppertal.de>.