
TRANSPORTATION SCIENCE

TRANSPORTATION SCIENCE
Vol. 39, No. 1, February 2005, pp. 1–24
ISSN 0041-1655 | EISSN 1526-5447 | 05 | 3901 | 0001

DOI 10.1287/trsc.1040.0108

Self-Organized Pedestrian Crowd Dynamics: Experiments, Simulations, and Design Solutions

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To test simulation models of pedestrian flows, we have performed experiments for corridors, bottleneck areas, and intersections. Our evaluations of video recordings show that the geometric boundary conditions are not only relevant for the capacity of the elements of pedestrian facilities, they also influence the time gap distribution of pedestrians, indicating the existence of self-organization phenomena. After calibration of suitable models, these findings can be used to improve design elements of pedestrian facilities and egress routes. It turns out that "obstacles" can stabilize flow patterns and make them more fluid. Moreover, intersecting flows can be optimized, utilizing the phenomenon of "stripe formation." We also suggest increasing diameters of egress routes in stadia, theaters, and lecture halls to avoid long waiting times for people in the back, and shock waves due to impatience in cases of emergency evacuation. Moreover, zigzag-shaped geometries and columns can reduce the pressure in panicking crowds. The proposed design solutions are expected to increase the efficiency and safety of train stations, airport terminals, stadia, theaters, public buildings, and mass events in the future. As application examples we mention the evacuation of passenger ships and the simulation of pilgrim streams on the Jamarat bridge. Adaptive escape guidance systems, optimal way systems, and simulations of urban pedestrian flows are addressed as well.

Key words: pedestrian crowd dynamics; panic behavior; evacuation dynamics; granular flow; self-organization
History: Received: December 2003; revision received: November 2004; accepted: November 2004.

1. Introduction

Designing pedestrian facilities is an art, as it is not enough that they should look pleasant. User-friendly solutions also require efficient flows, in particular when many people meet at one place. Typical examples are airport terminals, stadia, or theaters. These have to meet safety concerns as well. Crowd stampedes, for example, are nowadays still a problem. Within the last 100 years, they have caused 4,000 fatalities and 10 times that many serious injuries. Even within the last 10 years, more than 600 people died in panic situations. Hence, despite increased safety standards, the overall situation has not improved. Although the average number of victims per panic event seems to decrease, their total number increases with the frequency of mass events.

Since 1945, more than 30 large crowd panics have occurred, in which more than 1,000 people were killed and at least 3,400 were seriously injured. In 2001 there were two major crowd stampedes in soccer stadia of South Africa and Ghana, with over 160 fatalities. Even in the United States, dozens of people died in 2003 due to crowd panics in night clubs in Rhode Island and Chicago. In Japan, pedestrians were crushed on a bridge in 2004 due to dense counterflows, and the Jamarat bridge has experienced several sad accidents in the past. Moreover, a rock concert in Moscow was hit by a suicide attack in 2003, and crowded tourist sights have been a favored target of terrorists in recent years.

In many instances, the victims' fatalities or injuries were not caused by fire, explosions, poisonous gas,

Figure 1 **Panicking Soccer Fans Trying to Escape the Football Stadium in Sheffield**

Note. Hardly anybody manages to pass the open door, because of the clogging effect occuring at high pressures.

or other external hazards, but by the behavior of the crowd itself. The reasons for crowd stampedes are various: Apart from *real hazards* (such as the fire in the stadium of Bradford, 1985; or during the Great White concert in Rhode Island, 2003); one should mention *fans forcing their way* into a stadium or over barriers (Santiago, 1955; Cairo, 1974; Cincinnati, 1979; Mexico City, 1985; Sheffield, 1989, with 96 fatalities; Guatemala, 1986, with 80 fatalities; Monrovia, 2000; Johannesburg, 2001, with 43 fatalities); a *nonvalued goal* (Lima, 1964, with 318 fatalities); an outage of power supply (Nigeria, 1979); *pushy fans* leaving a stadium (Piraeus, 1981); provocations and *aggressions* by drunken fans or hooligans (Cali, 1982; Orkney, 1991; Brussels, 1985, with 38 fatalities); return of leaving fans after a *last-minute goal* (Moscow, 1982, with 340 fatalities), fans fleeing a *rain or hail storm* (Katmandu, 1988, with 93 fatalities; Minsk, 1999, with 51 fatalities; Addis Ababa, 2000), *overcrowding* (Mecca, 1990, with 1,425 fatalities; New York, 1991; Düsseldorf, 1997; Mecca, 2000); a *gun shot* (Las Vegas, 1997); *competition* of people for seats, jobs, or housing (Harare, 1998; Manila, 1998); or the use of *tear gas* (Lima, 1998; Durban, 2000; Lisbon, 2000; Harare, 2000; Ghana, 2001, with 126 fatalities; Chicago, 2003).

Therefore, a huge crowd can turn into a deadly hazard not only in an actually life-threatening situation

Figure 2 **Illustration of Typical Problems During Crowd Stampedes**

Notes. Top: The pressure in the crowd raises up to a painful and potentially lethal level. It can bend steel barriers. Bottom: Panicking people trample on others and are piled up one on top of each other.

(Waldau 2002), but also rather unexpectedly. In stampedes, the crowd starts pushing to get ahead faster. However, the people instead obstruct each other, and clogging effects may occur at exits and other bottlenecks (see Figure 1). Shock waves emerge in the crowd (Virkler and Elayadath 1994), and people may be crushed by the high pressure building up in the crowd (see Figure 2). When people lose their balance and fall down, the mass tramples them, as the pushing crowd is not controllable. The injured people may turn into obstacles for others, which can produce piles of fallen people (see bottom photographs in Figure 2). This urgently calls for particular architectural design solutions that can reduce the potential hazards during mass events and increase the safety of heavily frequented buildings.

2. Objectives, Related Literature, and Organization of the Paper

The aim of this paper is to develop some design elements that allow the increase of the efficiency and safety of pedestrian facilities (see §5). For their assessment, it is important to have a simulation model that describes the observations well. We will show that the "social force model" is a suitable approach (see §4). It is capable of reproducing the various emergent self-organization phenomena in pedestrian crowds, which have been overlooked for a long time. These turn out to be essential for the optimization of pedestrian flows, as they determine their efficiency (i.e., their average speed compared to the desired one) and potential sources of obstructions. In §3, we will discuss previous empirical observations and present new experimental results on self-organization phenomena at typical elements of buildings and pedestrian facilities, i.e., corridors and egress routes, staircases, entrances, exits, and intersections. It is, however, reasonable to start with a short discussion of the pedestrian literature.

Pedestrian crowds have been empirically studied for more than four decades now (Hankin and Wright 1958). Therefore, it is impossible to present a complete list of pedestrian literature here. However, a rather extensive summary of the state of the art of pedestrian and panic research was recently given (Helbing et al. 2002).

Probably the earliest systematic approach to the comfort and safety of pedestrian facilities was the *level-of-service concept* by Fruin (1971). Publications on *design elements* have a long tradition as well (Schubert 1967; Boeminghaus 1982; Pauls 1984; Whyte 1988; Helbing 1997; Helbing et al. 2001). A similar thing applies to *planning guidelines* (Kirsch 1964; Predtetschenski and Milinski 1971; Transportation Research Board 1985; Davis and Braaksma 1988; Brilon, Großmann, and Blanke 1993). However, the latter usually have the form of simple *regression relations*, which are not very well suited for the prediction of pedestrian flows in pedestrian zones and buildings with an exceptional architecture, or in extreme conditions such as evacuation (egress).

None of the above concepts adequately takes into account the self-organization effects occurring in pedestrian crowds (see §3), although these may lead to unexpected obstructions due to mutual disturbances of pedestrian flows. The discussion of these phenomena goes back to Helbing (1991, 1992b, c) and has recently been pursued by many researchers in the traffic sciences, physics, and biology. Meanwhile, more than 50 references are available on this subject.

Many self-organization phenomena had been discovered by the study of quick-time movies of pedestrian streams, but a quantitative evaluation was not possible at that time. Therefore, many results have been gained by computer simulation based on microsimulation models such as the social force model (Helbing 1991, 1992a, 1995; Helbing and Molnár 1995, 1997). There is still a lack of quantitative experimental studies, but the experimental basis has improved through the availability of cheap video technology and development of picture analysis software (Yin, Velastin, and Davies 1995; Masoud and Papanikolopoulous 1997; Antonini et al. 2004; Rigoll, Eickeler, and Yalcin 2000; Teknomo 2002; Teknomo, Takeyama, and Inamura 2000) and infrared detectors (Armitage et al. 2003). Recent empirical studies of pedestrian flows address:

- the evacuation of passenger ships (Yoshida, Murayama, and Itakaki 2001; Meyer-König, Klüpfel, and Schreckenberg 2002; Keßel et al. 2002) and classrooms (Klüpfel, Meyer-König, and Schreckenberg 2003; Helbing et al. 2003),
- the investigation of pedestrian speeds and flows on escalators and staircases (Xiang, Wai, and Chor 2003),
- the study of pedestrian movement characteristics at signalized intersections (Akcelik 2001; Das, Manski, and Manuszak 2004),
- the investigation of herding phenomena (Isobe, Helbing, and Nagatani 2004; Murakami et al. 2002), and
- the identification of rules of pedestrian behavior (Willis et al. 2000) and characteristic patterns of walking behavior (Johnson 2002; Daamen and Hoogendoorn 2002, 2003a, b).

The experimental investigation of crowd stampedes, however, is still a problem, as most experiments are too dangerous to perform. Nevertheless, a few empirical studies are available for the escape from fires and football stadia disasters (see, e.g., Keating 1982; Canter 1990; Jacobs and 't Hart 1992; Elliott and Smith 1993). With some exceptions, panics are observed in cases of scarce or dwindling resources (Mintz 1951; Keating 1982), which are either required for survival or anxiously desired. They are usually distinguished into escape panics ("stampedes," bank or stock market panics) and acquisitive panics ("crazes," speculative manias) (Miller 1985; Coleman 1990), but in some cases this classification is questionable (Johnson 1987). For a more detailed discussion of crowd panics in buildings, see Waldau (2002).

It is often stated that panicking people are obsessed by short-term personal interests uncontrolled by social and cultural constraints (Keating 1982; Miller 1985). This is possibly a result of the focused attention in situations of fear (Keating 1982), which also causes alternatives like side exits to be overlooked (Elliott and Smith 1993). Classically, this is attributed to herding behavior due to social contagion (Mintz 1951; Quarantelli 1957; LeBon 1960), i.e., a transition from individual to mass psychology, in which individuals transfer control over their actions to others (Coleman 1990), leading to conformity (Bryan 1985). Recent biological and medical studies, however, underline the role of physiological factors such as hormones in the change of human perception and reaction in situations of stress (Gonzales 2003; Hans 2003).

3. Self-Organization in Pedestrian Crowds: Experiments and Observations

Under certain conditions, pedestrian flows form collective patterns of motion such as

- shock waves in dense crowds,
- lanes of uniform walking directions in pedestrian counterflows,
- circulating flows at intersections,
- clogging effects or oscillatory flows at bottlenecks.

These can be understood as self-organized phenomena and will be discussed in detail later. Self-organization means that these patterns are not externally planned, prescribed, or organized, e.g., by traffic signs, laws, or behavioral conventions. Instead, the spatiotemporal patterns emerge due to the nonlinear interactions of pedestrians. These interactions are more reactive and subconscious than based on strategical considerations or communication; otherwise, they could not be reproduced so well by simple simulation models like the one proposed in §4.

3.1. Method of Investigation

Early investigations of self-organization phenomena in pedestrian crowds have been based on qualitative empirical observations and simulation studies. These include

(1) bidirectional pedestrian streams in corridors or alleys (Helbing 1991, 1997; Helbing et al. 2001),

(2) four intersecting pedestrian streams with and without guidance through obstacles and railings (Helbing 1997),

(3) the movement of pedestrians through a waiting crowd (Helbing 1997; Helbing and Molnár 1997),

(4) the escape of students from a room with a narrow exit, without pushing (Helbing et al. 2003), and

(5) the escape of disoriented people from a room (where some effects of dense smoke or an outage of power supply were imitated by wearing eye masks; Isobe, Helbing, and Nagatani 2004).

To get a more quantitative picture, we have recently performed video-based experiments. Based on a frame-by-frame analysis of video recordings, we have determined the passing times of pedestrians at certain cross sections and the related time headway (gross time gap) distributions for the following situations:

(6) uni- and bidirectional pedestrian streams in corridors with and without bottlenecks,

(7) two intersecting pedestrian streams, and

(8) pushy pedestrians rushing toward an exit with and without an obstacle in front of it.

Time gap distributions have also been investigated in a study by Hoogendoorn, Daamen, and Bovy (2003), which focuses on unidirectional pedestrian streams through bottlenecks of varying width.

For Scenarios 6 and 7, our experiments have been carried out with about 100 college students. Their average age was around 18 years. The students did not know anything about the spatiotemporal patterns we were studying. They were only familiarized with the experimental setup (i.e., the respective geometrical configuration), namely where they had to enter and how they had to return to maintain a continuous pedestrian stream (see Figures 4–8), but they did not have any knowledge about the goal or expected outcome of the experiments. The students were asked to walk at their comfortable speed and to behave naturally. Therefore, their speed resulted from the obstructive interactions among them. Recordings were made from about six-meter height, with two cameras installed above the experimental setup, one operating with a normal lens (focusing on the main interaction area) and another one operating with a wide-angle lens (recording the overall scene).

The panic-like Scenario 8 was recorded with three cameras: one in front of the exit, another one in the back, and the third one on top of the exiting crowd. The participating students were, on average, about 23 years old and were asked to rush toward the exit of 82 cm width when an accoustical signal was given. In contrast to another experiment performed with Japanese students (Helbing et al. 2003), the test persons started with approximately the same distance from the door and were supposed to force their way out of the room as fast as possible. In this manner, we

Figure 3 Representative Photographs of Lanes Formed in Bidirectional Pedestrian Streams (Left: London, Right: Budapest)

tried to imitate a panicking, pushy crowd of people. As this setup is potentially dangerous when too many people participate in it, we restricted ourselves to between 18 and 22 students altogether. Nevertheless, the results remind very well of the observations made during real escape panics (see Figure 1).

Problems in pedestrian crowds typically arise due to counterflows, bottlenecks, or intersecting flows. Entrances and exits, pressure reduction in dense crowds, and orientation are important subjects as well. In the following, we will therefore address some of these central issues of pedestrian dynamics in more detail. We should, however, add a word of caution: It is presently not clear to what extent experiments can reflect pedestrian behavior in real situations, but it is hard to find suitable places allowing one to observe both dense and undisturbed pedestrian flows under the required conditions. These can be best produced with experimental setups, but there are certainly limits to the generalization of the related results. For example, it is known that cultural influences and the composition of pedestrian crowds regarding age, gender, and trip purpose can matter. Daamen and Hoogendoorn (2002, 2003a, b) have tried to generate heterogeneous pedestrian behavior by giving different instructions to test persons. To some degree, the role of these factors can also be studied by microsimulation models with heterogeneous pedestrian parameters (see §§4 and 5).

3.2. Counterflows

Before we discuss our new experimental results, let us summarize the present knowledge about pedestrian counterflows, as this will be required for §5. Under everyday conditions, pedestrians with opposite directions of motion are often not equally distributed over cross sections of the walkway. Instead, one observes the separation of pedestrian counterflows into lanes of uniform walking direction; see Figure 3 (Helbing 1991, 1997; Helbing et al. 2001). This segregation phenomenon reduces the number of encounters with oppositely moving pedestrians, i.e., the interaction frequency and number of necessary braking or avoidance maneuvers. In such a way, the efficiency of walking—i.e., the average velocity in the desired direction of motion—is maximized. Therefore, this phenomenon can be viewed as a prime example of optimal self-organization (Helbing and Vicsek 1999). Interestingly enough, most pedestrians do not have the *intention* to show segregation behavior, nor do they communicate to establish it. It emerges automatically without the need for conscious support.

The number of lanes depends on the width and length of the walkway or corridor, the in- and outflows, the fluctuations and disturbances. The shape of the lanes is time dependent, as in other two-fluid flows (Kadanoff 1985; Stanley and Ostrowsky 1986). If pedestrian crowds moving in opposite directions meet each other (e.g., on a pedestrian crosswalk), they form small *channels* in the beginning, but these channels later merge to produce wider lanes. This phenomenon is related to fluctuation-induced ordering (Helbing and Platkowski 2000, 2002) and reduces the number of interfaces at which the "friction" between opposite directions of motion is high.

In cases of extreme densities, large disturbances, or nervous pedestrian crowds, ordered lanes can break down due to relentless overtaking maneuvers. Then, blocks of pedestrians with opposite desired directions of motion face each other, but cannot progress. This phenomenon is called "freezing by heating" and may emerge in counterflows of panicking pedestrians (Helbing, Farkas, and Vicsek 2000a).

In central Europe, pedestrians have a slight tendency to walk on the right-hand side. Although cars drive on the left-hand side in Great Britain, pedestrians in London tend to stay on the right-hand side as well. In Japan, the left-hand side is preferred, as it is in vehicle traffic. In other countries with right-hand traffic (e.g., Korea), pedestrians are reported to walk on the left-hand side. The preference for one side is a so-called symmetry breaking phenomenon, as both sides are, in principle, equivalent. This symmetry breaking can be explained by the increase in the efficiency of walking when the majority of people favors the same side. Therefore, a behavioral convention will form by means of self-organization. This can be understood by reinforcement learning (Bolay 1998) and by means of a selection-mutation or game-dynamical equation (Helbing 1991, 1995). According to this approach, humans would evade each other with probability 1/2 to the right and to the left in the beginning. However, when the frequency of usage of both sides would become somewhat unbalanced for some reason, or at random, it would be advantageous to join the more frequent behavior. In the end, the great majority would use one strategy. According to this theory, it is expected that different preferences emerge in different regions, as is actually observed.

We have now carried out several experiments for a corridor with bottlenecks to compare the effect of pedestrian counterflows and unidirectional flows. The setup of the experiments is sketched in Figures 4–8. Our approximately 100 test persons were flowing back into the system after they had left the corridor. As the boundaries were formed by tables rather than walls (implying that the effectively used width corresponded approximately to the actual width), and as the age distribution was not representative for an average population, we will not discuss *absolute* values of pedestrian flows over here. Instead, our conclusions are based on *relative* flow values and the *relative* variation of time headways for different setups, which we expect to be significant for experiments with other boundaries and other age groups as well.

Let us compare the average flow values of the experiments sketched in Figures 4 through 8, which are listed in Table 1: The first unexpected effect is that counterflows are significantly more efficient than unidirectional flows. Although this is rather surprising, it is consistent with observations by AlGadhi, Mahmassani, and Herman (2002). The reason for this increase in capacity is probably the better coordination between people who meet each other in opposite directions, as they can react to each other (Goffman 1971). In contrast, in unidirectional streams, pedestrians do not sufficiently react to what happens behind them (Helbing and Molnár 1995). This causes conflicts (e.g., suppressed overtaking maneuvers) and coordination problems, which reduce the efficiency of motion.

3.3. Bottlenecks

If there were no bottlenecks, the opposite flows would be about the same and the passing times at cross sections of the corridor would be regularly distributed (see Figure 8). This is also confirmed by the values given in Table 1, which indicates a small relative standard deviation $\sigma_i/\overline{T}_i \approx 0.24$ of the time headways (see Figure 9).

In contrast, in experiments with bottleneck areas, we have observed mutual obstructions and perturbations. These perturbations are reflected by a more irregular flow in the bottleneck area, i.e., the relative standard deviation of the time intervals between successive passings of a measurement cross section is more than doubled (see Figures 10 and 11). This reduces the pedestrian speed and flow at the bottleneck (see Table 1). Long bottlenecks seem to be worse than local obstructions.

If the opposing flows interrupt each other at a narrow bottleneck, we find irregular oscillations of the

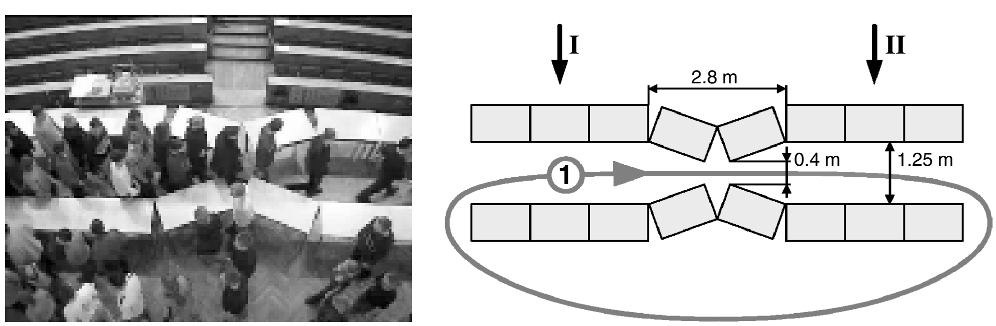

Figure 4 Snapshot (Left) and Sketch (Right) of the Experiment with Unidirectional Pedestrian Streams Passing a Short Bottleneck
Note. The tables were of the size 120 cm × 60 cm.

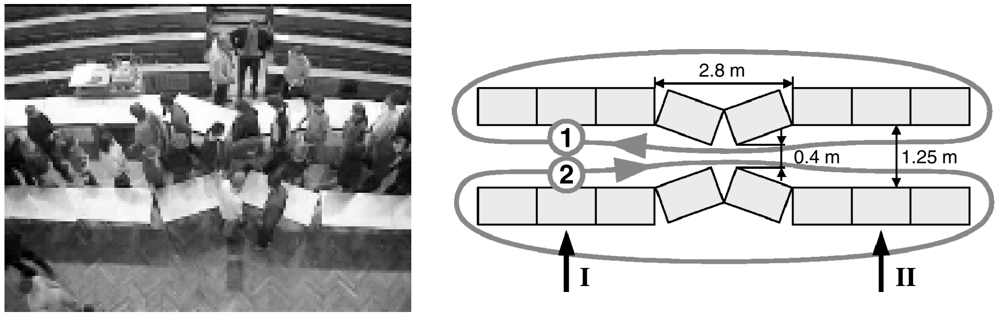

Figure 5 **Photograph (Left) and Schematic Illustration (Right) of an Experiment with Pedestrian Counterflows in a Corridor with a Short Bottleneck**

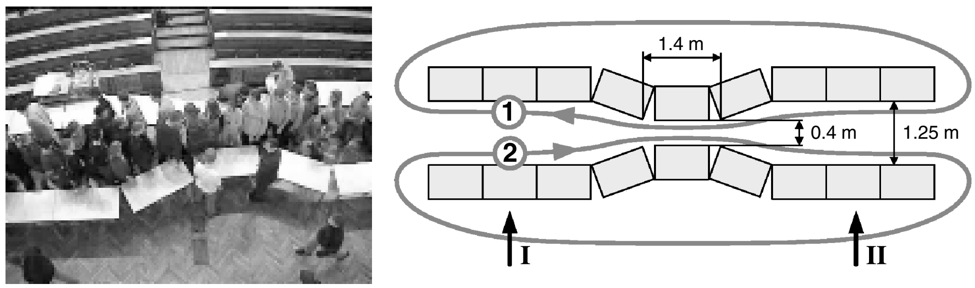

Figure 6 **Snapshot (Left) and Schematic Illustration (Right) of a Pedestrian Counterflow Experiment in a Corridor with a Long Bottleneck**

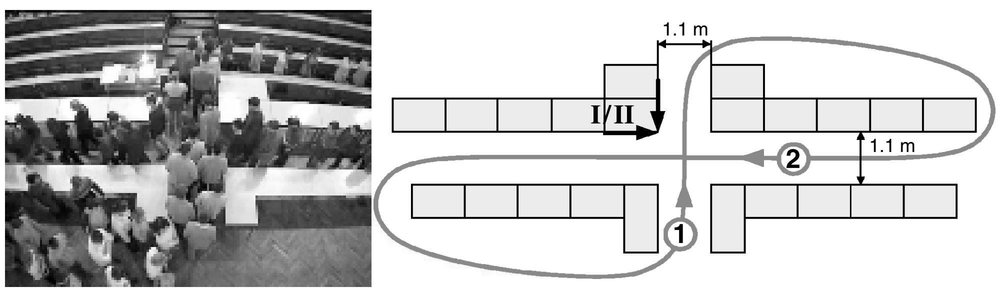

Figure 7 **Snapshot (Left) and Schematic Illustration (Right) of the Intersection of Two Perpendicular Pedestrian Streams**
Note. The majority of tables were of the size 120 cm × 60 cm.

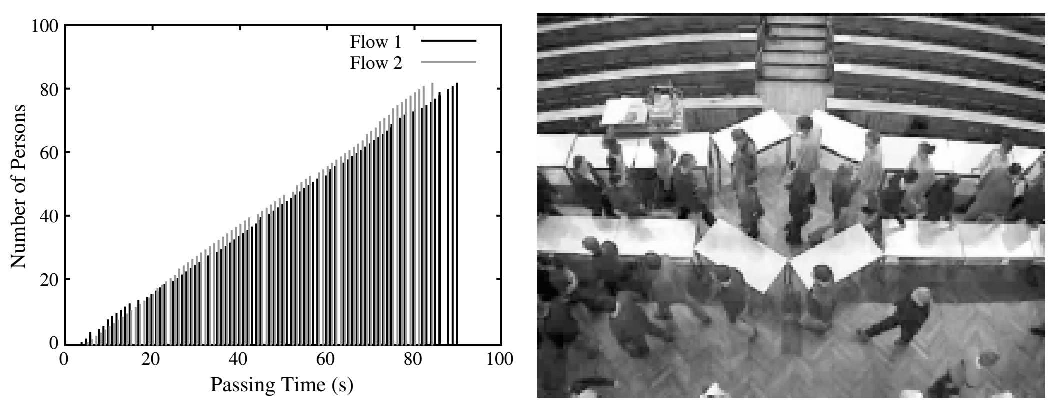

Figure 8 **Passing Times and Number of Passed Pedestrians (Left) at a Typical Cross Section of a Corridor Without Narrowings (Right)**
Notes. The two opposite flow directions are represented by different shades. The distance between successive bars of the same shade corresponds to the time headway between pedestrians moving in the same direction, while the slope defined by the top ends of the bars determines the pedestrian flow (the number of passing pedestrians per unit time).

Table 1 **Comparison of Average Flow Values of the Experiments in Figures 4 Through 8**

Scenario	Section	Q	$Q_1:Q_2$	$\overline{T}_1$	$\sigma_1/\overline{T}_1$	$\overline{T}_2$	$\sigma_2/\overline{T}_2$
Figure 4	I	72	140 : 0	0.832	0.708	—	—
Figure 4	II	67	140 : 0	0.884	0.445	—	—
Figure 5	I	87	71 : 69	1.321	0.616	1.362	0.443
Figure 5	II	90	70 : 70	1.338	0.448	1.331	0.418
Figure 6	I	72	72 : 68	1.532	1.001	1.633	0.581
Figure 6	II	68	69 : 71	1.637	0.805	1.563	0.780
Figure 7	I/II	96	69 : 71	1.242	0.740	1.163	0.713
Figure 8	I	115	69 : 71	1.047	0.209	0.974	0.240
Figure 8	II	112	69 : 71	1.061	0.221	1.017	0.277

Notes. Overall flow Q (pedestrians/min) measured for 140 test persons, relative share of the flow directions $Q_1:Q_2$, mean value $\overline{T}_i$ of the time headways T (s) in flow i, and relative variation $\sigma_i/\overline{T}_i$ of time gaps at two measurement cross sections I and II.

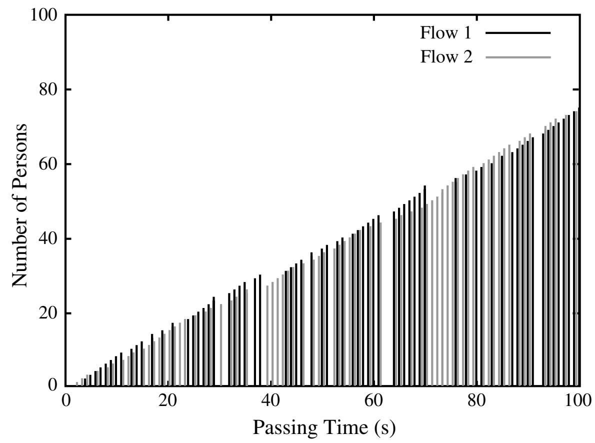

Figure 10 **Compared to the Flow Through a Corridor Without Narrowings (See Figure 8), the Pedestrian Flow After a Short Bottleneck Is Less Regular Due to Oscillations in the Passing Direction**

Note. Pedestrians of the same direction of motion have a slight tendency to cluster.

passing direction. This is reflected by the large variation in the time gaps of successive pedestrians (see Figures 12 and 13). The oscillation effect is more pronounced for longer bottlenecks (see Table 1), which have smaller oscillation frequencies (cf. Figures 10 and 11). Typically, it is groups of people rather than single individuals who pass the bottleneck from one side to the other before people from the other side have a chance to pass the bottleneck. As in the lane formation phenomenon, it is easier to follow someone than to move against an opposing stream. The resulting stream of people releases the pressure in the pedestrian crowd on one side, while the pressure on the other side increases, partially due to impatience. If the pressure difference becomes large enough, the unidirectional stream of people is stopped. Then, people from the other side start to occupy and pass the bottleneck.

In situations with bidirectional flows at narrow bottlenecks, their length should be short. Long narrow bottlenecks involve the risk that people try to turn the flow direction, but do not manage to do so. In these situations, the flow at the bottleneck drops significantly or stops completely. As time goes by, pedestrians reduce the distance to their predecessors, which eventually leads to a compression of the waiting crowd (see Figure 14). This psychologically induced queueing behavior can be frequently observed and mathematically described (Helbing 1991, 1992c, 1997; Helbing et al. 2001). The compression in the crowd is related to shock waves that produce the impression that the crowd is moving forward. However, if nobody can pass the bottleneck, impatience increases and people become more and more pushy. At some point in time, they may even start to interact physically, so that higher and higher pressures can build up in the crowd. In extreme situations, this causes

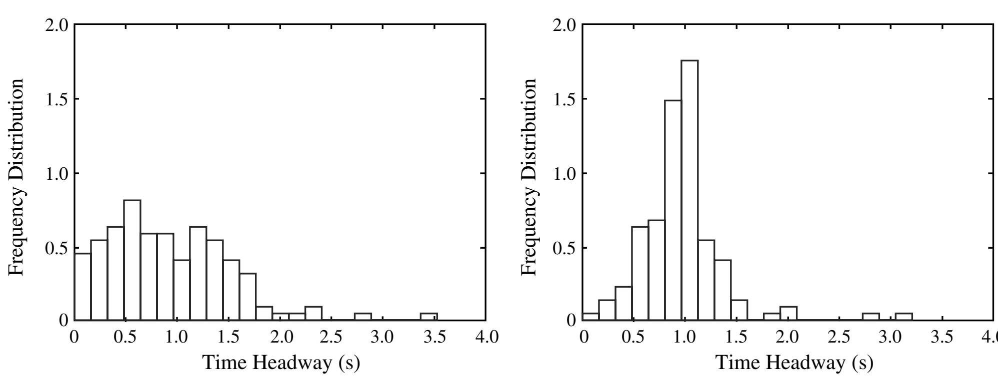

Figure 9 **Time Headway Distributions of Pedestrians in a Unidirectional Stream Before a Short Bottleneck (Left) and After It (Right)**

Notes. The mean values of the inverse time gaps (the flows) are the same before and after the bottleneck (see Table 1). However, due to the interactions in the bottleneck area, the most probable time gap is reduced, and the maximum is more pronounced after the bottleneck (right). The reduced and more regular time gaps may be understood as a sign of condensation or "crystallization" occuring in crowded areas. The geometry of the experiment and the measurement cross sections are illustrated in Figure 4.

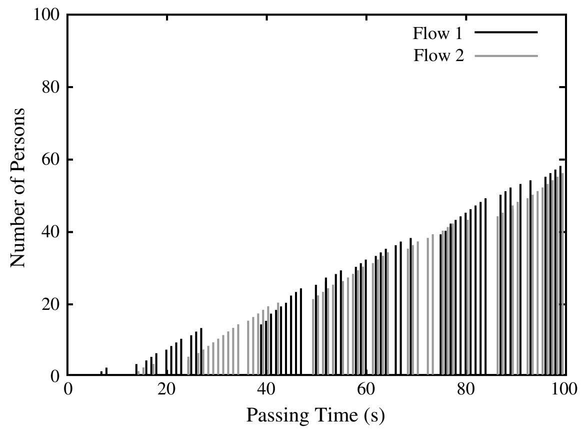

Figure 11 **At Long Bottlenecks, the Oscillations in the Passing Direction Are Significantly More Pronounced Than at Short Bottlenecks (cf. Figure 10)**

Notes. Moreover, the oscillation frequency is lower. There is a high tendency that the bottleneck to be passed by clusters of pedestrians with the same direction of motion rather than by single individuals in an alternating manner.

clogging phenomena due to mutual obstructions, at least temporarily.

In cases of crowd stampedes, clogging can even occur if all pedestrians are heading into the same direction. In Sheffield, for example, fleeing soccer fans did not manage to leave through an open emergency exit because they had seriously obstructed each other (see Figure 1). The same observation has been reported from other places and in the pedestrian literature (Predtetschenski and Milinski 1971). It is also found for granular media such as salt, rice, pills, granulates, or other grains (Ristow and Herrmann 1994; Wolf and Grassberger 1997; To, Lai, and Pak 2000), where clogging phenomena are a well-known problem of industrial filling processes.

Clogging of pedestrians leads to stopped or irregular outflows from a crowded place, as is reflected by the long steps in the curve representing the number of escaped persons as a function of the passing time of the door (see Figure 20). The reasons for this dynamic are finite space requirements of pedestrians and friction effects, when pushy people have physical interactions (Helbing, Farkas, and Vicsek 2000b). The "pressures" building up can reach orders of 1 to 4.5 tons per meter of railing of a wave breaker (Elliott and Smith 1993; Smith and Dickie 1993). This can bend steel barriers (see Figure 2) or tear down brick walls. In such situations, people are frequently crushed or trampled, turning them into obstacles for others. Moreover, the flow of people managing to escape is significantly decreased (Helbing, Farkas, and Vicsek 2000b).

3.4. Intersecting Flows

Intersections of pedestrian streams are one of the biggest problems and are practically unavoidable, as it is uncommon to use bridges for their separation. Let us first discuss what happens when two wide streams intersect. In this situation, the phenomenon of stripe formation has been observed (Ando, Oto, and Aoki 1988). For an illustration, see Figure 15. Like lanes, stripes are a segregation phenomenon, but not a stationary one. Instead, the stripes are density waves moving into the direction of the sum of the directional vectors of both intersecting flows (Dzubiella and Löwen 2002). Naturally, the stripes extend sidewards into the direction that is perpendicular to their direction of motion. Therefore, the pedestrians move forward with the stripes and sidewards within the stripes. This allows the pedestrian streams to penetrate each other in a continuous way, i.e., without having to stop. Lane formation corresponds to the particular case of stripe formation where both directions are exactly opposite. In this case, no intersection takes place, and the stripes do not move systematically. As in lane formation, stripe formation allows minimization of obstructing interactions and maximization of average pedestrian speeds.

We have carried out several experiments with two intersecting flows. Here we restrict ourselves to the

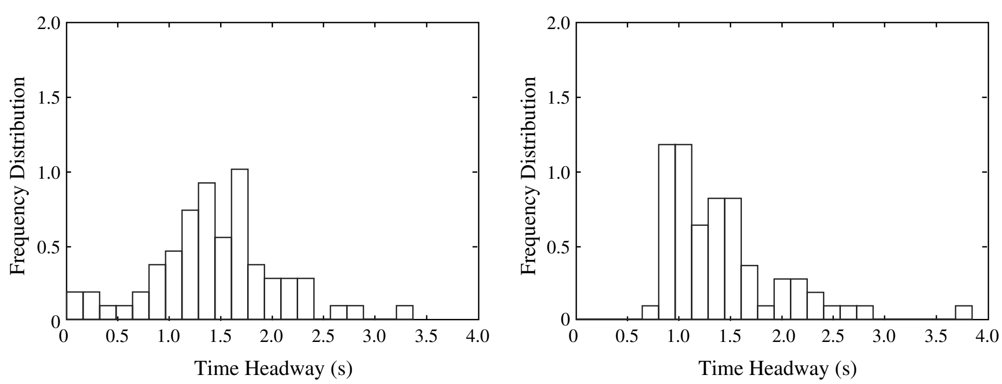

Figure 12 **Time Headway Distributions of Pedestrians in a Bidirectional Stream Before a Short Bottleneck (Left) and After It (Right)**

Notes. For an illustration of the experimental setup, see Figure 5. Compared to unidirectional flows (see Figure 9), the average time gap is smaller, corresponding to an increased flow. Again, the most probable time gap is reduced after the bottleneck as a result of interactions.

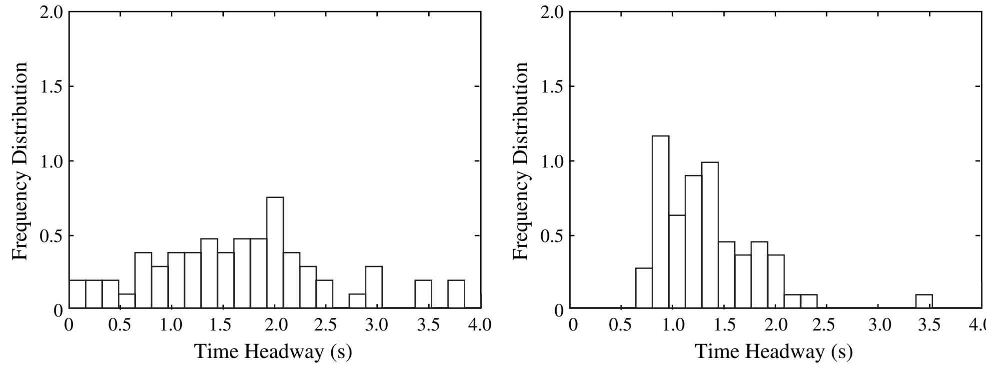

Figure 13 The Time Headway Distribution Is Very Flat Before a Long Bottleneck (Left) and Has a Pronounced Maximum After It (Right)
Note. The measurement cross sections are indicated in Figure 6.

case of a perpendicular intersection, where emerging stripes are expected to have an angle of 45 degrees. Compared to Figure 8, Figure 16 shows a significant degree of irregularity and clustering in the passing times, which indicates the presence of a self-organization effect. These data are compatible with the phenomenon of stripe formation. It is, however, hard to distinguish this effect from the irregular oscillation phenomenon observed at bottlenecks, partly because of the small spatial extension of our experimental system. For narrow and not too dense intersecting flows, one expects, in fact, that small channels are formed through the crossing flow, particularly at places where the density is accidentally lower due to statistical variations. The formation of these channels should be similar to the first stage of lane formation.

Previous investigations for four intersecting flows (Helbing 1997; Helbing and Molnár 1997; Helbing

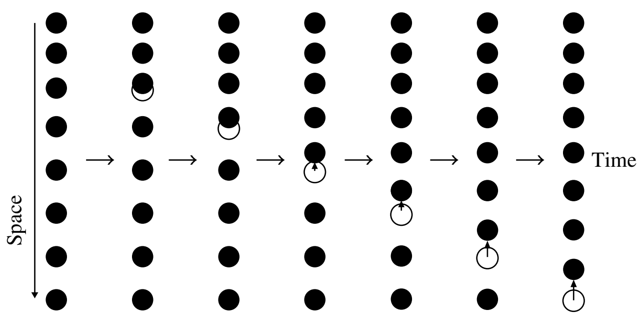

Figure 14 Illustration of the Observed Behavior in a Queue (After Helbing 1992c, 1997; Helbing et al. 2001)
Notes. When the front of a queue (top) is stopped, one can often observe the following phenomenon: After some time, one of the waiting pedestrians begins to move forward a little bit, as the preferred (equilibrium) distance to the pedestrian in front decreases due to impatience (the perceived "pressure of time"). This causes the successor to follow up and so forth, producing a wavelike propagation of the gap to the end of the queue and a compactification of the queue. Thereby, the tendencies of all individuals to move forward a little (in accordance with their steadily decreasing preferred equilibrium distance) add up toward the end of the queue, giving rise to larger and larger following-up distances. A more detailed explanation of this phenomenon considering the minimal length of pedestrian strides is presented elsewhere (Helbing 1991).

and Vicsek 1999) indicate that no stable pattern exists when three or more pedestrian streams intersect. Instead, one observes very short-lived patterns that destroy each other, producing an altogether rather chaotic appearance. These temporary patterns include:

• rotary traffic in a clockwise or counterclockwise direction,
• dominant pedestrian flows in opposite directions with the perperdicular directions waiting, and
• short-lived stripes in one of the four possible diagonal directions.

The steady competition and mutual destruction of these spatiotemporal patterns of motion leads to inefficient pedestrian streams, including temporary blockages.

4. Computer Simulation of Pedestrian Flows with the "Social Force Model"

The various self-organization phenomena described in §3 are good tests for pedestrian simulation models. Any serious evacuation simulation software should be able to reproduce these phenomena, otherwise it will not make reliable predictions. One plausible model, which realistically reproduces these phenomena, is the "social force model." Its underlying modeling philosophy is as follows: Because pedestrians mostly face standard situations, they will usually not make complicated decisions between various possible alternative behaviors. Instead, they will apply opti-

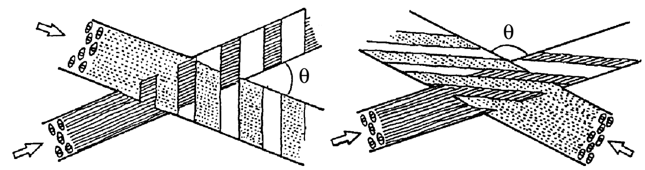

Figure 15 A Characteristic Observation for Two Intersecting Pedestrian Streams Is the Formation of Stripes Perpendicular to the Sum of the Directional Vectors of Both Streams (After Ando et al. 1988)

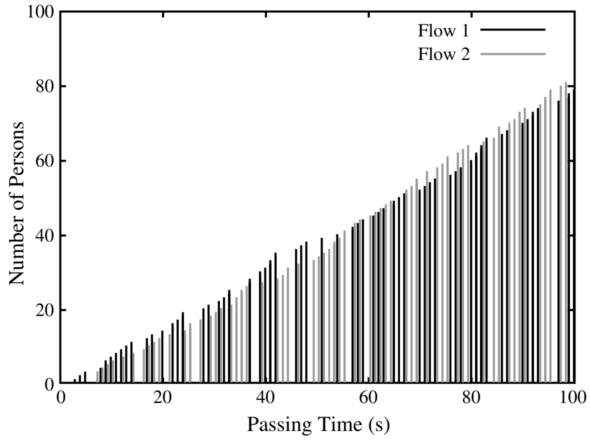

Figure 16 **The Irregularity of Time Gaps at Cross Sections Behind the Intersection of Two Flows (See Figure 7) and the Slight Tendency of Pedestrians of the Same Flow Direction to Cluster Indicate Some Kind of Oscillatory Pattern in Time**

mized behavioral strategies that have been learned in the course of time. Hence, a pedestrian will react to obstacles, other pedestrians, etc., in a rather automatic way. This is comparable to the behavior of an experienced driver, who usually reacts automatically to the respective traffic situation without thinking about the detailed actions to be taken.

The (statically) optimal pedestrian behavior can, in principle, be determined by simulating the learning behavior of pedestrians (Bolay 1998; Helbing et al. 2001). Assuming that pedestrians behave optimally (which is normally a good approximation, but less true for children and tourists), it is possible to predict pedestrian streams with a surprisingly high accuracy. For reliable simulations of pedestrian crowds we do not need to know whether a single pedestrian, say, turns to the right at the next intersection. It is sufficient to have a good estimate of what percentage of pedestrians turns to the right. This can be either empirically measured or calculated by means of a route choice model (Borgers and Timmermans 1986a, b; Hoogendoorn, Bovy, and Daamen 2002). In some sense, the uncertainty about the individual behaviors is averaged out at the macroscopic level of description.

We favor a microsimulation approach to the interactive motion of individual pedestrians, as this is a simple and flexible approach that allows to consider heterogeneous behavior. The "social force model" specifically describes the behavior of pedestrians by a superposition of "generalized forces" reflecting motivations and environmental influences. While the wish to move with a certain desired velocity toward a specific destination is delineated by a driving term, the tendency to keep a certain distance from other pedestrians, obstacles, borders, and dangers is reflected by repulsive forces. The effect of a stage or of window displays is described by attractive forces. The same applies to the tendency of group or family members to stay together.

Let us now give a mathematical formulation of the basics of the social force model (Helbing 1991, 1995, 1997; Helbing and Molnár 1995; Helbing and Vicsek 1999; Helbing, Farkas, and Vicsek 2000b; Molnár 1996a, b), for which Hoogendoorn, Bovy, and Daamen (2002) have recently given an interpretation in terms of optimal control and differential games. Because the position of a pedestrian α can be represented by a point $\vec{r}_\alpha(t)$ in space, which changes continuously in the course of time t, his or her speed $\vec{v}_\alpha(t)$ is governed by the following *equation of motion*:

$$\frac{d\vec{r}_\alpha(t)}{dt} = \vec{v}_\alpha(t). \tag{1}$$

If the overall social force $\vec{f}_\alpha(t)$ represents the sum of the different systematic influences (of the environment and other pedestrians) on the behavior of a pedestrian α, and the fluctuation term $\vec{\xi}_\alpha(t)$ reflects random behavioral variations (arising from accidental or deliberate deviations from the optimal behavior), we have the following equation for the acceleration or deceleration of pedestrian α as well as the directional change:

$$\frac{d\vec{v}_\alpha}{dt} = \vec{f}_\alpha(t) + \vec{\xi}_\alpha(t). \tag{2}$$

In our specification of $\vec{f}_\alpha(t)$, we take into account an acceleration force $\vec{f}^{\,0}_\alpha(\vec{v}_\alpha)$, repulsive effects $\vec{f}_{\alpha B}(\vec{r}_\alpha)$ due to boundaries, repulsive interactions $\vec{f}_{\alpha\beta}(\vec{r}_\alpha, \vec{v}_\alpha, \vec{r}_\beta, \vec{v}_\beta)$ with other pedestrians β, and attraction effects $\vec{f}_{\alpha i}(\vec{r}_\alpha, \vec{r}_i, t)$:

$$\vec{f}_\alpha(t) = \vec{f}^{\,0}_\alpha(\vec{v}_\alpha) + \vec{f}_{\alpha B}(\vec{r}_\alpha) + \sum_{\beta(\neq\alpha)} \vec{f}_{\alpha\beta}(\vec{r}_\alpha, \vec{v}_\alpha, \vec{r}_\beta, \vec{v}_\beta) + \sum_i \vec{f}_{\alpha i}(\vec{r}_\alpha, \vec{r}_i, t). \tag{3}$$

The single-force terms are discussed in the following.

- Each pedestrian wants to walk with an individual *desired speed* v^0_α into the direction $\vec{e}_\alpha$ of his/her next destination. Deviations of the *actual velocity* $\vec{v}_\alpha$ from the *desired velocity* $\vec{v}^{\,0}_\alpha = v^0_\alpha \vec{e}_\alpha$ due to disturbances (by obstacles or avoidance maneuvers) are corrected within the so-called *"relaxation time"* $\tau_\alpha \approx 1$ s:

$$\vec{f}^{\,0}_\alpha(\vec{v}_\alpha) = \frac{1}{\tau_\alpha}\left(v^0_\alpha \vec{e}_\alpha - \vec{v}_\alpha\right). \tag{4}$$

In normal situations, the desired speed v^0_α is approximately Gaussian distributed with a mean value of 1.3 m/s, possibly smaller, and a standard deviation of around 0.3 m/s. To compensate for delays, the desired speed $v^0_\alpha(t)$ is often increased in the course of time. One may describe this, for example, by the formula

$$v^0_\alpha(t) = [1 - n_\alpha(t)]v^0_\alpha(0) + n_\alpha(t)v^{\max}_\alpha. \tag{5}$$

Herein, $v_\alpha^{\max}$ is the maximum desired velocity and $v_\alpha^0(0)$ the initial one, corresponding to the expected velocity of leaving. The time-dependent parameter

$$n_\alpha(t) = 1 - \frac{\bar{v}_\alpha(t)}{v_\alpha^0(0)} \tag{6}$$

reflects the *nervousness* or *impatience*, where $\bar{v}_\alpha(t)$ denotes the average speed into the desired direction of motion. Altogether, long waiting times decrease the actual velocity compared to the desired one, which increases the desired velocity. This mechanism can explain the shock waves illustrated in Figure 14. It may also lead to pushy behavior and generate high pressures in the crowd. Tragically, at high pressures, clogging effects may occur and people may be crushed (Helbing, Farkas, and Vicsek 2000b).

• Pedestrians keep some distance from borders to avoid the risk of getting hurt. The closer the border is, the more uncomfortable a pedestrian feels. This effect can be described by a repulsive force $\vec{f}_{\alpha B}$, which decreases monotonically with the distance $\|\vec{r}_\alpha - \vec{r}_B^\alpha\|$ between the place $\vec{r}_\alpha(t)$ of pedestrian α and the nearest point $\vec{r}_B^\alpha$ of the border. In the simplest case, this force can be expressed in terms of a repulsive potential V_B:

$$\vec{f}_{\alpha B}(\vec{r}_\alpha) = -\nabla_{\vec{r}_\alpha} V_B(\|\vec{r}_\alpha - \vec{r}_B^\alpha\|). \tag{7}$$

Similar repulsive force terms $\vec{f}_{\alpha\beta}(\vec{r}_\alpha, \vec{v}_\alpha, \vec{r}_\beta, \vec{v}_\beta)$ can describe that each pedestrian α keeps a situation-dependent distance to the other pedestrians β. In the simulations of this paper, the repulsive interaction force has been specified according to the formula

$$\begin{aligned}\vec{f}_{\alpha\beta}(t) = {} & A_\alpha^1 \exp[(r_{\alpha\beta} - d_{\alpha\beta})/B_\alpha^1]\vec{n}_{\alpha\beta} \\ & \cdot\left(\lambda_\alpha + (1-\lambda_\alpha)\frac{1+\cos(\varphi_{\alpha\beta})}{2}\right) \\ & + A_\alpha^2 \exp[(r_{\alpha\beta} - d_{\alpha\beta})/B_\alpha^2]\vec{n}_{\alpha\beta}.\end{aligned} \tag{8}$$

The first term on the right-hand side reflects the tendency to respect a *private sphere* (*territorial effect*) and helps to avoid collisions in cases of sudden velocity changes, while the second term describes physical interactions at high densities and in pushy crowds (when frictional effects are neglected). A_α denotes the respective interaction strength and B_α the range of the repulsive interaction, which are individual parameters and partly dependent on cultural conventions. Here we have chosen $A_\alpha^2 = 3\ \text{m/s}^2$ and $B_\alpha^2 = 0.2$ m, while A_α^1 is often set to zero to speed up simulations in crowded situations. For the analogous repulsion of walls we have chosen $A = 5\ \text{m/s}^2$ and $B = 0.1$ m. $d_{\alpha\beta}(t) = \|\vec{x}_\alpha(t) - \vec{x}_\beta(t)\|$ is the distance between the centers of mass of pedestrians α and β, $r_{\alpha\beta} = (r_\alpha + r_\beta) \approx 0.6$ m the sum of their radii r_α and r_β, and $\vec{n}_{\alpha\beta}(t) = [\vec{x}_\alpha(t) - \vec{x}_\beta(t)]/d_{\alpha\beta}(t)$ the normalized vector pointing from pedestrian β to α. Finally, with the choice $\lambda_\alpha \approx 0.75$, we can take into account the anisotropic character of pedestrian interactions, as the situation in front of a pedestrian has a larger impact on his or her behavior than things happening behind. $\varphi_{\alpha\beta}(t)$ denotes the angle between the direction $\vec{e}_\alpha(t) = \vec{v}_\alpha(t)/\|\vec{v}_\alpha(t)\|$ of motion and the direction $-\vec{n}_{\alpha\beta}(t)$ of the object exerting the repulsive force, i.e., $\cos\varphi_{\alpha\beta}(t) = -\vec{n}_{\alpha\beta}(t)\cdot\vec{e}_\alpha(t)$. One may, of course, take into account other details such as a velocity dependence of the forces and noncircular shaped pedestrian bodies, but this does not have *qualitative* effects on the dynamical phenomena resulting in the simulations. In fact, most observed self-organization phenomena are quite insensitive to the specification of the interaction forces, while it may, of course, influence the quantitative results.

• Pedestrians show a certain joining behavior. For example, families, friends, or tourists often move in groups. In addition, pedestrians are sometimes attracted by window displays, sights, special performances (street artists), or unusual events at places $\vec{r}_i$. Both situations can be modelled by (often temporally decaying) attractive forces $\vec{f}_{\alpha i}(\vec{r}_\alpha, \vec{r}_i, t)$ similarly to repulsive effects, but with an opposite sign and a longer range of interaction.

Once the model parameters have been calibrated with empirical data of pedestrian streams, the corresponding computer simulations yield, according to our experiences in the past, realistic results, even for new geometries and situations, without having to adapt the model or parameters again. That is, the social force model has predictive value, and it allows one to investigate new scenarios for which experiments would be costly, difficult, or dangerous. This is particularly important for the planning and optimization of escape routes. We will come back to this

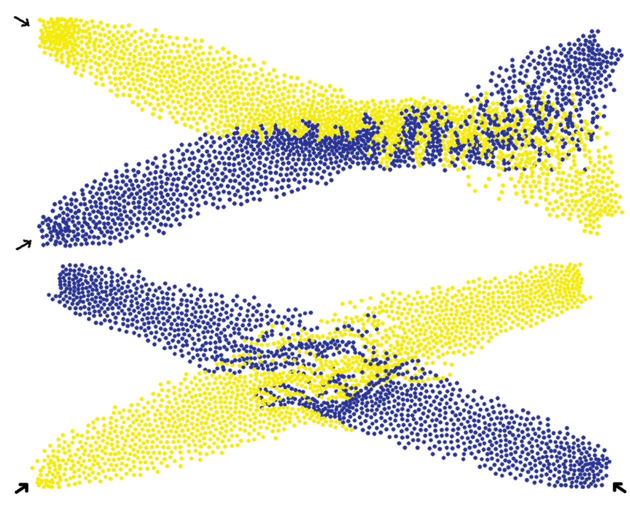

Figure 17 Representative Simulation Results of Two Intersecting Pedestrian Streams Using the Social Force Model

Note. The computational results reproduce the observed phenomenon of stripe formation quite well (cf. Figure 15).

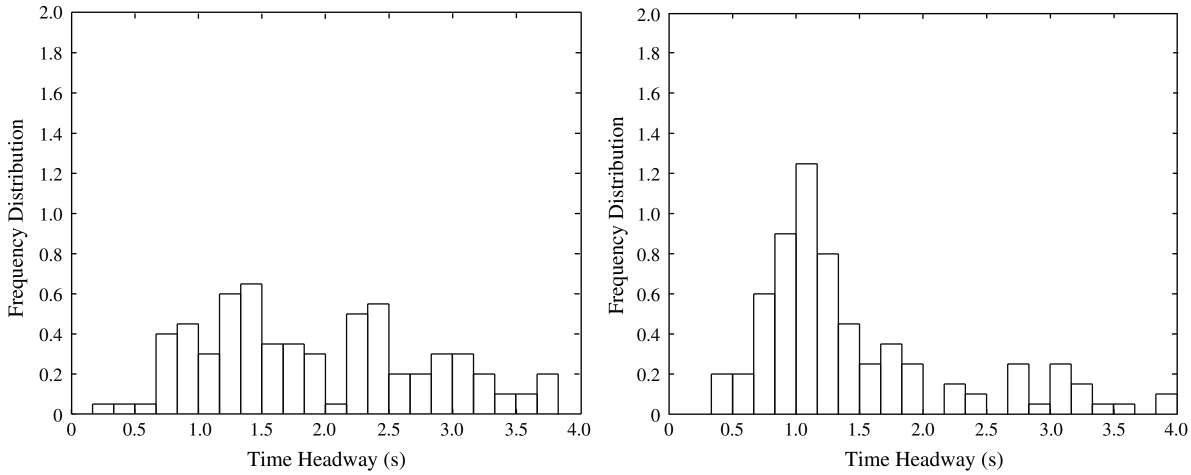

Figure 18 **Time Headway Distributions According to a Pedestrian Simulation with the Social Force Model**
Note. As in the empirical observations displayed in Figure 13, the distribution is flat before a long bottleneck (left), but has a pronounced maximum after it (right).

in the next section. Here we will focus on showing simulation results of stripe formation (see Figure 17) and of time gap distributions close to bottlenecks (see Figure 18), as *lane formation* (Molnár 1996a, b; Helbing and Molnár 1995; Helbing 1997; Helbing and Vicsek 1999) and *oscillations* of the passing direction at bottlenecks (Molnár 1996a, b; Helbing and Molnár 1995; Helbing 1997) have been already demonstrated in previous publications. The social force model also successfully describes coordination problems due to *excluded volume effects* related to the discrete ("granular") nature of pedestrian flows, and it reproduces the related *clogging phenomena* in panicking pedestrian crowds ("faster-is-slower" effect, see Helbing, Farkas, and Vicsek 2000a, b; Helbing et al. 2002).

5. Improved Design Solutions for Pedestrian Facilities

The complex interaction of several pedestrian streams can lead to completely unexpected results, which is a consequence of their nonlinear dynamics. Therefore, the planning of pedestrian facilities with conventional methods does not guarantee the avoidance of jams, obstructions, or blockages, particularly not in emergency situations. In contrast, a skillful flow optimization utilizing the self-organization phenomena emerging in pedestrian streams can increase the efficiency and safety of pedestrian facilities at comparable costs and even with less available space.

In the following, we will discuss some improved design solutions for entrances, exits, and egress routes of stadia, theaters, and lecture halls that may also be transferred to other highly frequented places such as hotels, convention centers, exhibition halls, business centers, shopping malls, railway stations, or airport terminals. These are a direct consequence of the various observed self-organization phenomena described above.

5.1. Counterflows

Counterflows are most efficient when they are organized in a few wide lanes with stable interfaces. However, at mass events, opposite flow directions must be artificially separated, as the lanes become sensitive to perturbations (Helbing, Farkas, and Vicsek 2000a) and tend to obstruct each other due to attempted overtaking maneuvers. If the lanes break down, dangerous blockages are likely to emerge, which may finally trigger crowd stampedes.

Surprisingly, the desired separation of opposite flow directions can be supported by series of obstacles such as railings, trees, or columns (see Figure 19). Such kinds of solutions are permeable, but have psychologically and physically similar effects as a separating wall. They prevent pedestrians from using small gaps in the opposite flow for overtaking maneuvers, which could cause broader streams in one direction than the other, later on provoking an interaction-induced reduction in the walking speed, and serious obstructions. However, when the other side is rarely frequented, a permeable design allows pedestrians to use the other side as well. For this reason, a series of obstacles is flexible and can reduce the frequency of braking and avoidance maneuvers. In this way, the average velocity is increased, although some space is used up by the series of obstacles.

Similar solutions are useful at doors: It is better to have two separate doors for the two opposite directions of motion than one door that is twice as big. These will typically be used by one flow direction each (Molnár 1996a, b; Helbing 1997; Helbing and Molnár 1997; Helbing et al. 2001). In contrast, one door tends to produce oscillatory changes in the

Figure 19 When the Density of Pedestrians and the Variation of their Desired Velocities Are High, the Interfaces (i.e., the Sideward Boundaries) of Pedestrian Flows Can Be Efficiently Stabilized by a Series of Columns (Snapshot of Videorecordings in a Tunnel of Budapest's Metro System at Deak Tér)

Note. Nevertheless, the permeability allows for a flexible usage in accordance with the respective pedestrian traffic volumes in both directions.

passing direction with intermediate periods of standstill, during which both directions struggle with each other. This struggling can produce a dangerous pressure in the crowd, which does not build up when there is a reasonable and continuous flow in both directions through separate doors.

5.2. Bottlenecks and Clogging in Pushy Crowds

One possibility to improve the situation at bottlenecks is a funnel-shaped design (which, by the way, requires less walkable space). However, a funnel-shaped design is not sufficient in big pedestrian crowds, when large pressure builds up. Under particular circumstances this can turn mass events into deadly stampedes. Appropriately placed columns (pillars) can improve the situation. Their functioning is similar to conventional wave breakers. They can absorb pressure in the crowd and reduce it to a subcritical level. However, they do not seriously obstruct the movement toward the exits, as wave breakers (i.e., transversal railings) would do. The performance of various alternative design solutions for exit areas has recently been compared by means of computer simulations (Escobar and de la Rosa 2003). This independent study is recommended reading.

Figure 20 shows an experiment we performed to determine the effect of an obstacle on a pushy crowd. Without an obstacle, we found a clogging effect that

Figure 20 Snapshots of an Experiment Imitating Conditions of Panic

Notes. The participants had comparable distances to the exit in the beginning. They were asked to rush toward the door after an accoustical signal was given and to behave in a pushy way. Without an obstacle, the experiment showed clogging effects and a tendency of people to fall (left). In another setup, a board served as an obstacle (right). Despite of the strong forces in the crowd (the board was shaking), the clogging effect could be significantly reduced. This increased the efficiency of escape and diminished the tendency of falling.

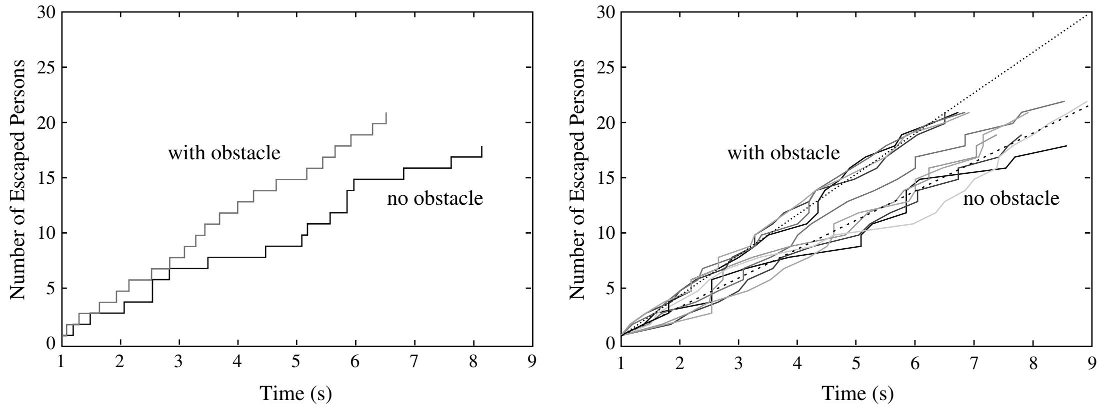

Figure 21 Escape Times and Number of Escaped Persons in Experiments Imitating Conditions of Escape Panic With and Without an Obstacle in Front of the Exit

Notes. The left figure illustrates the slower and less regular escape without an obstacle. Long steps reflect the clogging effect, i.e., long periods during which nobody manages to leave the room. In the right figure, the lines are not shown in a stepwise manner to allow one to distinguish the different curves, which just connect the measurement points of leaving persons. The broken lines are a guide for the eyes. Their slopes allow comparison of the average flows with and without an obstacle in front of the exit.

considerably reduced the efficiency of escape and produced high pressures in the crowd. Placing an obstacle (here, a board) in front of the exit could avoid the clogging effect. This becomes visible in the cumulative counts of the number of escaped persons over time (see Figure 21): Without an obstacle, one observes long plateaus indicating a temporarily stopped flow. Placing an obstacle (a board of width 45 cm) in front of the exit reduces the plateaus and increases the rate of escape. This also becomes obvious from the experimental data listed in Table 2.

An obstacle can reduce both the mean value and the relative standard deviation of the time intervals between successive escapes from the room. The outflow under panic-like conditions was increased by about 30% (see Table 2 and Figure 21). According to recent simulation results, even larger improvements are expected for bigger crowds (Escobar and de la Rosa 2003; Helbing, Farkas, and Vicsek 2000b). Clogging effects and irregular flows typically occur in pushy crowds when the pressure exceeds a certain level. They become more serious when more people are involved. Under conditions of normal leaving, however, the outflows for rooms with and without pillars will be about the same.

Table 2 Overall Flow Through a Door in Condition of Panic

Experiment	Q	$\overline{T}$	$\sigma/\overline{T}$
Panic 1	135	0.446	1.015
Panic 2	159	0.378	0.659
Panic 3	167	0.359	0.663
Panic 4	173	0.346	0.780
Panic 5	169	0.355	0.780
Panic 6	159	0.377	0.742
Obstacle 1a	209	0.287	0.636
Obstacle 1b	205	0.292	0.553
Obstacle 2a	218	0.275	0.604
Obstacle 2b	203	0.296	0.563

Notes. Overall flow Q (pedestrians/min) through a door of 82 cm width, average time gap $\overline{T}$ (s), and relative variation $\sigma/\overline{T}$ of time gaps in an experiment imitating conditions of panic without and with an obstacle (a board of 45 cm width). The obstacle increased the flow by about 30% and decreased the variation in the time gaps by about the same amount, indicating a smoother evacuation from the room.

5.3. Intersections

In intersecting flows, mutual obstructions are practically unavoidable. They are, therefore, the greatest challenge to architects, urban planners, and organizers of mass events (e.g., Olympic games). We have seen that two intersecting flows result in the formation of efficient, moving stripes that allow pedestrian streams to penetrate each other without major obstructions. However, when three or more flow directions intersect, the situation is more difficult. In these situations, coherent stripes cannot form, as stripes in several directions would have to propagate through each other, which would destroy any existing stripes. Patterns in intersection areas are, therefore, very unstable, "chaotic," and inefficient.

Nevertheless, the different flows at an intersection (and turning maneuvers) can be organized in a way that supports a stable pattern. It is remarkable that in computer simulations an obstacle in the middle of an intersection has been found to improve the efficiency of motion, although it reduces the space available for pedestrians (Molnár 1996a). This becomes understandable when we spatially separate the different flow directions in a way that only two flow directions can intersect at one place. For a four-way intersection, this can be done in various ways (see Figure 22). All intersection areas of two flows are expected to produce efficient stripes as described above. Good solutions give rise to rotary traffic, while bad solutions are expected to produce disturbances.

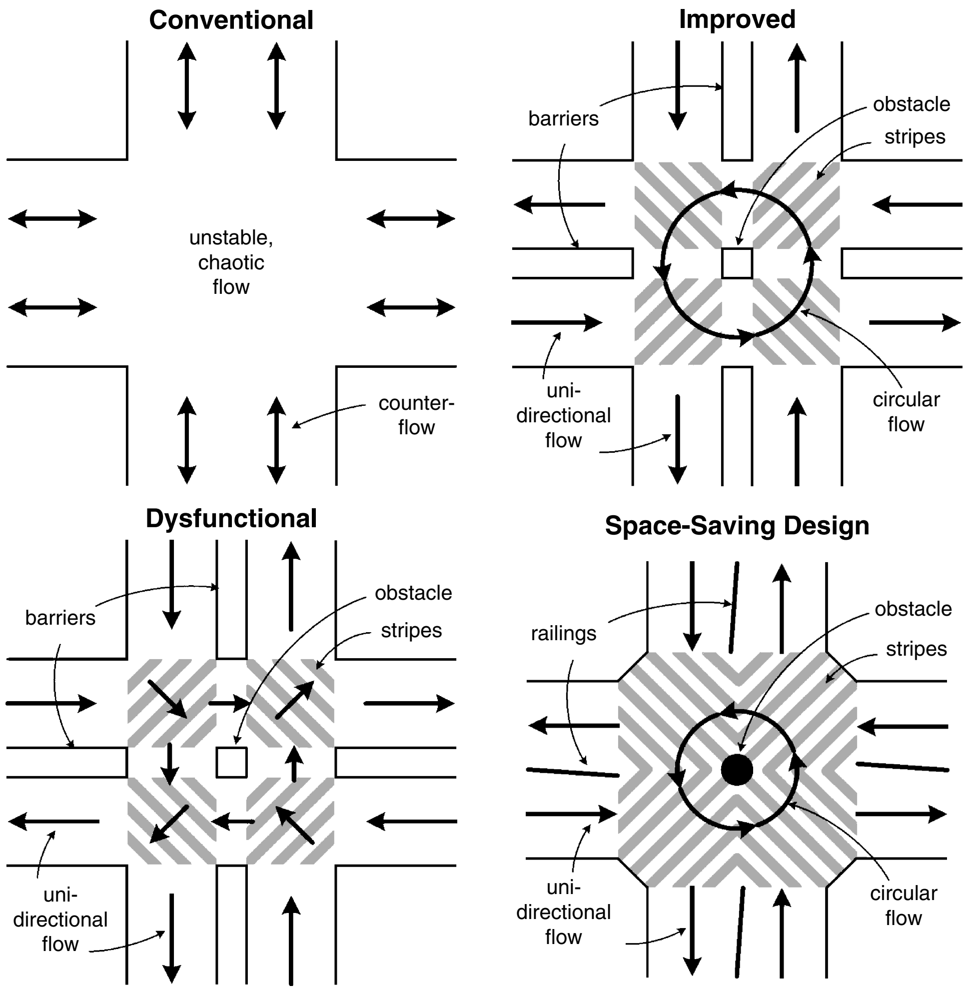

Figure 22 **Various Designs of an Intersection**

Notes. Upper left: At conventional intersections, one observes continuously changing patterns of motion, i.e., the pedestrian streams are unstable, "chaotic," and inefficient. Upper right: If four intersecting pedestrian flows are separated by barriers, one-way regulations, and an obstacle in the center of the intersection, one can expect the formation of stripes in all four intersection areas of two pedestrian streams, which propagate perpendicularly to their sideward extension. As a consequence, an efficient roundabout traffic emerges at high densities. Lower left: If the different flow directions meet in the wrong order, the resulting pattern of motion is expected to be dysfunctional. Lower right: Space-saving variant of the intersection design proposed in the top right figure. Despite the reduced space requirements compared to the upper left intersection design, the pedestrian streams can get ahead more efficiently. The design makes use of the preference of the right-hand side in central European pedestrian streams. In other countries such as Japan, it would be reasonable to invert the flow directions.

Rotary traffic will be most pronounced when the crossing is heavily frequented. In periods of light traffic, some pedestrians may try to move opposite to the main stream. During these periods, however, a deviation from rotary motion does not matter a lot. Our first empirical investigations confirm this assessment. In conclusion, there are particular solutions for intersections of three or more flow directions that are better than conventional designs. These are recommended for the organization of heavily frequented places and mass events.

5.4. Egress Routes of Theaters, Classrooms, and Lecture Halls

In 1903, 602 people died in a theater fire, and in 1970, 46 people were killed by a fire in a ballroom in St. Laurent-du-Pont. (More examples are discussed by Waldau 2002.) Even after these tragic events, theater fires have cost many lives and were considered to be so dangerous that fire fighters had to be on the spot during every show. Today, it should be possible to evacuate theaters within three minutes. Therefore, the minimum width of egress routes is regulated by law, and it is seldomly exceeded. However, it is not always reasonable that egress routes have a constant width. The number of persons wishing to leave increases with each floor, each deck, or each row of seats that is closer to the exit. Therefore, the time to leave grows not only due to longer walking distances, but also due to longer waiting times in queues. This can cause impatience in the crowd, particularly in situations of danger, which can produce a pushy behavior with all

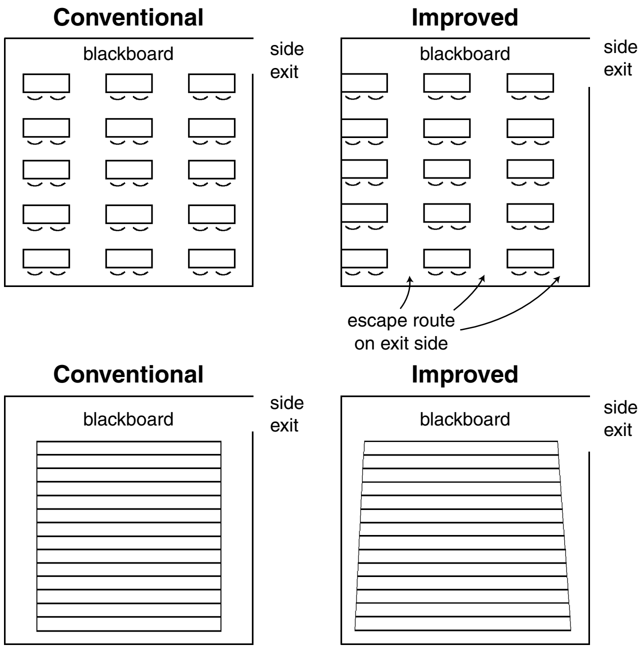

Figure 23 **Various Distributions of Seats in a Classroom and a Lecture Hall**

Notes. Upper left: While the classical distribution of seats in classrooms is symmetrical to the middle, this configuration produced jamming in an evacuation experiment, as people mainly used the escape route to their right (Helbing et al. 2003). Upper right: The escape routes should be completely on the side that is closer to the exit to take into account the orientation behavior of pedestrians. Bottom: In a lecture hall, additional people enter the corridor from every row. Therefore, similar to the stream of a river, corridors should become wider toward the door(s). This makes egress more fluid and reduces the dangerous pushing behavior in emergency situations. The widening effect should be more pronounced on the side that is closer to the exit, as more persons are heading into this direction.

its possible consequences: clogging phenomena, dead and injured people. As a consequence, it would be reasonable to have increasing widths of egress routes, similar to the stream of a river. In this way, it is possible to avoid long waiting times in the forming pedestrian queue and to accelerate the evacuation of people. The *average* width of egress routes does not have to be greater than today, so that the usable area and potential profit are not reduced. Figure 24 compares a typical design of theaters with improved solutions, in which the blocks of seats have a trapeziform rather than a rectangular shape. For large crowds it can also make sense to place columns at suitable places in front of the exits (see Figures 21 and 24). These can serve to absorb the pressure in the crowd like a wave breaker, to relieve the strain on the escaping people at the exit, while allowing pedestrians to get around the obstacle.

Although obstacles might be argued to decrease the architectural value, columns are often needed for statical reasons anyway, so that no additional cost would incur. As a consequence, columns may also serve safety functions by optimizing pedestrian flows, if properly placed. Depending on their design, they may reduce visibility or increase orientation. Aesthetic (e.g., especially illuminated) designs and flexible solutions (such as telescope columns activated only in critical situations) are conceivable.

5.5. Staircases and Exits of Stadia

Staircases are a serious obstacle in any panic situation. Practically, it is only a matter of time until persons in the pushy crowd fall, especially as it is not possible to see the exact location of the single stairs in a dense crowd. The danger is greatest for staircases going down. The crowd stampede in a nightclub in Chicago on February 17, 2003, is charateristic of this. It was triggered by a relatively harmless event: Staff members tried to separate two fighting guests by using pepper spray. However, some others assumed a terror attack with poisonous gas,

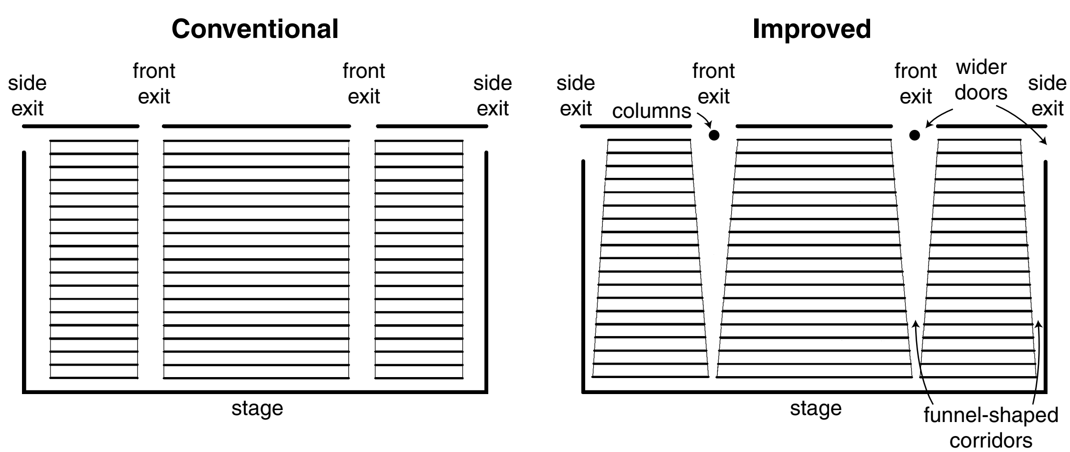

Figure 24 **Various Designs of Corridors in a Theater**

Notes. Left: A uniform width of the corridors in a theater implies long waiting times. Right: With an identical number of seats, a funnel-shaped design can reach shorter waiting times, which reduces the danger of pushing behavior in emergency situations. Columns in front of the main exits are optional and can decrease the pressure in a pushy crowd similar to wave breakers. The wider exits reduce the risk of jam formation and clogging.

as the government had activated the second-highest alert level (Code Orange). Therefore, several guests ran toward the exit and alarmed other people. Most of them rushed toward the main exit, while the available side exits were used by only a few people. On the long staircase leading down to the exit, people lost their balance, and people fell over them. In the end, people were piled up in many layers (see, for example, the bottom photos in Figure 2). Attempts to draw exhausted individuals out of this heap of people failed. Deaths totaled 21, and 50 were injured.

The danger of falling on staircases can be reduced by replacing them with ramps where possible. However, the hazards of long downward staircases can also be reduced by dividing them into small enough segments pointing in different directions. Figure 25 illustrates the suggested zigzag design toward a stadium exit. It limits the pushing-related build-up of pressure in a crowd (see Figure 26) and avoids situations where many fallen people are piled up on top of each other. Although upward staircases may act as obstacles for escaping individuals as well, the problem of heaps of fallen people is typical for downward staircases. Upward staircases can even reduce the pressure of the crowd rushing toward the exit, as they separate the people in a vertical direction. Consequently, it makes a big difference whether egress routes lead upward or downward.

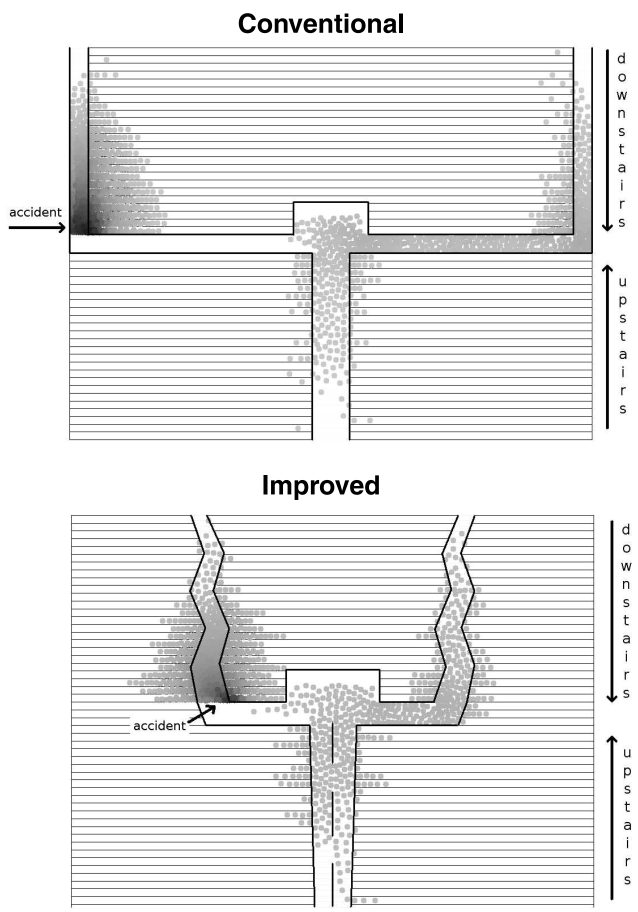

Figure 25 Conventional and Improved Design of a Stadium Exit

Notes. Top: Conventional design of a stadium exit in an emergency scenario, where we assume that some pedestrians have fallen at the end of the downward staircase to the left. The dark color indicates high pressures, because pedestrians are impatient and pushing from behind. The different queue lengths in the different rows are due to heterogeneous desired pedestrian velocities. Bottom: In the improved design, the increasing diameter of corridors can reduce waiting times and impatience (even with the same number of seats), thereby accelerating evacuation. Moreover, the zigzag design of the downward staircases changes the pushing direction in the crowd.

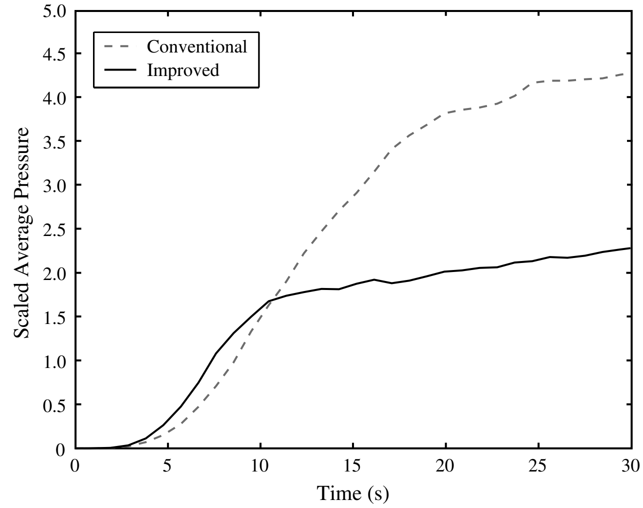

Figure 26 A Zigzag Design of Downward Staircases (cf. Figure 25) Avoids that an Overcritical Pressure Is Produced in a Pushy Crowd and that Many Falling People Are Piled up on Top of Each Other (cf. Figure 2)

Note. This promises to safe the lifes of people in critical situations.

5.6. Queues at Entrances

On July 5, 2003, terrorists wearing explosive belts committed a suicide attack at a rock festival in the north of Moscow, when the entrance control found them behaving suspiciously. Deaths totaled 18, and 49 others were injured, some of them very seriously. Nevertheless, the concert was not terminated, as the organizers were afraid of a crowd stampede.

Unfortunately, dense crowds are generally an attractive goal of terrorists, as the poissonous gas attacks in Japanese metro tunnels and the bombings of mosques and tourist attractions have recently shown: The potential number of victims is large, the attention by the public media certain, and the security level comparatively low. Hence, the changed security situation in the world calls for innovative solutions.

Figure 27 illustrates how queues due to ticket and security controls in front of stadia or concert halls and before mass events can be organized: First of all, the waiting queue can be canalized into two queues per entrance. By means of a safety separation between the segments of the queues, the density of the crowd

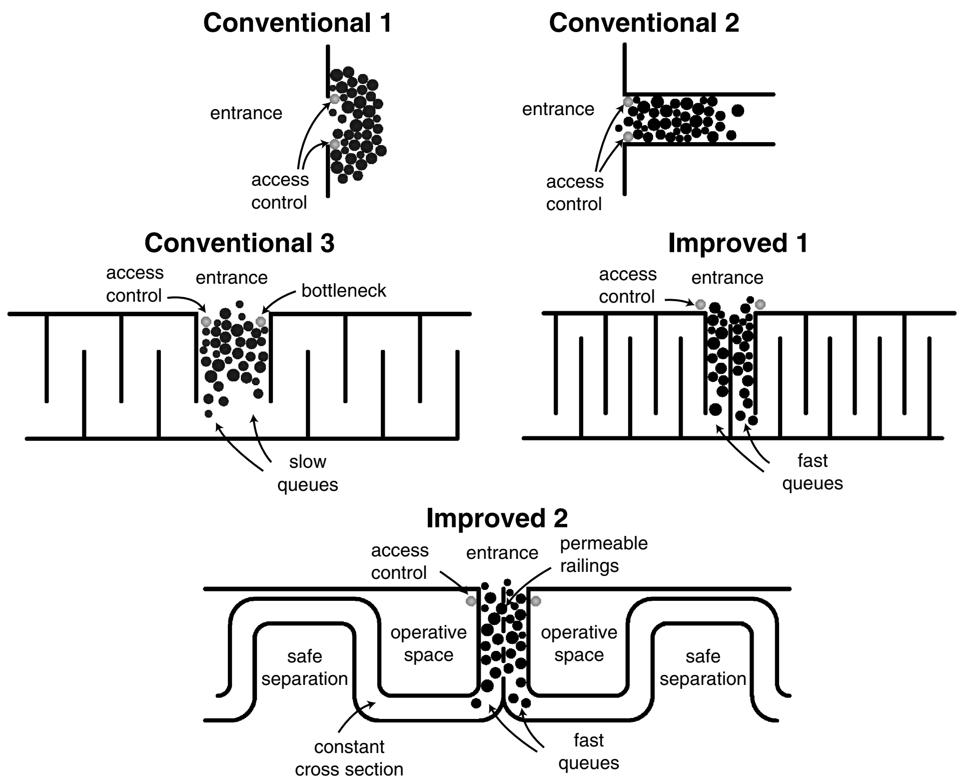

Figure 27 Various Organizations of Queues Around an Entrance

Notes. Upper left: Without railings, a waiting crowd may distribute in a semicircular or clumped manner around the entrance. In an impatient crowd, this could produce a high pressure level and clogging. Upper right: Railings on the sides can reduce the risk of clogging, but the pressure in the crowd may still be high. Middle left: Queues are often guided in a snake-like manner. A positive side effect is the interruption of the pushing direction. If the different elements of the queue are short enough, overcritical pressure cannot build up anymore. Middle right: If the ticket and security control are moved inside the building and the queue width is narrow, the people get ahead faster. This reduces their impatience and the tendency of pushing. Bottom: A sideward separation of the queue avoids the build up of an overcritical pressure. As it also reduces the average density of the crowd before the access control, the impact of terrorist attacks would be significantly reduced. Permeable railings in front of the exit are for a sideward pressure control.

can be considerably reduced, so that the number of victims in case of a terrorist attack would be minimized. This also reduces the attractiveness and likelihood of attacks. Furthermore, the sideward separation offers space for selling beverages, etc., and for an access control that does not produce bottlenecks. Altogether, the people in the queues are expected to move forward in a faster way. This effect reduces the impatience of the people waiting to enter and is further supported by a narrow design of the queues. However, even in situations of pushy crowds when the people were hindered from getting ahead for a considerable period of time, a broken direction of motion (as indicated in the bottom sketch of Figure 27) keeps the pressure below a critical level.

5.7. Optimal Way Systems

Relevant insights have been also gained for the pedestrian-friendly design and optimization of way systems (Helbing, Keltsch, and Molnár 1997a, b). For example, pedestrians do not accept detours of more than 20%, so that they often leave paved ways to take shortcuts. The underlying pedestrian behavior can be simulated with a computer model taking into account orientation behavior and the ease of walking as a function of the intensity of trails that pedestrians leave on deformable ground like green areas (Helbing, Keltsch, and Molnár 1997a, b). It turns out that perpendicular intersections do not fit the pedestrian behavior very well. It is better to replace T-shaped junctions of different ways by a Y-shaped design (see Figure 28). Moreover, way systems can be made cheaper and more efficient by a suitable bundling of ways into similar directions (Helbing, Keltsch, and Molnár 1997a, b).

5.8. Practical Applications of the Social Force Model

It is impossible to cite all the available studies of the social force model here. It should, however, be stated that there is not only theoretical interest in this approach, but also practical applications. We can mention only a few (see also contributions in Galea 2003). Figure 29, for example, illustrates the evacuation of two decks of a ship or two levels of a hotel. The underlying study has shown that the model is also suitable to treat different personalities (the

Figure 28 If Three Trails Meet, the Preferable Way Design Is Y-Shaped (Rather Than T-Shaped) with an "Island" in Between, as Pedestrians Like to Avoid Detours

different characteristic behaviors in emergency situations), complex geometries, and three-dimensional interactions at staircases (Werner and Helbing 2003). Hoogendoorn, Bovy, and Daamen (2002) have simulated multidestination flows at Schiphol airport in the Netherlands. With today's computer power, it is possible to simulate the evacuation of 10,000 or more people (Quinn, Metoyer, and Hunter-Zaworski 2003). The model has also been used to simulate pedestrian flows on the Jamarat Bridge, which has to cope with several million pilgrims within a few days (AlGadhi and Mahmassani 1990). Figure 30 illustrates the scenario and shows the development of zones of high density and pressure behind the three circular basins around pillars symbolizing the devil. These pillars are to be stoned with seven pebbles each, which takes time and delays pedestrian motion.

5.9. Herding and Adaptive Escape Guidance Systems

Finally, herding behavior is another problem of evacuation that needs to be discussed. It is relevant for the problem of distributing people over all available exits. In evacuation simulations and the dimensioning of public buildings, it is normally assumed that all exits are equally used, i.e., that there is a *load balancing*. According to this assumption, people would use neighboring exits if the queues in front of these are shorter (similar to queues at the counters of supermarkets). This behavior is actually found for situations with good orientation and visibility (Nagatani et al. 2003). However, when the visibility is low (e.g., under conditions of smoke or an outage of electricity), a herding effect occurs. In an experiment with test persons wearing eye masks imitating orientationless

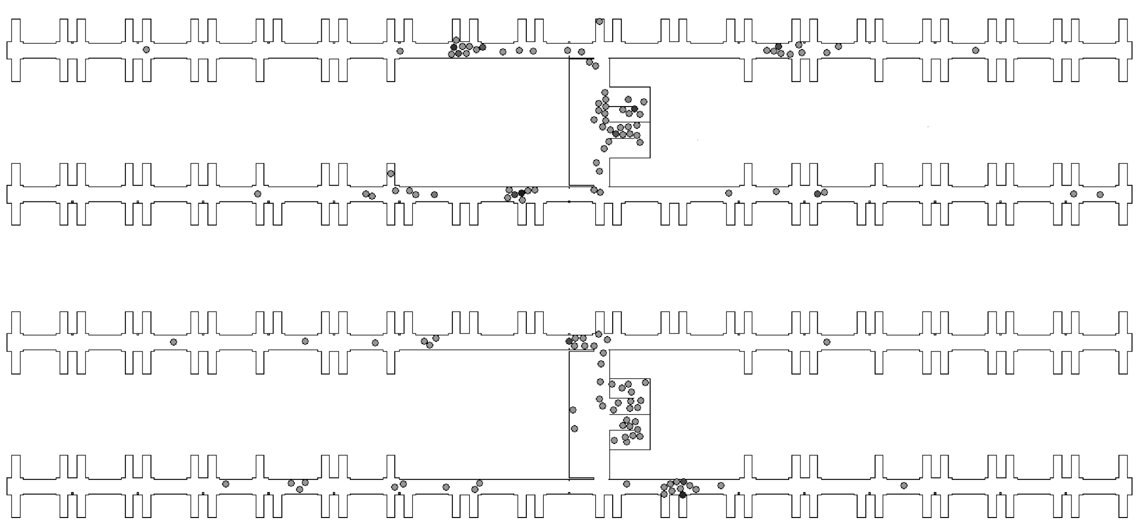

Figure 29 Snapshot of the Computer-Simulated Evacuation of Two Decks of a Ship (or Two Floors of a Hotel)

Notes. The corresponding study has demonstrated that the social force model can cope with complex geometries, three-dimensional interactions at staircases, different personalities, and large numbers of pedestrians. For more details of the simulation, see Werner and Helbing (2003).

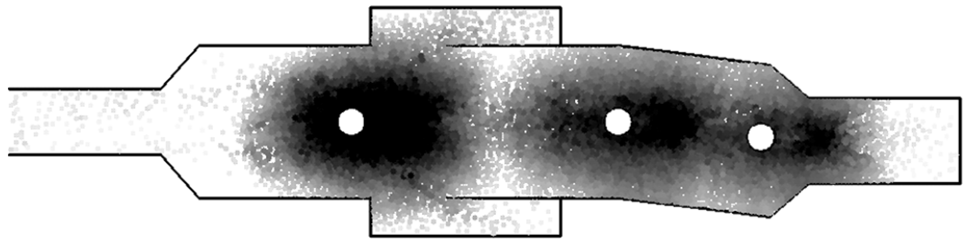

Figure 30 Simulation of the Jamarat Bridge Which Has to Cope Each Year with Millions of Pilgrims Within a Few Days
Notes. The pilgrims need to get close to the circular area to throw stones at the Jamarah (the pillar in the center representing the devil). This could potentially lead to high pressures around the pillars (dark elliptical areas), if no additional measures are taken.

people (Isobe, Helbing, and Nagatani 2004), we found the following behavior: First, the test persons turned around their own axis into the direction where the exit was believed to be. Then, they moved forward very slowly, until they hit the wall. Afterward they turned to the left or to the right with probability 1/2 and moved along the wall until they found an exit. Once somebody managed to leave, the other persons recognized the location of the exit in an accoustical way, and they adapted their direction of motion accordingly. Under such circumstances, most persons tend to use the same exit, even if alternative exits are available.

Herding is also observed when the orientation in an unfamiliar environment is unsatisfactory (Quarantelli 1957; Keating 1982; Johnson 1987; Elliott and Smith 1993; Helbing, Farkas, and Vicsek 2000b; Helbing et al. 2002; Saloma et al. 2003): People either follow other people who are believed to know the best way, or they use the exit they are familiar with (typically the main exit they have entered). This can cause severe congestion at a few exits, and high pressures, as all people want to leave at the same time. After mass events, this can lead to serious problems, even if there is no emergency situation.

Therefore, it is very important to increase the orientation ability in a way that corresponds to human instincts and psychology. Instead of displaying confusing plans of escape routes, this could be reached by optical and accoustical guidance systems. Such systems could work with light effects attracting the people toward the exits or with directional sound, which is also effective in a smoky environment. These measures could significantly increase the orientation of people and support them in subconsciously or instinctively taking the right actions and directions. Some aspects of this are discussed by Waldau (2002).

6. Summary and Discussion

Pedestrian dynamics has recently received a high level of interest due to the evacuation of the World Trade Center on September 11th, the crowd panics in nightclubs in Rhode Island and Chicago in 2003, and the sad accidents during the holy pilgrimage in Mecca.

During the last years, video-based techniques (time-lapse recordings and single-frame analysis) have led to a deeper understanding of the dynamics and interaction of pedestrian streams. We have used these techniques to explore the effects of bottlenecks, obstacles, and intersections. Our empirical results on pedestrian flows in normal and panic-like situations show that the geometric boundary conditions are not only relevant for the capacity of the elements of pedestrian facilities. They also influence the time gap distribution of pedestrians, indicating the existence of self-organization phenomena. These findings can be used to improve design elements of pedestrian facilities and egress routes.

The great challenge of simulation models is the reproduction of the observed collective phenomena in pedestrian crowds. This includes lane formation in corridors and oscillations at bottlenecks in normal situations, while different kinds of blocked states are produced in panic situations. By means of microsimulations based on a generalized force model of interactive pedestrian dynamics, the spatiotemporal patterns in pedestrian crowds can be successfully reproduced and interpreted as self-organized phenomena.

The advantage of the social-force-based simulation approach is its simple form and its small number of parameters, which do not need to be calibrated anew for each situation. Therefore, the model is suitable for the prediction of pedestrian streams in novel architectures and new situations. Even counterintuitive effects are well reproduced. This includes the "faster-is-slower effect" and stripe formation in intersecting flows. At the same time, the model suggests innovative measures to improve pedestrian flows, both in normal and panic situations.

A proper knowledge of self-organization phenomena allows us to change the patterns of motion and their efficiency by suitable specification of the boundary conditions. For example, we propose to use suitably located "obstacles" to stabilize flow patterns and to make them more fluid. We also suggest increasing the diameters of egress routes in stadia or theaters to avoid long waiting times for people in the back and shock waves due to impatience. In addition, zigzag-shaped geometries and columns can reduce the pressure in panicking crowds, if properly designed and placed. This can help to increase the efficiency and safety of, for example, shopping malls, cinemas, theaters, public buildings, hotels, or passenger ships in the future. Moreover, by parallel simulation of the social force model on parallel PC clusters, it becomes possible to evaluate mass events, airport terminals, railway stations, and stadia in advance. Nowadays, one can also simulate pedestrian flows in extended urban areas (Batty, Desyllas, and Duxbury 2003; Helbing, Johansson, and Buzna 2004). This allows one to assess the attractiveness of certain locations for new shops, but also the impact of new buildings like theaters or malls on the overall pedestrian flows.

Acknowledgments

The first author is grateful to T. Vicsek, I. J. Farkas, P. Molnár, J. Keltsch, K. Bolay, J. Hahne, and C. Kühnert for the fruitful cooperation throughout 15 years of exciting pedestrian research. Special thanks go to Stefan Lämmer as well as Tilo Grigat for producing the schematic illustrations. The authors appreciate that Roger Hughes drew their attention to the interesting study by Ando et al. (1988). Last but not least, they would like to thank the German Research Foundation (DFG Project He 2789/7-1) for partial financial support.

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