The effect of social groups on the dynamics of bi-directional pedestrian flow: a numerical study

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Abstract. We investigate the effect of groups on a bi-directional flow, focusing on self-organisation phenomena, and more specifically on the time needed for the occurrence of pedestrian lanes, their stability and their effect on the velocity-density relation, and the amount of physical contact in the crowd. We use a novel collision avoidance model considering the asymmetrical shape of the human body, and combine it to a mathematical model of group behaviour. The presence of groups results to have a significant effect on velocity and lane organisation, and a dramatic one on collision. Despite the limitations of our approach, we believe that our results show the great theoretical and practical relevance of group behaviour in pedestrian models, and suggest that realistic results may hardly be achieved simply by adding together modular models.

Keywords: crowd dynamics, social groups, simulation

1 Introduction

Pedestrian physical crowds, i.e. not sharing a social identity [1], are nevertheless characterised by the presence of a large number of social groups [2]. It has to be expected that these pedestrians, that move together with peculiar velocity patterns and spatial formations [3, 4], may strongly influence the dynamics of the crowd[5]. Although a few microscopic models of group have been recently introduced, [6–16], a quantitative assessing of the effect of groups on crowd dynamics has not been achieved. This is also due to the fact that, related to the absence of quantitative empirical data, we are still lacking realistic models of how groups behave *at different density ranges* (not to mention how they behave under different conditions e.g. commuting vs shopping vs evacuation; [17] shows that purpose, relation, gender, age and height have a strong impact on group dynamics). To investigate the relevance of these issues, we are going to: i) use a realistic mathematical model for the behaviour of pedestrian groups in low to moderate density settings, ii) combine it to a realistic and efficient collision avoidance model, and iii) use the resulting model to investigate the effect of the presence of groups on self-organisation properties of a bi-directional flow.

2 Computational model

In [3, 18], we introduced a pair-wise interaction potential describing the dynamics of socially interacting pedestrian groups[5]. This model is based on observations of pedestrian behaviour at low to medium density settings, and it is able to reproduce the behaviour of pedestrians in such situations. In this work, we are using the strong (and probably wrong) assumption that the model may be used under general density conditions, and study its consequences.

[21] shows that the group model of [3, 18] may be effectively combined with the collision avoidance module of [19], which is a second order (force) model that implicitly introduces a velocity dependence by using repulsive forces based on, instead of current distances, future distances at the time of maximum approach to an obstacle or pedestrian (computed using a linear approximation)[5].

The model of [19] was designed for moderate densities and did not take in account the shape of the human body. In order to describe the motion of pedestrians at high density is necessary to consider at least the fact that the 2D projection of the human body is not symmetrical (this asymmetry may be first approximated by using ellipses instead of circles). When such an asymmetry is introduced, even if we still limit ourselves to the motion of pedestrians on a 2D plane, we need to introduce a new degree of freedom, body orientation angle θ. Assuming body orientation to be equal to velocity orientation would be a too strong limitation, since it would not allow pedestrians to rotate their torso while avoiding a collision without changing considerably their motion direction[22]. We thus introduce a model that approximates human bodies as ellipses with axes (A, B) (45 and 20 cms), and use a system of coupled second order differential equations for the pedestrian linear and angular acceleration $\ddot{\mathbf{r}}$ and $\ddot{\theta}$, as functions of $\mathbf{r}$, $\dot{\mathbf{r}}$, θ and $\dot{\theta}$. For reasons of space, we direct the reader interested in the details of the model to the technical document [20], where it is explained how acceleration and torque are computed on the basis of predicted collisions between ellipses and obstacles (including other ellipses, i.e., other pedestrians), which are estimated using a linear approximation on velocity and angular velocity, and an event driven algorithm [23]. As explained in detail in [20], the proposed collision avoidance model is actually a linear combination between the model of [19], that does not use information concerning the shape of the human body, and the proposed module using the elliptical approximation. The combination is performed in such a way that information concerning the shape of the human body is used only for collisions that will happen in short time.

As explained in detail in [20], the parameters of the collision model are optimised in such a way that pedestrians try to minimise collisions while walking as straight as possible watching towards their goal, at their preferred velocity and while keeping groups together. The important point to keep in mind is that the collision avoidance module is optimised to be effective at relative high densities (optimisation is performed in an environment with an average density

[5] Details on cited models [3, 18, 19] may be found in the original works, while a short introduction concerning their use in this work may be found at [20].

of 1 ped/m^2) in presence of groups, while the group model uses the original parameters calibrated on human behaviour *at low densities* in [3].

3 Experiments

3.1 Experimental setting

In our simulations we use a corridor of width 3 meters and length 20 meters, and periodic boundary conditions. The width of the corridor is chosen is such a way that two 3 people groups walking in opposite directions may not cross without changing their formation, based on the group spatial size as reported in [3]. We use four different density conditions, $\rho = 1$ ped/m^2, i.e. 60 pedestrians, $\rho = 2$ ped/m^2, (120 pedestrians), $\rho = 3$ ped/m^2, (180 pedestrians) and $\rho = 4$ ped/m^2 (240 pedestrians). We also use two different group rate r_g conditions, namely without groups $r_g = 0$ and with half of the pedestrians in groups, $r_g = 0.5$. When groups are present, 20% of pedestrians are in triads, and 30% of them in dyads. We thus have 8 conditions depending on the values of ρ and r_g. For example, when $\rho = 4$ ped/m^2 and $r_g = 0.5$ we have 120 individual pedestrians, 36 dyads and 16 triads. Initial conditions are determined by dividing the corridor in cells of equal size, and placing pedestrians in randomly chosen cells, regardless of their flow direction[6]. The pedestrians' preferred velocities are chosen from a normal distribution with $\mu = 1.2$m/s and $\sigma = 0.2$ m/s [7]. Each group or pedestrian has a probability 0.5 of belonging to each one of the flows[8]. For each condition, 10 different simulations with independent initial conditions are used and the observables defined below are averaged over these initial conditions.

3.2 Observables

For each experimental condition, we define the following observables:

1. rate of velocity over preferred velocity, $\nu = v/v_p$,
$$\nu = \frac{v}{v_p} \tag{1}$$
2. energy exchanged in collisions E,
3. number of lanes n_l,
4. rate of pedestrians in lanes, $r_l = (\sum_{i \in n_l} s_i)/N$, where s_i is the number of pedestrians in lane i and N is the overall number of pedestrians.

Lane recognition is performed using the algorithm introduced in [24], whose relation to the current work is explained in detail in [20]. For each observable we first compute the average over pedestrians and time for each independent initial

[6] Pedestrians in the same group are nevertheless located in neighbouring cells.
[7] Pedestrians in the same group have the same preferred velocity.
[8] Thus flows have the same weight only in average.

condition, and then compute the average, standard deviation and standard error over the different independent conditions. The latter are the values shown in the figures. In order to show also time dependence, time averages are computed over 10 slots of length $T_i = 20$ s.

4 Results

Figure 1 shows the time evolution of the ν observable in the $\rho = 1$ and $\rho = 4$ ped/m^2 conditions. We may observe that the effect of groups on velocity is very strong in the medium density range, in which flows without groups present a clearly higher velocity. The velocity difference is higher than the one between groups and individuals in moderate density settings [4]. On the other hand, the effect of the presence of groups on velocity is not present at very high densities. Figure 2 shows the time evolution of the E observable in the $\rho = 1$ ped/m^2 and $\rho = 4$ ped/m^2 conditions. We may observe that the amount of collision is strongly increased in presence of groups for any value of ρ. Figure 3 on the left shows the number of lanes in the $\rho = 3$ ped/m^2 condition in absence and presence of groups. We may see that in presence of groups, the system needs more time to converge to an asymptotic state, furthermore the asymptotic number of lanes is different (3 in absence of groups, and 2 in presence of groups; the presence of groups occupying a wider space makes the formation of three lanes more difficult, [20]). Finally, Figure 3 on the right shows the rate of pedestrians in lanes in the $\rho = 2$ condition in absence and presence of groups. As it happens in general, a larger number of pedestrians is organised in lanes when groups are absent.

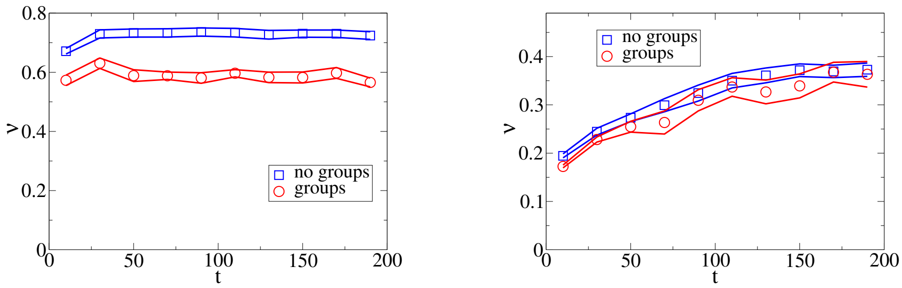

Fig. 1. Left: $\nu(t)$ for the $\rho = 1$ ped/m^2 condition. Blue and squares correspond to $r_g = 0$, red and circles to $r_g = 0.5$. Continuous lines correspond to standard error intervals. Right: corresponding result for $\rho = 4$ ped/m^2.

5 Conclusions

We have verified that by combining a realistic model for group behaviour at moderate crowd density with an efficient collision avoidance model, the presence

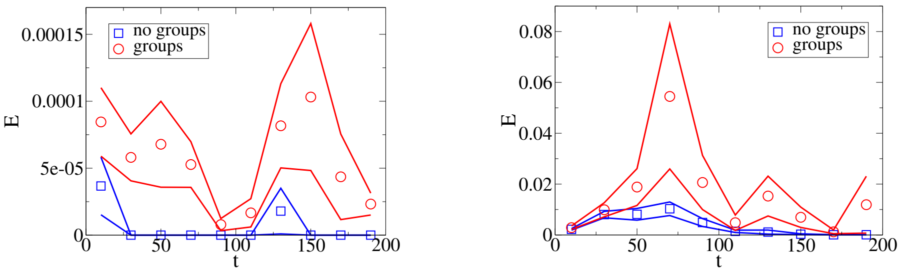

Fig. 2. Left: $E(t)$ for the $\rho = 1$ ped/m^2 condition. Blue and squares correspond to $r_g = 0$, red and circles to $r_g = 0.5$. Continuous lines correspond to standard error intervals. E is measured as kinetic energy (using unit mass) exchanged in average by a pedestrian each second. Right: corresponding result for $\rho = 4$ ped/m^2.

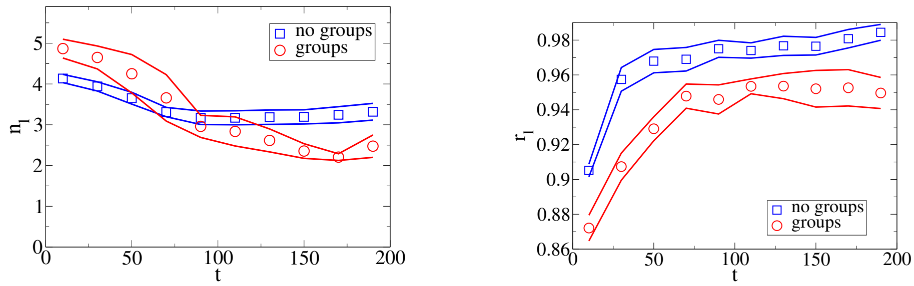

Fig. 3. Left: $n_l(t)$ for the $\rho = 3$ ped/m^2 condition. Right: $r_l(t)$ for the $\rho = 2$ ped/m^2 condition. Blue and squares correspond to $r_g = 0$, red and circles to $r_g = 0.5$. Continuous lines correspond to standard error intervals.

of groups has a strong impact on the dynamics of bi-directional flows, affecting the velocity of pedestrians, the amount of collisions between pedestrians, the number of lanes and the rate of pedestrians organised in lanes. By trying to move on specific formations to enhance not only proximity but also communication between the group members (abreast and V formations) groups occupy a larger portion of the corridor and have less moving flexibility. Their presence decreases the average velocity of the crowd, makes organisation in lanes more difficult and increases the number of collisions.

We have no claim that these results reflect the reality of the effect of groups on crowd dynamics. Although the impact on velocity and lane organisation goes in the expected direction and seems reasonable at least from a qualitative point of view, it is questionable that crowds with groups present such a larger amount of collisions. Just combining a collision avoidance and a group behaviour model could overlook important aspects such as a specific behaviour of pedestrians *towards* groups, and a density-dependent tendency of groups to give up communication and thus spatial formations to avoid collisions. We nevertheless believe that our preliminary results seriously hint at problems and difficulty of a naive approach to the presence of groups in crowds.

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