

Unidirectional and bidirectional flow in a narrow corridor with body rotation

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Abstract - In this paper, we developed a new pedestrian model, where pedestrians are represented with three circles and rotate their body to avoid others. In most pedestrian models, the body posture of pedestrians is statically connected with the walking direction; however, they may become different in our model, in other words, pedestrians can walk sideways. We conducted simulation on bidirectional flow in a narrow corridor where body rotation is necessary to avoid collisions and succeeded to reproduce realistic fundamental diagram.

Keywords: collision avoidance; body rotation; fundamental diagram; unidirectional; bidirectional

1. Introduction

Straight sections are common features in many facilities accommodating pedestrian traffic. Corridors, walkways or crosswalks are the most representative example of this class of structures. The movements of pedestrians inside this particular geometry are constrained by boundaries which limit the lateral motion either in a physical way (i.e. walls in corridor) or by visual means (i.e. lines in the crosswalks).

Pedestrian dynamics inside those structures therefore becomes movement along the longitudinal direction with limited lateral motion. In general, there are two types of flow situations which are possible in such straight sections: unidirectional and bidirectional flow. The first is characterized by a group of people moving in the same direction, while the second has a portion of the crowd moving in the opposite direction.

The unidirectional motion has very close characteristics with the vehicular traffic, and its properties have been known for a long time [1]. Although lane changing is less frequent in the case of vehicles (compared to pedestrians), we consider that a group of pedestrians moving in a corridor can be viewed in the same way as vehicles moving over a multi-lanes highway. In both cases, the fundamental diagram is not much different from the single-file dynamics [2], with the case of bicycles also showing strikingly similar characteristics [3]. The similarities between the two different types of fundamental diagrams are clearly seen by comparing Fig. 1(a) [2] and the scatter plot with red-circle markers relative to the unidirectional flow in Fig. 1(b) [4-6]. Although units for density and flow are different (several lanes are possible in the case of Fig. 1(b)), both shows very similar profiles.

While also simple in its nature, the properties of bidirectional flow have been more difficult to explain. In this case, it is not possible to compare with vehicular traffic, since collision avoidance is only present in pedestrians. Although there have been several simulation models and methods which tried to reproduce the mechanisms when pedestrians walk in different directions ([7-9] are the oldest and most known), there are still several aspects which are not clear. For instance, a different fundamental diagram is obtained in the bidirectional flow with peculiarities which are not shown in the unidirectional case [10, 11]. Moreover, the flow-peak is observed at larger density, and the decrease of flow in the jamming-phase is less marked in the bidirectional flow than in the unidirectional flow (Fig. 1(b)).

Some simulation models managed to reproduce the experimental results by employing enhanced algorithms and making use of several parameters and succeeded to achieve accurate results [12-14]. In addition, a theoretical study [15] managed to highlight the different properties of the uni- and bidirectional fundamental diagram, and the authors were able to describe both fundamental diagrams analytically.

Corridor width in these studies is much larger than the sum of the shoulder width of two pedestrians, thus, pedestrians can avoid others by changing their walking direction if density is not very large. However, when pedestrians need to pass each other in a narrow corridor or in a very high-density situation, they need to rotate their bodies and walk sideways to avoid collisions [16-17].

Although body rotation is considered in some pedestrian models, the body posture of pedestrians is statically connected with the walking direction, thus, pedestrians do not walk sideways [18, 19]. Therefore, we developed a model, where pedestrians can walk sideways, and validated it by comparing the fundamental diagrams depicted from our simulations and experiments.

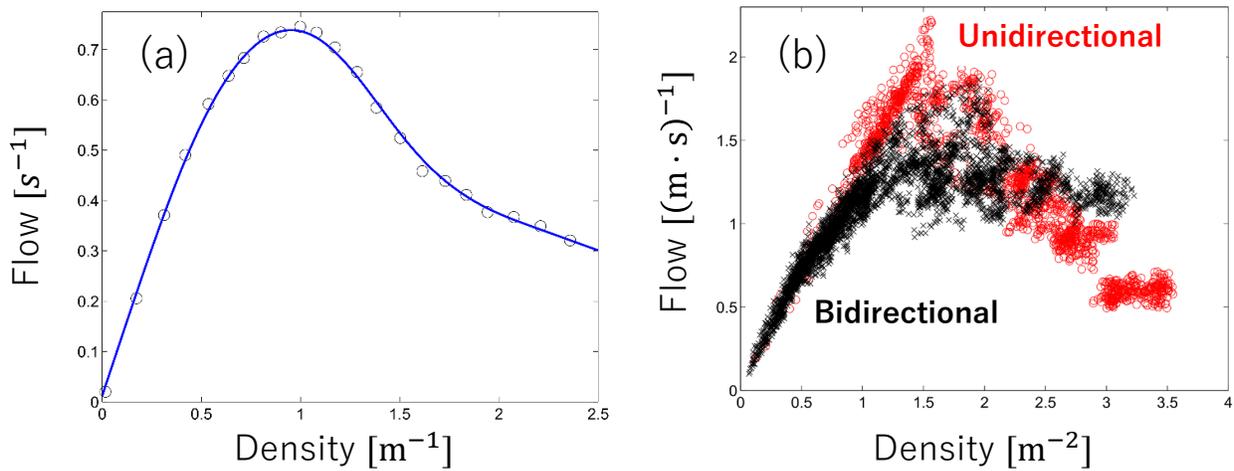


Figure 1: (a) Single lane experimental fundamental diagram [2]; the fitting curve is a common smoothing spline. (b) Experimentally obtained fundamental diagram for the unidirectional and bidirectional flow when multiple lanes are possible. Both plots have been drawn by analysing data from the Julich Research centre [4-6]. Note that the units of density and flow are different in the left and right figures.

2. Pedestrian model for passing in a narrow corridor

In this section, we developed a pedestrian model for passing in a narrow corridor. We consider that pedestrians rotate their body and decrease their effective width by walking sideways when they need to avoid collisions with opponent pedestrians; therefore, we implemented such mechanism in our model.

2.1. Walking speed function without body rotation

To model pedestrian movement and depict fundamental diagram, first, the speed-headway relation should be considered in addition to the body-rotation model. We assumed that the walking speed without body rotation $|v_0|$ is given by the following piecewise-linear function:

$$|v^0| = \begin{cases} 0 & (0 \leq h \leq h_0), \\ |v^{\max}| \frac{h - h_0}{h_1 - h_0} & (h_0 \leq h \leq h_1), \\ |v^{\max}| & (h_0 \leq h \leq h_1), \end{cases} \quad (1)$$

where h [m] is the headway distance. The maximum speed $|v^{\max}|$ [m/s], h_0 [m], and h_1 [m] are the parameters of the walking-speed function. We exploited the experimental data of unidirectional flow in Fig. 1(b) and determined these three parameters through the least squares method. The results were

$|v^{\max}| = 1.39$ m/s, $h_0 = 0.49$ m, and $h_1 = 1.46$ m. Figure 2 shows the plots of the experimental data and the calibrated walking-speed function (1), which were confirmed to agree well with each other ($R^2 = 0.73$).

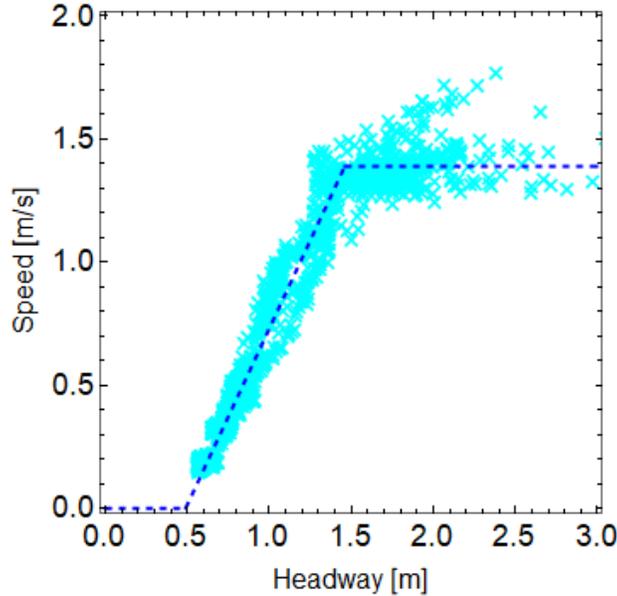


Figure 2: Speed-headway relation in unidirectional flow. The cyan crosses and blue-dashed plot represent the result of the experiments in [4-6] and the calibrated walking-speed function (1), respectively. The parameters are set as $|v^{\max}| = 1.39$ m/s, $h_0 = 0.49$ m, and $h_1 = 1.46$ m.

By using the calibrated walking-speed function (1), we performed the unidirectional-flow simulations in the periodic corridor (circuit), whose length and width were $L = 10$ m and $W = 0.5$ m, respectively. We controlled the number of pedestrians N from 1 to 17 by 1 and positioned them at equal intervals in the corridor at the beginning of the simulations. Overtaking was not considered, therefore, evading or body-rotational behaviours were not observed. Thus, the walking-speed function (1) dominated the system. As we can see from Fig. 6(a), the experimental and simulation results agree well each other in the flow-density relation as well as the speed-headway relation (Fig. 2).

2.2. Evasion and body rotation to avoid opponent pedestrians

Next, we explain the evasion and body rotation mechanism in our model. Each pedestrian was modelled with three circles. Their shoulder width and bust depth are $2a$ [m] and $2b$ [m], respectively, as in Fig. 3(a). Then, pedestrians are no more rotationally symmetric to their centre, so that pedestrians can control their effective width d [m] by rotating their body by θ [deg] as in Fig. 3(b). In our model, pedestrians do not change their walking direction when they rotate their body. In other words, pedestrians walk sideways when they need to avoid opponent pedestrians

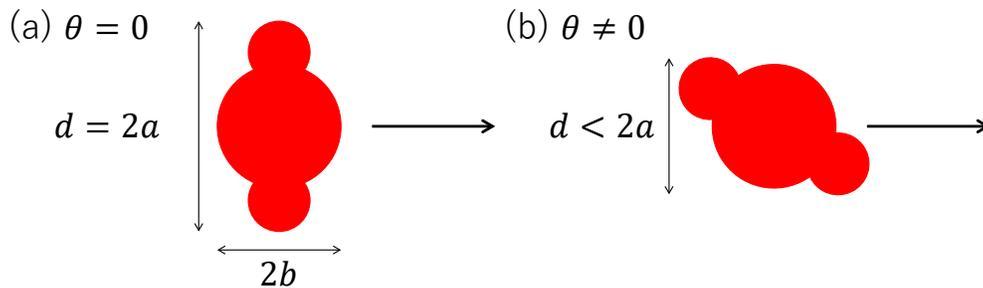


Figure 3: Schematic view of effective width of pedestrians in our model. (a) When pedestrians do not rotate their body, i.e., $\theta = 0$, the effective width is equal to the shoulder width of pedestrians, i.e., $d = 2a$. (b) On the other hand, $2b \leq d < 2a$ when pedestrians rotate by $\theta (\neq 0)$.

Pedestrians avoid collisions with their opponent pedestrians in bidirectional flow by both evasion and body rotation as follows. The position and rotational angle of pedestrian i are represented by (x_i, y_i) and θ_i , respectively. When an opponent pedestrian j come close to pedestrian i , i.e., $|x_i - x_j| \leq s_{cr}$, both pedestrians try to evade each other in the perpendicular direction (y) to their moving direction (x) and rotate their body to decrease the overlap length l as in Fig. 4. (Pedestrians start evading and rotating at the same time.) Thus, pedestrians gradually control their position y_i and rotational angle θ_i proportional to the overlap length l . Furthermore, the walking speed of pedestrians becomes smaller during walking sideways. (We assumed that walking speed becomes zero at $\theta_i = 90^\circ$ and 270° .) Therefore, the equations of motion of pedestrians before passing are described as follows:

$$\frac{dx_i}{dt} = v_i^0 \cos \theta_i, \quad (2)$$

$$\frac{dy_i}{dt} = k_y^A l \cdot \text{sign}(y_i - y_j), \quad (3)$$

$$\frac{d\theta_i}{dt} = k_\theta^A l, \quad (4)$$

where, v_i^0 is the walking velocity without body rotation determined from (1). The parameters k_y^A and k_θ^A are sensitivity parameters for the overlap length. The function $\text{sign}(z)$ gives the sign of the argument z .

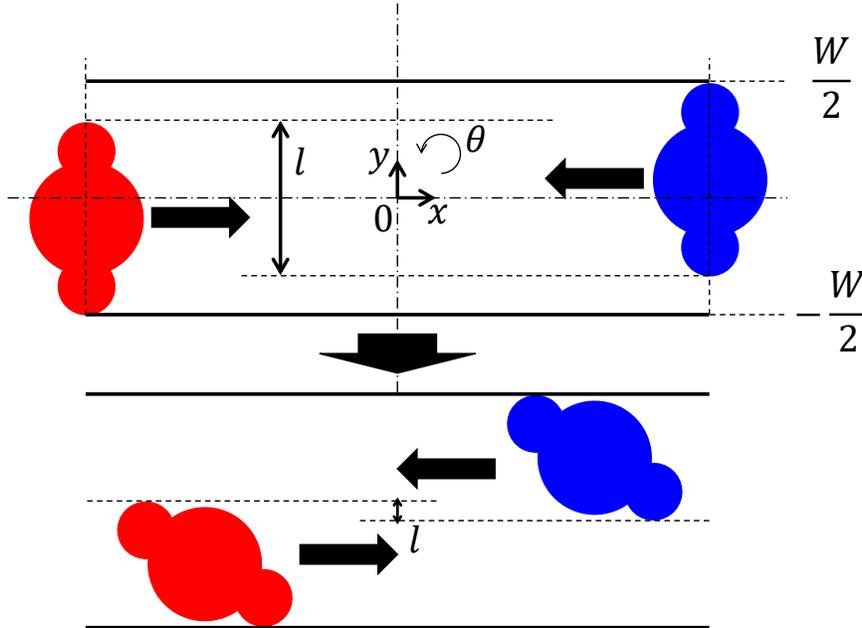


Figure 4: Schematic view of collision avoidance by evasion and body rotation.

When there are no opponent pedestrians close to pedestrians i or after passing, pedestrian i tries to restore his/her body postures and move as fast as they can. We assume that the restoring behavior is proportional to the evading distance and the rotational angle, so that the equations of motion of y and θ after passing are described as follows:

$$\frac{dy_i}{dt} = -k_y^R (y_i - y_j^0), \quad (4)$$

$$\frac{d\theta_i}{dt} = -k_{\theta}^R(\theta_i - \theta_i^0), \quad (5)$$

where, k_y^R and k_{θ}^R are sensitivity parameters for the deviation from the initial position (y_i^0) and the initial rotational angle (θ_i^0), respectively.

The parameters in the model were calibrated by using the experimental data in [17]. Their values are $a = 0.249$ m, $b = 0.155$ m, $s_{cr} = 1.5$ m, $k_y^A = 9.0$ m/(m·s), $k_{\theta}^A = 6.0$ deg/(deg·s), $k_y^R = 5.0$ m/(m·s), and $k_{\theta}^R = 7.0$ deg/(deg·s).

2.3. Bidirectional flow simulations

By using the calibrated model, we conducted bidirectional-flow simulations. We considered a straight corridor, whose length $L = 10$ m, with periodic boundary condition (the left end and the right end of the corridor were connected). The corridor width was controlled from $W = 0.8$ m to 1.0 m by 0.1 m. The number of total pedestrians N was controlled from 2 by 2 until the density achieved 3.4 m^{-2} . The number of the right-going (red) and left-going (blue) pedestrians were the same ($N/2$). Both types of pedestrians were positioned at equal intervals in the corridor at the beginning of the simulations. The sum of the shoulder widths of the two pedestrians $2 \times 2a = 0.996$ m was larger than $W = 0.8$ and 0.9 m, therefore, the pedestrians needed to evade others and rotate to pass each other in such narrow corridors. Figure 5 shows a schematic view of the bidirectional-flow simulation.

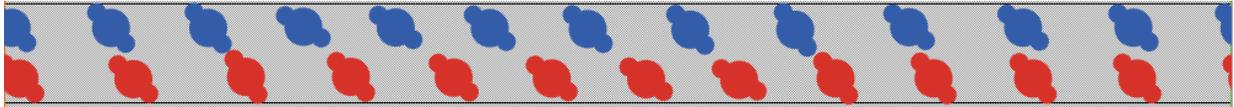


Figure 5: Schematic view of simulation on bidirectional flow. There are two kinds of pedestrians. Red pedestrians are moving from left to right, and the blue pedestrians are moving from right to left. We see that pedestrians rotate their body to avoid collisions with opponent pedestrians.

3. Fundamental diagram

The results of the bidirectional-flow simulations ($W = 0.8$ m) are presented with those of experiments [4-6] in Fig. 6(a). We can see that the simulation results are in agreement with the experimental results.

By comparing the experimental results of the unidirectional and bidirectional flows, we can observe that unidirectional flow achieves larger value of flow than bidirectional flow when the density is smaller than the critical density ($\approx 2.3 \text{ m}^{-2}$). When the density is greater than the critical density, the values of bidirectional flow become larger than those of unidirectional flow. These characteristic phenomena were successfully reproduced in our simulation results. In the low-density situation, pedestrians can move freely in unidirectional flow; however, they have to interact with opponent pedestrians to avoid them in bidirectional flow. Thus, flow is greater in unidirectional flow than in bidirectional flow. In the high-density situation, interactions with other pedestrians are unavoidable in both flows. Overtaking is difficult in unidirectional flow because pedestrians cannot see behind themselves. It is difficult for them to give way to fast followers. Thus, the fundamental diagrams are mainly dominated by the simple speed-headway relation. In contrast, pedestrians can see opponent pedestrians, give way, and pass by each other through evasion and rotation in bidirectional flow. Due to these avoidance behaviours, flow of bidirectional flow remains larger than those of unidirectional flow in the high-density situation. Our simulation model succeeded in reproducing this phenomenon by introducing avoiding behaviours, i.e., evasion to the perpendicular direction and body-rotation. Further, we would like to mention that the introduction of evasion alone was insufficient for bidirectional-flow simulations in a narrow corridor.

Since the sum of the shoulder widths of the two pedestrians $2 \times 2 a = 0.996$ m was larger than the corridor width $W = 0.8$ m, body rotations were necessary to avoid deadlocks.

Figure 6(b) shows the fundamental diagrams of bidirectional for various corridor width ($W = 0.8, 0.9$ and 1.0 m) depicted from the results of the simulations. We see that the flow become larger (smaller) as the corridor width increases when the density is smaller (larger) than the critical density ($\approx 2.3 \text{ m}^{-2}$). The density for the same number of pedestrians decreases when the corridor width increases because the area of the corridor (circuit) increases. Thus, the fundamental diagram just shifts to left if the longitudinal movement of pedestrians does not change at all by the corridor width. In fact, the fundamental diagrams do not simply shift from right to left as the corridor width increases, and the increase of flow cannot be explained by this effect. Therefore, longitudinal movement of pedestrians changed by the corridor width.

When the corridor width $W = 1.0$ m, which was larger than the sum of the shoulder widths of the two pedestrians $2 \times 2 a = 0.996$ m, pedestrians did not need to evade or rotate to pass each other. This situation can be considered that there were two independent corridors whose width is 0.5 m for right- and left-going pedestrians, respectively. Therefore, the flow achieved similar values as in the unidirectional flow. When the corridor width became smaller than 0.996 m, pedestrians had to evade and rotate to avoid their opponent pedestrians. Body rotation forced the pedestrians to walk sideways and decreased the walking speed by (2). Thus, the flow decreases as the corridor width decreases when the density is smaller than the critical density.

When the density is larger than the critical density, the flow becomes larger as the corridor width decreases. In this case, the effect of density-increase due to the decrease of corridor-width overwhelms the effect of speed-decrease due to sideway-walking.

If the corridor is much larger than the sum of the shoulder widths of the two pedestrians, minor change of the corridor width may not greatly affect the fundamental diagram because pedestrians can control both longitudinal and lateral distances with other pedestrians and avoid continuous sideway-walking. However, when the corridor width is small, pedestrians have to keep walking sideways to avoid collisions. Hence, the flow decreases due to the reduction of the walking speed. This result indicates that the value of flow in bidirectional flow is not only determined by the density, but also affected by the corridor width.

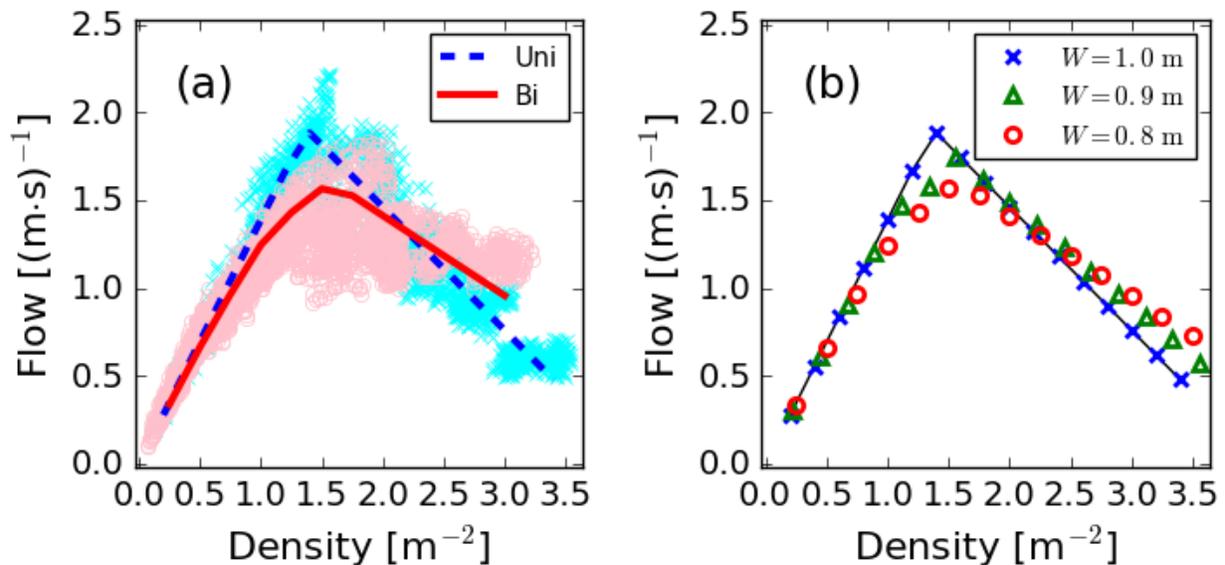


Figure 6: (a) Fundamental diagram obtained from the experiments in [4-6] and our simulation when $W = 0.8$ m. The legends are as follows: cyan crosses: experimental unidirectional flow, pink circles: experimental bidirectional flow, blue-dashed line: simulation unidirectional flow, red-solid curve:

simulation bidirectional flow. (b) Fundamental diagram obtained from our simulation for various corridor width. The legends are as follows: black line: unidirectional flow, blue crosses: bidirectional flow ($W = 1.0$ m), green triangles: bidirectional flow ($W = 0.9$ m), red circles: bidirectional flow ($W = 0.8$ m).

4. Conclusion

In this research, we developed a model, where pedestrians rotate their body to avoid others. In our model, the body posture is not statically connected with the walking direction. Hence, pedestrians walk sideways when they rotate their body. Then, we conducted simulation of both the unidirectional and bidirectional flow and depicted the fundamental diagram. The result of our simulation and that of the experiment agree well each other. Since the corridor width in the bidirectional simulation was smaller than the sum of the shoulder width of the two pedestrians in the simulation, introduction of the body-rotation mechanism (sideway-walking) was necessary to perform simulation. If the pedestrians cannot rotate their body and walk sideways, deadlocks occur in the corridor.

We also investigated the effect of corridor width on the fundamental diagram. Our simulation results show that the flow decreases (increases) as the corridor width decreases even at the same density when the density is smaller (larger) than the critical density ($\approx 2.3 \text{ m}^{-2}$). This result indicates that the value of flow in bidirectional flow is not only determined by the density. The difference of corridor width has influence on the flow when the corridor width is small.

In the future, we are planning to extend our model to perform simulations in more complex scenarios such as cross-flow incorporating with pedestrians' body rotation to investigate the effect of body rotation on congested situations.

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