Study on the efficacy of crowd control and information provision through a simple Cellular Automata model

Claudio Feliciani[1], Kenichiro Shimura[1], Daichi Yanagisawa[1,2], Katsuhiro Nishinari[1,2]

[1] Research Center for Advanced Science and Technology, The University of Tokyo, Tokyo 153-8904, Japan
[2] Department of Aeronautics and Astronautics, Graduate School of Engineering, The University of Tokyo, Tokyo 113-8656, Japan

Abstract. This study presents a simple Cellular Automata model which allows to estimate the combined effect of crowd control and information provision on pedestrian dynamics. We assume the case of a closed loop consisting of two lanes connected in only two points where pedestrians are allowed to move from the inner to the outer loop and in the opposite direction. Both lanes are virtually divided by a wall which does not allow to visually inspect the other side except on the locations connecting them. To investigate the effect of information provision we assume that a given number of pedestrians have information on the speed in both lanes. In addition, we assume that lane changing locations are guarded by security staff which can give orders to the crowd on which lane to choose. However, only a given number of pedestrians are compliant and will obey to the orders. Initial settings for the simulation have been set so that free flow in both lanes is obtained only when the number of lane changes is limited and density is equal in both inner and outer loops. Results show that crowd control strategy, compliance ratio and information provision have a clear impact on the overall group speed. The combined analysis of all variables showed that efficient information provision is the most reliable method to ensure an adequate speed (and flow) even when crowd control fails or when compliance is low.

1 Introduction

The urbanization trend of the last decades has led to an increasing interest to topics related to pedestrian traffic, with crowd management and (real time) information provision taking an important role in this context. A large number of simulation models have been created to allow predicting the motion of pedestrians inside buildings during normal operation and in case of evacuation. Although early simulation models considered pedestrian crowds in a very homogeneous way and were designed for very specific situations [1], modern simulation tools allow to consider very diverse crowds and to take into account architectural features such as stairs or escalators [2], thus making results more accurate.

It is therefore now possible to design buildings such as transportation hubs or events' venues already considering pedestrian traffic at the early stages of the planning process. This represents a considerable advantage in making those structures more safe and comfortable in regard to pedestrian traffic, since modifications for finished structures are hard to make and very costly.

However, even the most accurate and complex simulation models are still not able to account for psychological features, which represent an important aspect in pedestrian motion [7]. Although research is showing an increasing interest in this direction, it will take a long time until mechanisms of collective psychology will be completely understood and numerical models developed. Even then, very peculiar behavior for a specific type of crowd (football fans, protesters...) may be not exactly modeled as the outbreak of some behaviors is mostly random and dependent on the surrounding events (a goal scored, arrival of the police...). In addition, it is always possible that a mass event taking place in a carefully designed location may deteriorate into a chaotic situation due to poor event planning, thus vanishing the effort made in the design phase for that building.

A consequence of the above discussion is that active crowd control (or guidance) will always play a central role even with the increase in accuracy of simulation models. Having an efficient crowd control strategy (i.e. having a system or staff providing guidance to the crowd) is therefore fundamental to ensure safe and comfortable mass events. While this aspect may be straightforward in theory, practical aspects are much more complex and very specific for the environment and the crowd to be controlled. In addition, while accurate data are not available, it is known that some people (sometimes most of the crowd) tend to not follow suggestions from guidance personnel and under those conditions crowd control is therefore ineffective.

To ensure smoother pedestrian motion, information provision may also help, thus allowing the crowd itself to take decisions based on accurate facts rather than their own perception. With this said, it is not always possible (or easy) to inform everyone (for example in the case of people with hearing/visual disabilities) and some people may ignore information surrounding them.

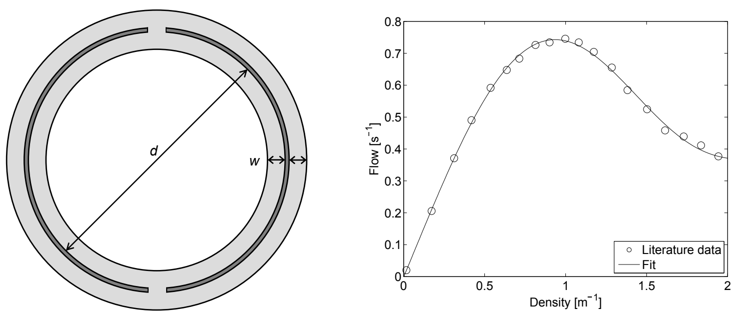
In this study we consider a simple scenario and investigate how the different aspects discussed above relate to each other's and which strategy is the most effective to increase pedestrian flow and speed in a specific situation.

2 Selected case study

The scenario presented here has been inspired by the "fork case" often considered in vehicular traffic; a situation which occurs when a large road connecting two locations get divided into two smaller roads for most of its length. When all the cars take one road, traffic jams occur and average travel time between both destinations increases. To ensure that both roads are used equally, optimal information provision is required at the time drivers decide which road to use. A number of studies [8, 10, 9, 4, 5] have focused their attention on these optimal strategies and the type and information which is required to avoid traffic jam.

To adapt it to pedestrian traffic and also account for the effect of crowd control, we will consider a partially different design. The general idea is to recreate a situation where a structure generating a large amount of pedestrian flow is connected to another point attracting it (like a train station and a stadium for example). It is often the case that different direct paths are connected each other's by smaller transverse routes which allow to change path in case of congestion.

In simulations, it is convenient to consider a loop, which allows to recreate an infinite path. We can therefore assume a loop consisting of two paths: an inner route and an outer route. Both paths get connected in two opposite locations where pedestrians may move from one path to the other in case of need. A schematic representation of the scenario considered for this study is given in Fig. 1(a).



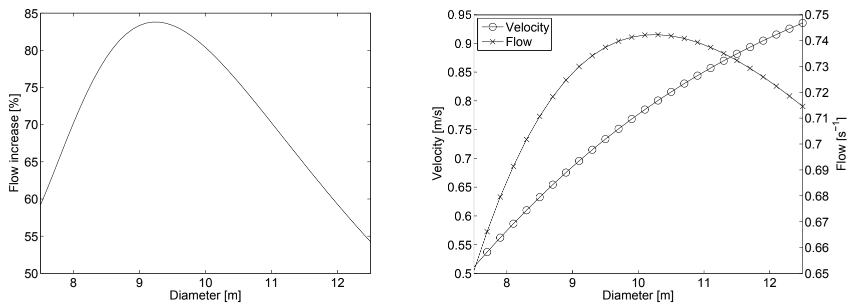
(a) Scenario configuration (b) Fundamental diagram [6]

Fig. 1. Scenario considered for the simulation and fundamental diagram for pedestrian unidirectional motion. Chosen values are: $d = 10$ m and $w = 0.8$ m.

Now, in order to enforce the need for crowd control it is necessary to choose initial conditions which will either require an action from the crowd to avoid congestion or an external intervention. We can further assume that in the locations where lane change is allowed, pedestrians either decide to change by themselves or are forced by guidance personnel present on-site (supervisors).

To choose the best initial configuration it is necessary to consider the fundamental diagram for pedestrians, which is presented in Fig. 1(b) using data from the literature by Jelic et al. [6]. Given the diameter of the loop, the width of both paths and the number of pedestrians for each route in the initial setup it is possible to compute the flow. By selecting a very different number of pedestrians between the inner and outer loop the total flow will be lower than the optimal flow reached when density is uniform everywhere (given in Fig. 2(b)).

To create a realistic scenario which could possibly be reproduced experimentally in the future, a crowd of 60 people is chosen. Fig. 2(a) shows the ratio between the total initial flow and the optimal flow for a starting configuration having 50 people in the inner loop and 10 people in the outer one (both figures



(a) Optimal/initial flow gain (b) Optimal conditions

Fig. 2. Optimal conditions (right) and increase in flow relative to the initial configuration (left) for different values of mid-diameter. Both graphs are created using the fitting of the the experimental data by Jelic et al. given in Fig. 1(b).

are chosen to create a large optimal/initial difference). The maximum gain in Fig. 2(a) is found for a diameter of about 9.2 m and consequently we decided to use a mid-diameter (between inner and outer loop) of 10 m. Under these circumstances the optimal speed is about 0.78 m/s (see Fig. 2(b)).

3 Cellular Automata model

The hypothetical scenario presented above has been written into a Cellular Automata simulation model whose characteristics are described in this chapter. To simplify the computational algorithm instead of two loops two horizontal parallel paths have been used. The end of each path is connected with its start so that the endless characteristic of the loops is recreated. Path width was chosen equal 0.8 m with a cell size of 0.4 m. Considering those dimensions and the mid-diameter chosen earlier, the internal and external loops had a length of 73 and 85 cells respectively. Lane change locations have been set at a uniform distance along the mid-path [1].

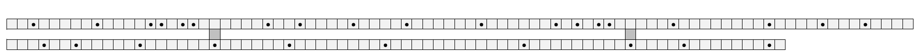


Fig. 3. Computational grid used in the model. Positions for lane change are given in dark gray and pedestrians as dots.

Motion inside each loop is computed based on the Fukui–Ishibashi model [3]. This model was chosen because it allows to reproduce the fundamental diagram

[1] Since inner and outer loop have different lengths, lane change location is not exactly uniformly distributed in the linear representation. On average there is a 6 cells difference between both lane change positions in both loops.

of pedestrian motion with good accuracy and account for its asymmetry in regard to density (see Fig. 1(b)). In addition, its rules for position update are rather simple, thus allowing more flexibility in adding more important aspects specific for this study.

In the Fukui–Ishibashi model, particles (or pedestrians in this case) can proceed for a maximum of u_{max} cells with a hopping probability $p = (0, 1]$ if they have at least u_{max} empty cells in front. If the empty space is less than u_{max} cells, they will proceed as many cells as possible with the same hopping probability p. In this study $u_{max} = 2$ and $p = 0.85$ have been taken to fit with the experimental fundamental diagram found in the literature.

In our analysis we will always consider long time intervals (several hours) to generate results. Under this assumption, it is possible to use the following equation to get a velocity expressed in physical units which can be useful to quickly evaluate the results:

$$V = \frac{X}{S \cdot N} \cdot \frac{v_{free}}{p \cdot u_{max}} \tag{1}$$

In (1) X is the total distance traveled by all pedestrians (in cells), N is the number of pedestrians (60 here), S is the total number of simulation time steps and v_{free} is the free walking speed (set at 1.20 m/s here).

The time step has been chosen considering that the maximum distance traveled by one person in one time step is stochastically given by $\Delta x \cdot u_{max} \cdot p$ with Δx being the mesh length. Considering the free walking speed and the numerical values provided earlier, the time step can be computed as:

$$\Delta t = \frac{\Delta x \cdot u_{max} \cdot p}{v_{free}} = 0.57 \text{ s} \tag{2}$$

Parallel update is used for computing positions at each iteration, i.e. pedestrians reserve their position before actually moving and conflicts (which occur only when changing loop) are resolved with equal probability among contenders.

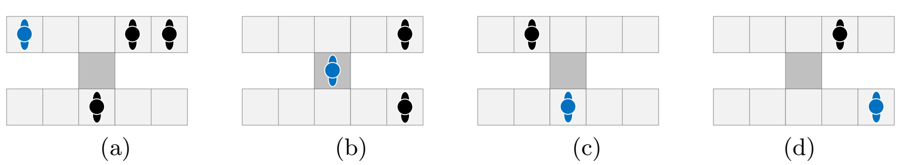


Fig. 4. Example for a lane change from outer to inner loop. Pedestrian considered is given in blue (dark gray). Images from (a) to (d) are in sequential order.

An additional important aspect in the dynamics of the model are the rules used for lane change. A pedestrian is allowed to change lane when he/she is at a distance of one or two cells from the lane change position (remember that pedestrians are allowed to move a maximum of two cells per iteration). If the cell used for lane change is empty he/she is allowed to move to that location and later enter the opposite loop. If the central cell is occupied he/she will have to keep moving and may have a chance to change loop at the next location. Fig. 4 shows an example for a pedestrian moving from the outer to the inner loop. In all the cases, lane change results in a slowdown (in particular when entering the new loop) as it should be in the real case.

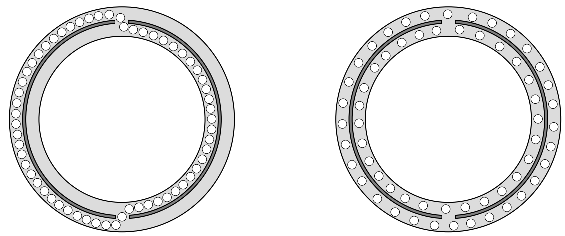
In our model, we assume that each lane change position is supervised, i.e. switching direction (move to inner or outer loop) is given by the corresponding supervisor. We further assume that pedestrians can be compliant (i.e. will follow any order given) or non-compliant (ignore orders). Compliant ratio is the ratio of compliant pedestrians over the total number. Finally, we assume that a variable portion of pedestrians have access to reliable information (informed pedestrians), i.e. they know the walking speed for each loop. In practical terms, we can consider those people as having access to navigation systems or paying attention to information given in monitors along the path. Informed ratio is the number of informed pedestrians over the total.

Under those assumptions lane change for a given pedestrian may occur under the following conditions:

- *The pedestrian is compliant.* If a lane change is ordered he/she will move to the loop indicated by the corresponding supervisor. Non-compliant pedestrians can ignore those orders and follow their own intuition as given below.
- *The pedestrian is non-compliant.* If that pedestrian has information on the speed in both loops (informed pedestrian), he/she can decide to move based on a rational decision (i.e. he/she will choose the fastest one if the difference is larger than 0.1 m/s). All pedestrians are able to remember the walking speed for the last 10 s. Consequently, non-informed pedestrians can decide to change loop by comparing their recent walking speed with the one of the opposite loop when the lane change position is reached. If the other lane is faster they will move in it.

To account for the effects of crowd control, different strategies has been used to determine how supervisors give information to pedestrians in each lane change location. The three scenarios considered here are listed as follow:

- *Worst-case scenario:* each supervisor has a limited field of view (90 degrees) and take decisions by his/her own. Order for lane change will be issued so that both lanes have the same number of pedestrians. This quickly leads into a long lane taking half of the inner and half of the outer loop (see Fig. 5(a)).
- *Best-case scenario:* each supervisor has a complete overview (360 degrees) of the area and knows the density in each loop. In addition, both will work together until the density difference between both loops is below 0.05 m^{-1}. The final outcome will be something like the case shown in Fig. 5(b).
- *Realistic scenario:* each supervisor has a limited view (again 90 degrees) but both are communicating with each other's considering a communication delay of 2 s and a reaction time before acting of 3 s (this "reaction time" also includes the decision making process, hence the relative long time used).



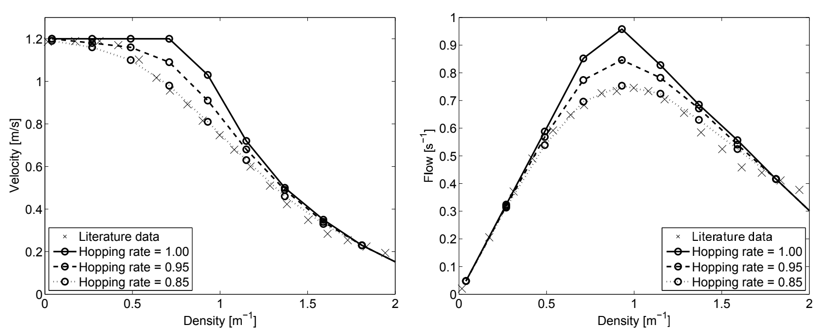
(a) Worst-case scenario (b) Best-case scenario

Fig. 5. Typical results for different crowd control strategies.

4 Results

Using the model presented above a number of simulations have been run by changing the compliant ratio, the number of people informed and the crowd control strategy. Starting condition for each simulation has been of 50 people in the inner loop and 10 in the outer loop, mid-diameter has been chosen of 10 m. Average overall speed has been used as a parameter to calibrate and validate the model and to measure the efficacy of crowd control strategies and information provision.

4.1 Validation of fundamental dynamics



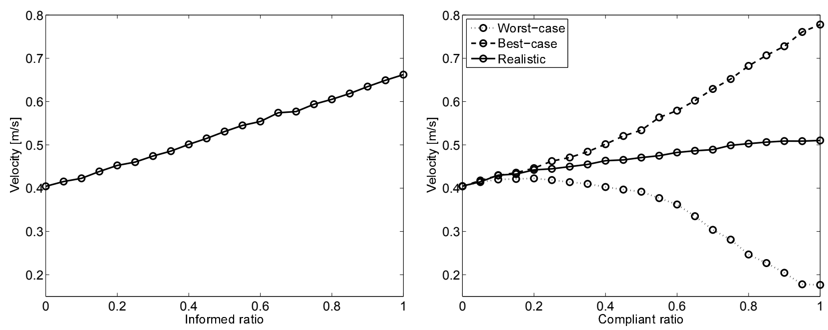
(a) Speed – density (b) Flow – density

Fig. 6. Comparison between experimental fundamental diagram from literature [6] and numerical results obtained using the Fukui–Ishibashi model.

First of all, in order to find the most appropriate parameters and check the validity of the Fukui–Ishibashi model used for the dynamics of pedestrians, we run a number of simulations for the simplest case, i.e. without loop change and with the same density in both loops. Results for different values of hopping probability are given in Fig. 6. Each simulation has been run for a corresponding time of one hour. In general, a fairly good agreement is found for a hopping probability of 0.85 for the whole range of densities considered in this study (a maximum of 1.76 m^{-1} is found when all the 60 people are in the inner loop).

4.2 Effect of information provision and compliance

We can now consider the case where it is possible to change lane and those locations are supervised by crowd control personnel. Results for simple situations considering information provision and compliance *separately* are given in Fig. 7. To study information provision, we assumed that pedestrians are free to choose (in other words all are non-compliant and crowd control strategy is irrelevant), while for compliance we assumed a completely non-informed crowd.



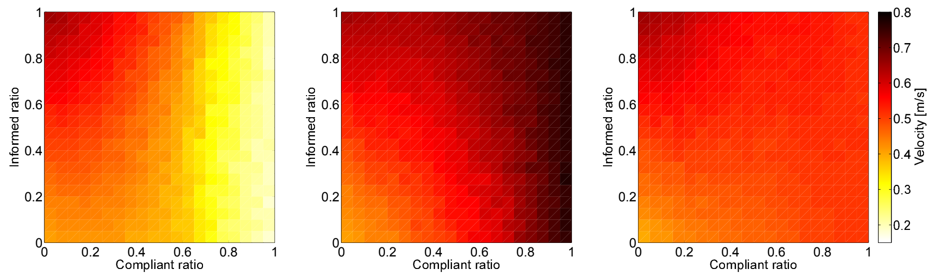
(a) Information provision (b) Compliance

Fig. 7. Simple effect of information provision and compliance on the speed of the crowd for different crowd control strategies.

From Fig. 7(a) it is seen that information provision has a linear effect on the overall speed of the group. The more people are informed the faster the crowd moves. The relation with compliance clearly depends on the strategy used for crowd control, with the realistic case lying between both extreme scenarios. In general, compliance has a slightly non-linear relationship, which becomes more evident for high level of compliance.

4.3 Combined effect and relation with crowd control

Finally, we wish to consider the effect of compliance and information provision *together* and see how this may affect the overall speed of the group in regard to the different crowd control strategies presented earlier. In this regard, both the compliant and the informed people ratio have been varied for the three crowd control strategies generating the three diagrams shown in Fig. 8. A variable number of 10 to 40 one-hour simulations were run to generate each dot.



(a) Worst-case (b) Best-case (c) Realistic

Fig. 8. Influence of compliance and information provision on the overall speed of the group considering three different crowd control strategies. Color scale is the same for the three cases and is given on the right.

In the worst-case scenario it is clearly seen that when compliance is high pedestrians are at the mercy of supervisors, who, by failing in their control strategies, contribute to considerably slowing down the whole crowd. When compliance is low (and pedestrians are basically free to choose) then information provision plays a more important role and the maximum speed is found for the non-compliant case where everyone is informed. It is important to notice that in the worst-case scenario difference between minimum and maximum speed is large (around 0.50 m/s) and the optimal speed is never reached.

The best-case scenario shows the opposite result compared to the previous case. The maximum speed, which is equal to the optimal one in this case, is found for fully compliant crowds. In this case, compliance seems to play a minor role when all people are informed, making the upper part of Fig. 8(b) almost constant. In the best-case scenario speed difference is lower than the previous case (0.37 m/s), showing that optimal crowd control strategies benefit in all conditions.

Finally, we can consider the realistic case, whose result is a sort of average between the worst-case and best-case scenario. As for the previous cases, speed is obviously constant along the full-compliant line. In this case, it is however interesting to notice that the non-compliant informed case has an higher speed (0.72 m/s) than the compliant uninformed case (0.55 m/s). Overall, the three cases show that having an informed crowd is more important than focusing on crowd control and compliance. While only a small improvement is found in the best-case scenario, differences get easily larger as the crowd control strategy fails.

5 Conclusions

In this study, a hypothetical scenario where both pedestrians' compliance and information provision have an impact on the overall performance of the system has been presented and studied through a Cellular Automata simulation model. Results clearly showed that when compliance is high, the crowd control strategy has a dramatic effect on the overall system and the advantages of having an informed crowd are nullified. On the other hand, having an informed crowd represents the best tradeoff, guaranteeing that even when crowd control is not optimal, good results in terms of crowd dynamics are obtained. Results also show that in case of a complete failure of crowd control an informed not-compliant crowd may still represent the best outcome given the worst-case condition.

Although the case studied here is very simple and more research need to be done on the subject by also considering more in detail decision making for large crowds, results may suggest that, when a choice is needed, informing a crowd should be prioritized on enforcing organizers' decision, especially when the outcome of crowd control is uncertain.

Acknowledgments

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