ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

From Self-Organizating Pedestrians to Crowd Disasters

Prof. Dr. rer. nat. Dirk Helbing

Chair of Sociology, in particular of Modeling and Simulation

www.soms.ethz.ch

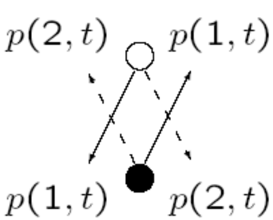
with Anders Johansson, Wenjian Yu, Mehdi Moussaid,

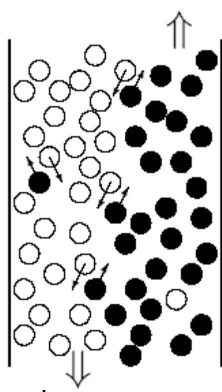
Illes Farkas, Peter Molnar, Tamas Vicsek and others

Emergent Collective Behavior by Human Interactions

What interests me most about social systems is the emergence of new, functional or complex system behaviors, particularly cooperation or coordination patterns based on elementary individual interactions.

For example, lanes of uniform walking direction emerge due to self-organization.





Do pedestrians behave as individuals or social beings?

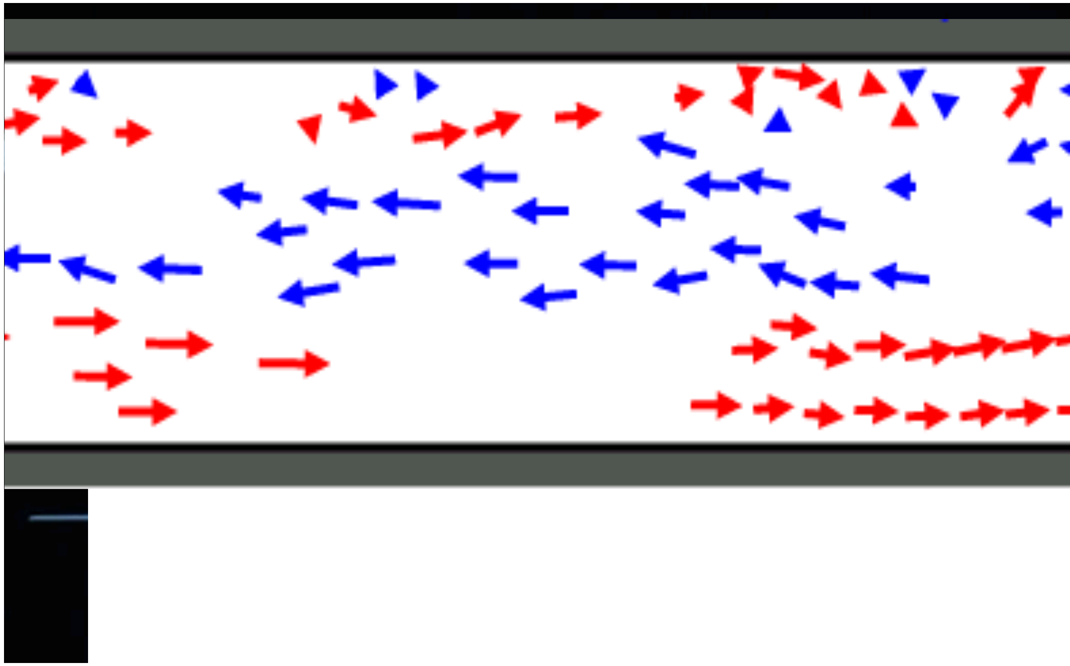
Preference of right-hand side is a convention, which can be understood by evolutionary game theory, as the payoff is larger for individuals who follow the majority behavior (B. Arthur'89/A. Rapoport'93)

Underlying Mechanisms?

Lane Formation in Pedestrian Counter Flows

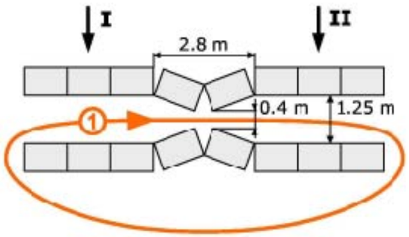
Emergence of Coordination in Pedestrian Counterflows

Acts like Adam Smith's "invisible hand"

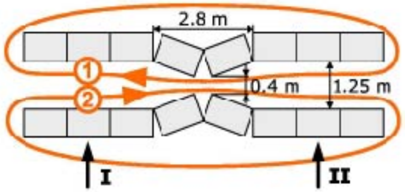


Based on individual interactions, lanes of uniform walking directions emerge in pedestrian crowds by self-organization. This constitutes a „macroscopic" social structure. Nobody orchestrates this collective behavior, and most people are not even aware of it. A behavioral convention „institutionalizes" a side preference.

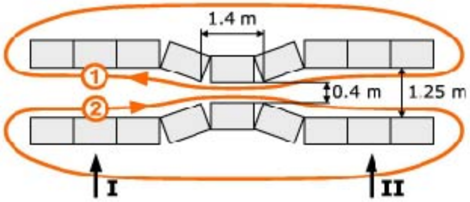
Experiments: Corridor with Bottlenecks



Experiment 1: Uni-directional pe-destrian streams passing a short bottleneck

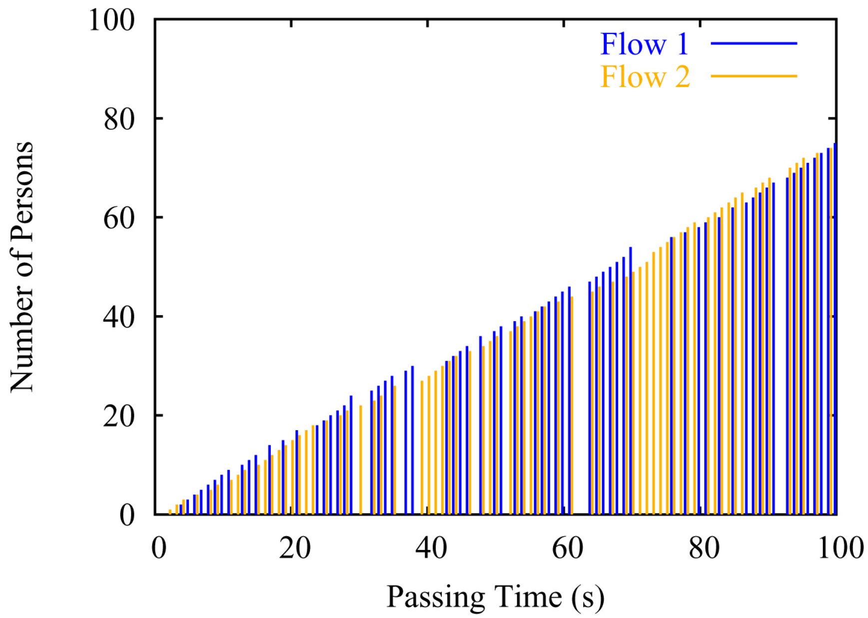


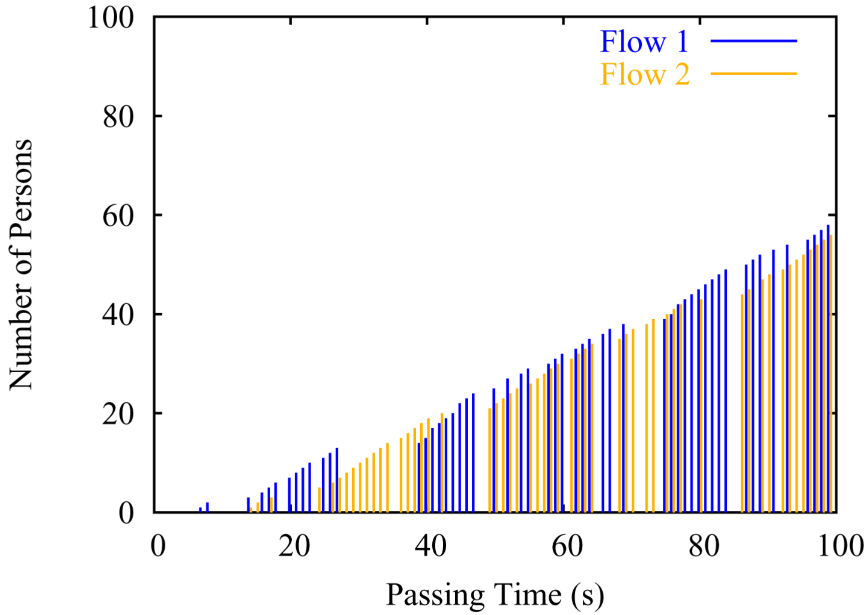
Experiment 2: Pedestrian counter-flows in a corridor with a short bottle-neck



Experiment 3: Pedestrian counter-flow in a corridor with a long bottleneck

Bottlenecks

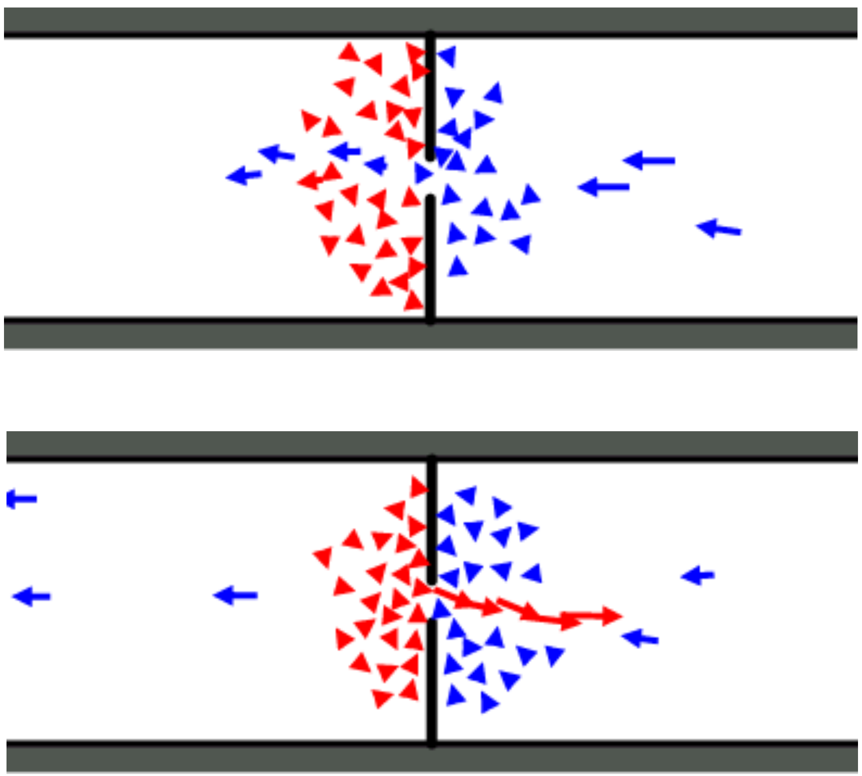




Compared to the flow through a corridor without narrowings the pedestrian flow after a short bottleneck is less regular due to oscillations in the passing direction. Pedestrians of the same direction of motion have a slight tendency to cluster (left).

At long bottlenecks, the oscillations in the passing direction are significantly more pronounced than at short bottlenecks. Moreover, the oscillation frequency is lower. There is a high tendency that the bottleneck is passed by clusters of pedestrians with the same direction of motion rather than by single individuals in an alternating manner (right).

Self-Organized Oscillations at Bottlenecks and Synchronization

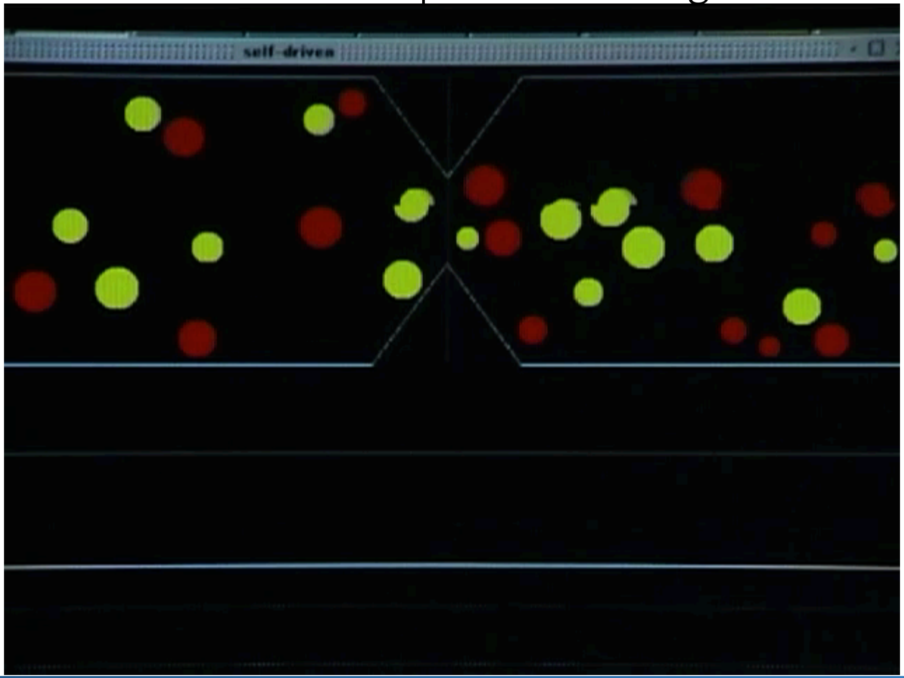


Pressure-oriented, autonomous, distributed signal control:

- Major serving direction alternates, as in pedestrian flows at intersections
- Irregular oscillations, but ‘synchronized’

In huge street networks:

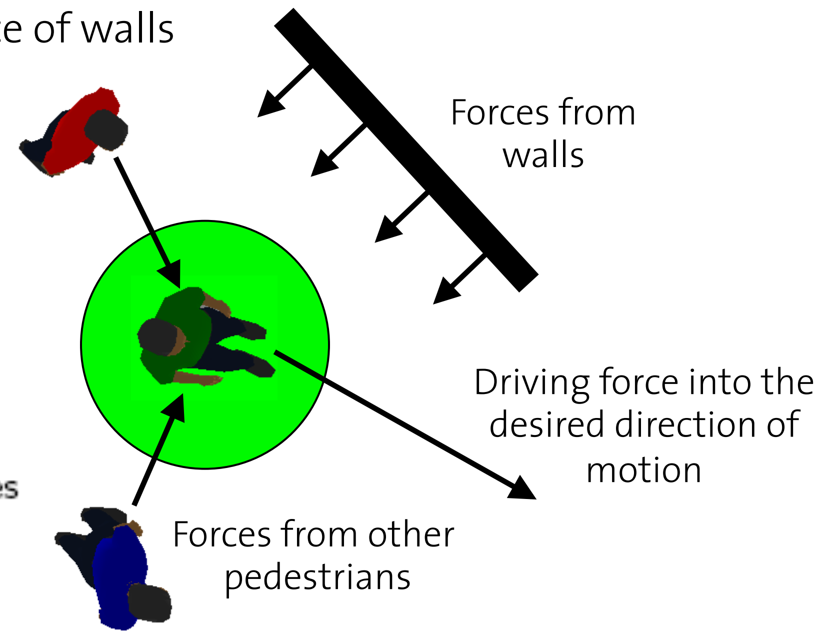
‘Synchronization’ of traffic lights due to vehicle streams spreads over large areas



The Social Force Model

The social force model assumes individual goals (to reach a certain destination efficiently), social interactions (e.g. avoidance of collisions), and institutional setting (e.g. walls). It is composed of the following forces:

- Driving forces (to maintain the desired walking direction and speed)
- Social repulsive forces (to keep a private sphere around oneself)
- Social attractive forces among group members
- Repulsive forces reflecting the influence of walls
- Fluctuation forces describing variations in behavior



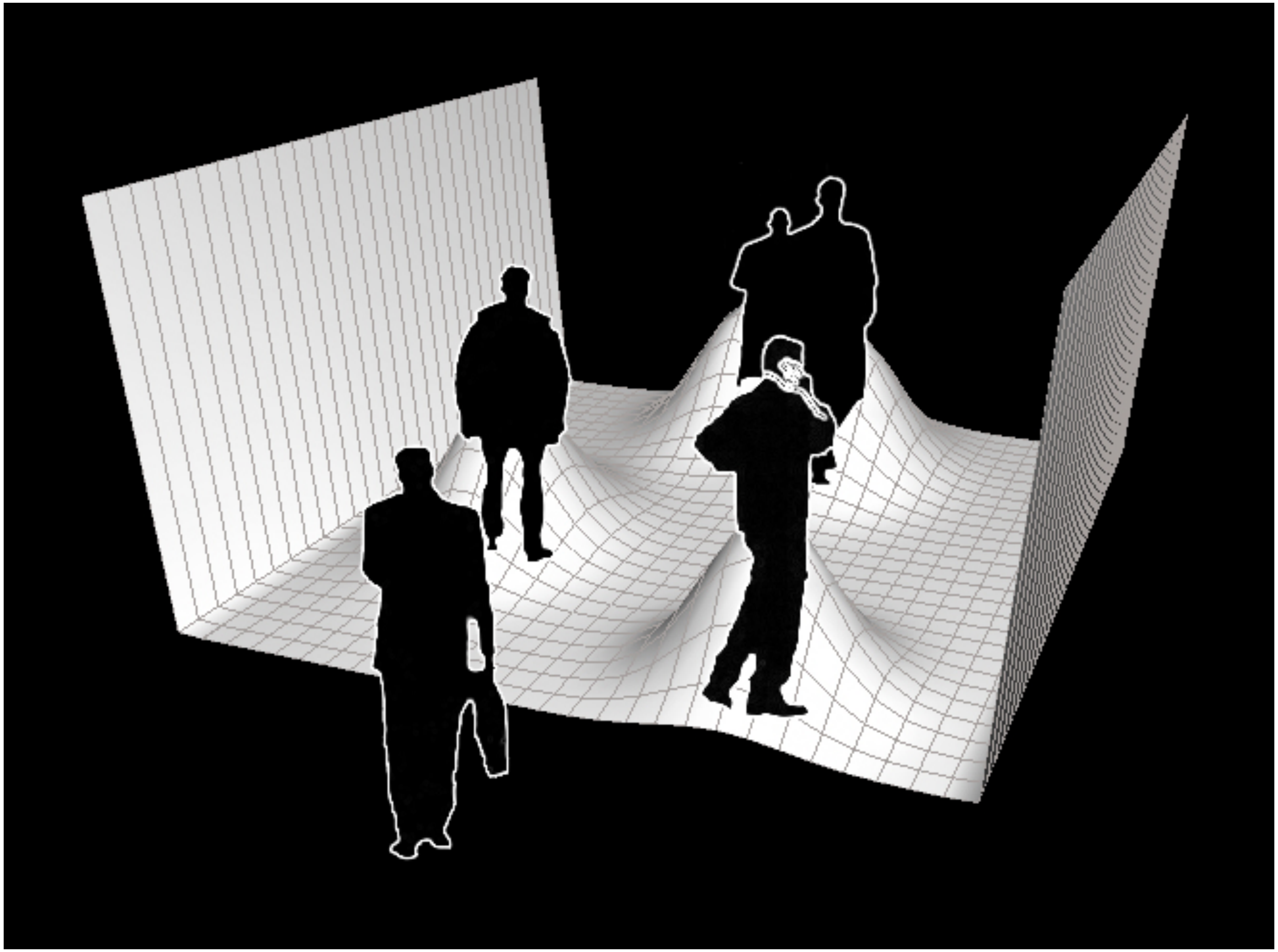
$$\frac{dx_\alpha}{dt} = v_\alpha(t)$$ (equation of motion)

$$\underbrace{\frac{dv_\alpha}{dt}}_{\text{acceleration}} = \underbrace{\frac{1}{\tau_\alpha}(v_\alpha^0 e_\alpha^0 - v_\alpha)}_{\text{driving force}} + \underbrace{\sum_{\beta(\neq\alpha)} F_{\alpha\beta}^{\text{int}}}_{\text{interactions}} + \underbrace{F_\alpha^{\text{walls}}}_{\text{boundaries}}$$

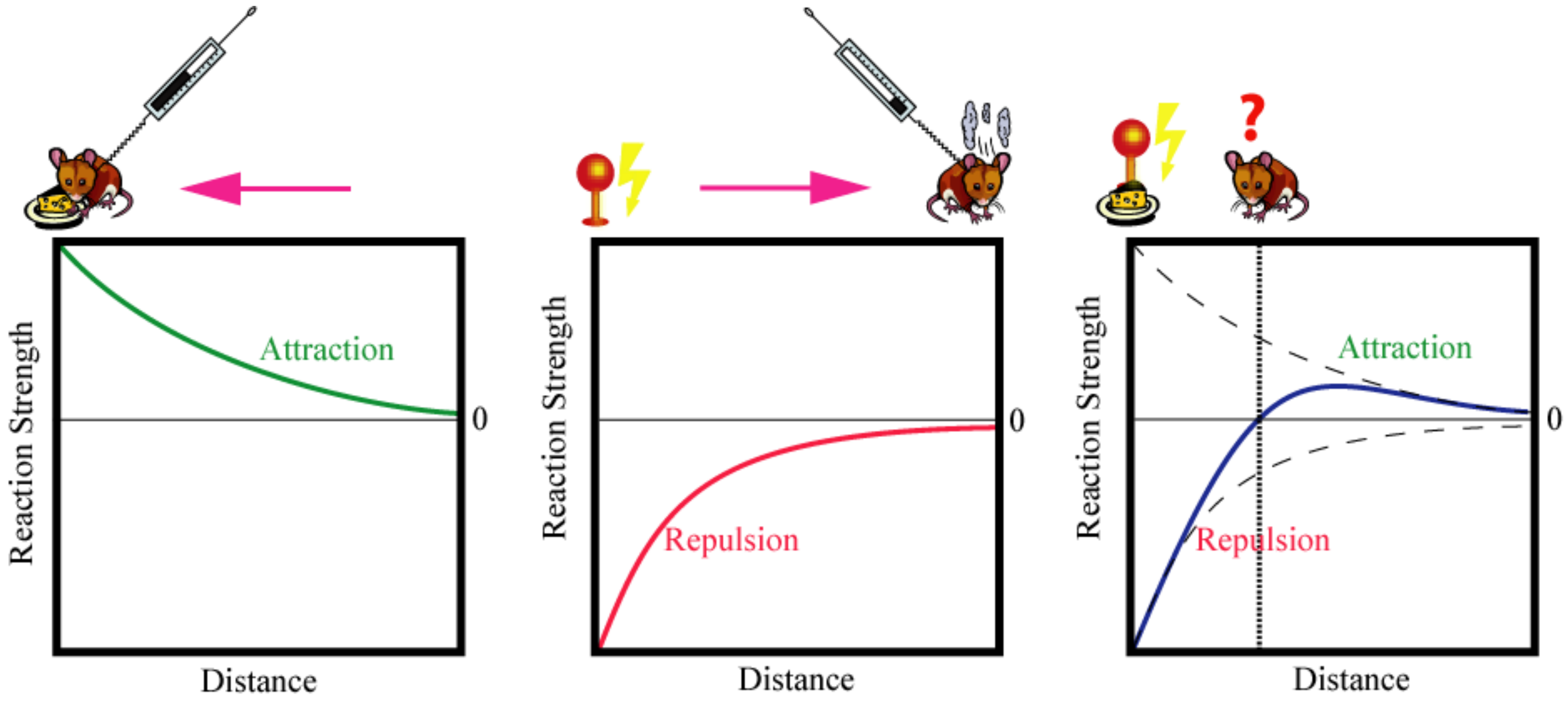
(acceleration equation)

As people show a pretty standard behavior in walking interactions and constrain each others' motion, the dynamics of crowds can be relatively well predicted.

Visualization of Repulsive Interactions in the Social Force Model



Behavior in Conflict Situations and Superposition of Forces



Social Force Model of Pedestrian Dynamics

Equation of Motion:

$$\frac{d\vec{x}_i(t)}{dt} = \vec{v}_i(t)$$

Acceleration Equation for Pedestrians:

$$\underbrace{m_i \frac{d\vec{v}_i(t)}{dt}}_{\text{Acceleration}} = \underbrace{\frac{m_i}{\tau_i}\left(v_i^0 \vec{e}_i(t) - \vec{v}_i(t)\right)}_{\text{Driving Force}} + \underbrace{\sum_{j(\neq i)} \vec{F}_{ij}^{ww}(t)}_{\text{Interactions}} + \underbrace{\vec{F}_i^{b}(t)}_{\text{Borders, Fire}} + \underbrace{\sum_k F_{ik}^{att}(t)}_{\text{Attractions}} + \underbrace{\vec{\xi}_i(t)}_{\text{Fluctuations}}$$

$$\vec{F}_{ij}^{ww}(t) = \underbrace{\vec{F}_{ij}^{psy}(t)}_{\text{Psychological Repulsion}} + \underbrace{\vec{F}_{ij}^{ph}(t)}_{\text{Physical Interactions}} + \underbrace{\vec{F}_{ij}^{att}(t)}_{\text{Attractions between People}}$$

$\vec{x}_i$ = Place; t = Time; $\vec{v}_i$ = Speed; m_i = Mass; $\hat{o}_i$ = Acceleration Time; v_i^0 = Desired Velocity;
$\vec{e}_i$ = Desired Direction

Elliptical Social Force Model

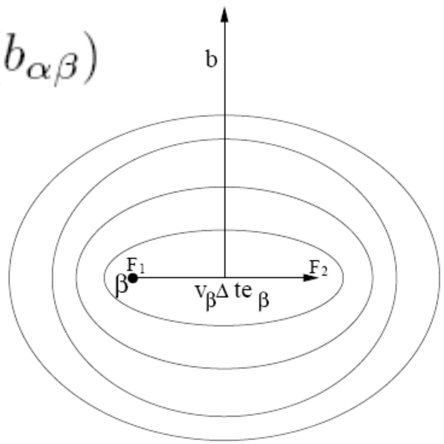
An improved, elliptical, specification of the social force model has been proposed, taking into account velocity and relative velocities. Δt reflects the time for a stride and b is the semi-minor axis of an ellipse directed into the direction of motion:

Repulsive potential:

$$V_{\alpha\beta}(b) = AB\,\mathrm{e}^{-b_{\alpha\beta}/B}$$

Repulsive force:

$$\vec{g}_{\alpha\beta}(\vec{d}_{\alpha\beta}) = -\vec{\nabla}_{\vec{d}_{\alpha\beta}} V_{\alpha\beta}(b_{\alpha\beta})$$



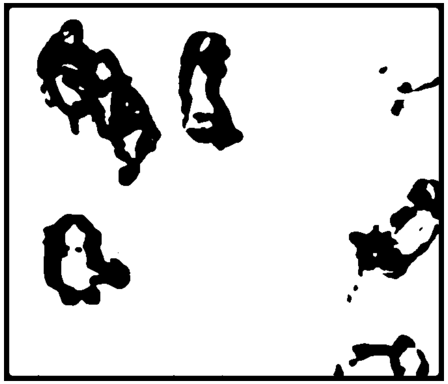
Elliptical specification I:

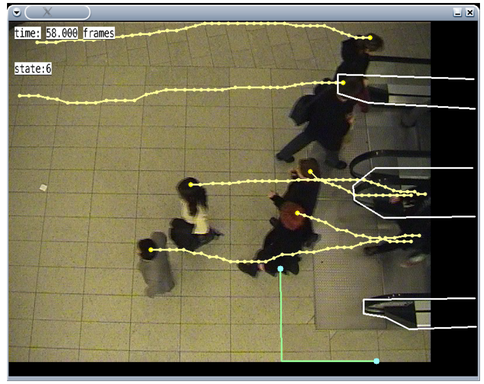
$$2b = \sqrt{(\|\vec{d}_{\alpha\beta}\| + \|\vec{d}_{\alpha\beta} - v_\beta\,\Delta t\,\vec{e}_\beta\|)^2 - (v_\beta\,\Delta t)^2}$$

Elliptical specification II:

$$2b = \sqrt{(\|\vec{d}_{\alpha\beta}\| + \|\vec{d}_{\alpha\beta} - (\vec{v}_\beta - \vec{v}_\alpha)\Delta t\|)^2 - [(\vec{v}_\beta - \vec{v}_\alpha)\Delta t]^2}$$

Evaluation of Pedestrian Trajectories



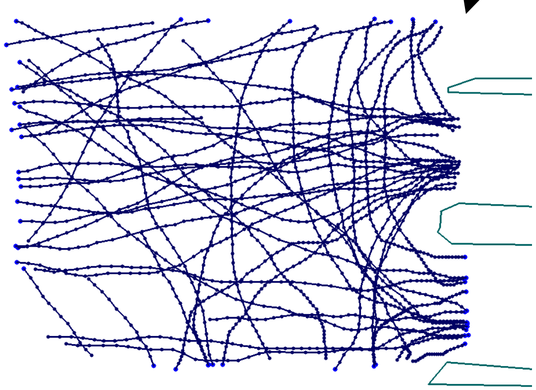


Calculate trend matrices:

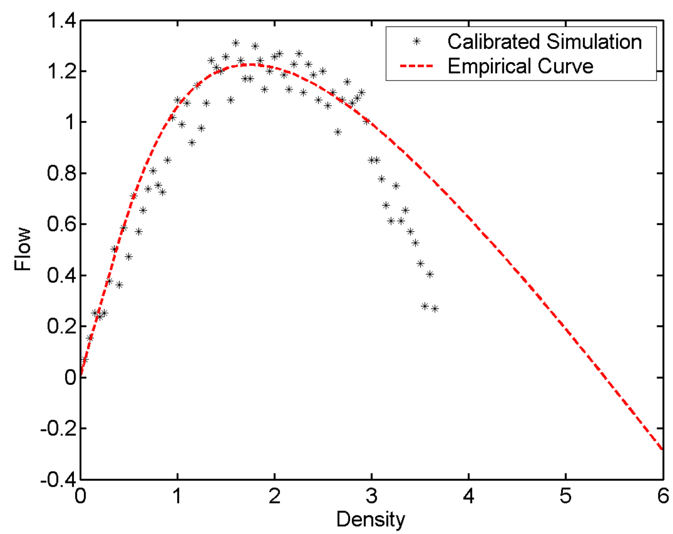
$\mathrm{Trend}_0 = \mathrm{Frame}_n - \mathrm{Frame}_{n-1}$

$\mathrm{Trend}_1 = \mathrm{Frame}_{n-1} - \mathrm{Frame}_{n-2}$

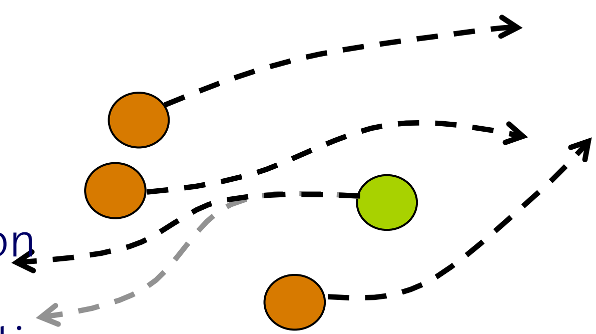
Recognize movement by searching for similarities in the local neighborhoods around each point in the trend matrices.



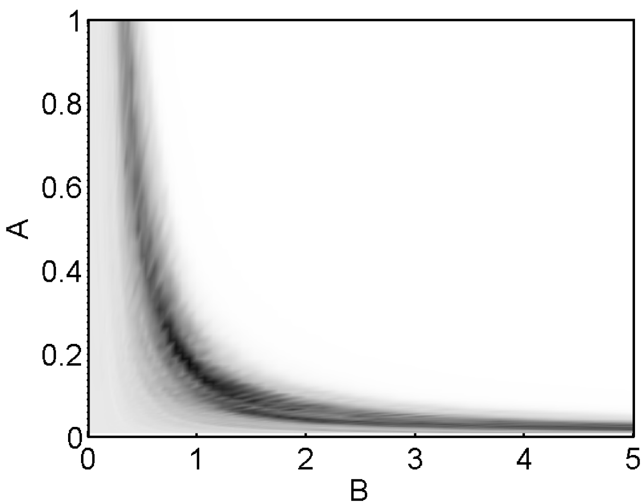
Transform the trajectory coordinates into the ground plane, by approximating each human to be 170 cm high.



Calibration with Genetic Algorithms



We use a hybrid model where n-1 of the n pedestrians are moving according to the trajectories from the videos, and 1 pedestrian is controlled by a micro-simulation. Then we have an error measure related to the deviation from our simulated position and the actual position from the video. With this error measure we can iterate a calibration process that will find an optimal set of simulation parameters.



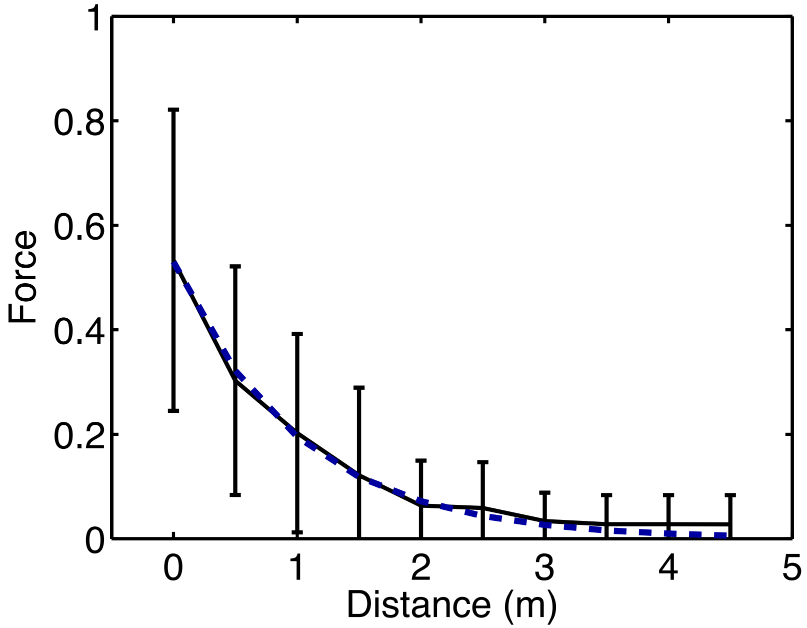
Model	A	B	λ	Fitness
Circular	0.11 ± 0.06	0.84 ± 0.63	1	-0.65
Elliptical I	1.52 ± 1.65	0.21 ± 0.08	1	-0.67
Elliptical II	4.30 ± 3.91	1.07 ± 1.35	1	-0.47
Circular	0.42 ± 0.26	1.65 ± 1.01	0.12 ± 0.07	-0.60
Elliptical I	0.11 ± 0.01	1.19 ± 0.45	0.16 ± 0.04	-0.59
Elliptical II	0.04 ± 0.01	3.22 ± 0.67	0.06 ± 0.04	-0.39

Distance Dependence

The distance-dependent function is investigated at the distances, 0m, 0.5m, 1m, ..., 4.5m, and when fitting these values with the videos (black curve) it matches very well to an exponential function (blue dotted curve).

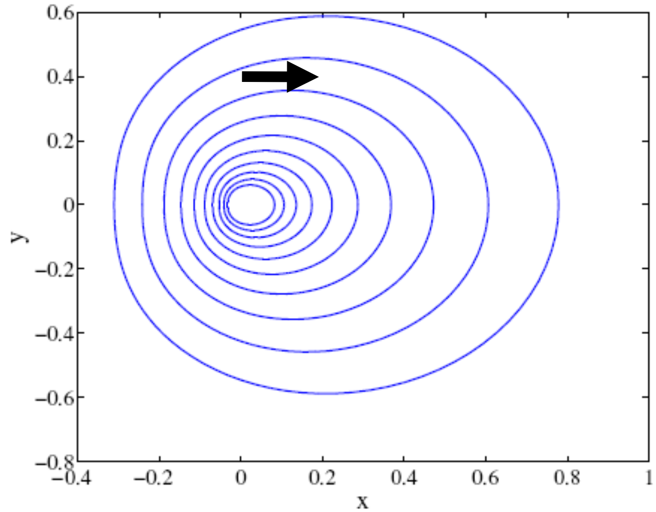
Black curve obtained from videos

Blue curve: exp(-d/0.5)

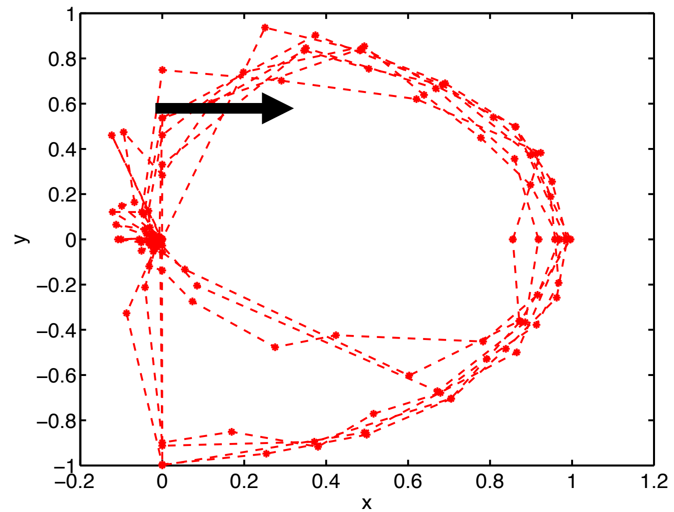


Angular Dependence

Similarly to how the distance-dependent function was obtained, we fit a polygon with 32 points distributed around each pedestrian, at fixed angles. When calibrating to the videos, it turns out that the angular dependence can be approximated with a half circle around the pedestrian.



$$w(\varphi_{\alpha\beta}(t)) = \left(\lambda_\alpha + (1-\lambda_\alpha)\frac{1+\cos(\varphi_{\alpha\beta})}{2}\right)$$

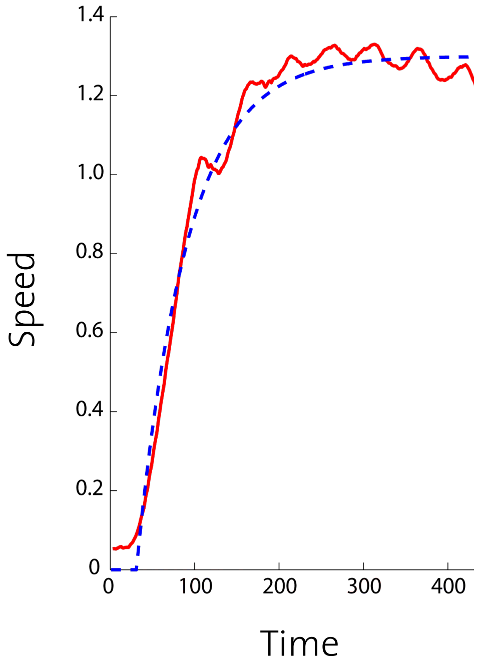


Polygons obtained from videos

Individual Behavior

Setup 1

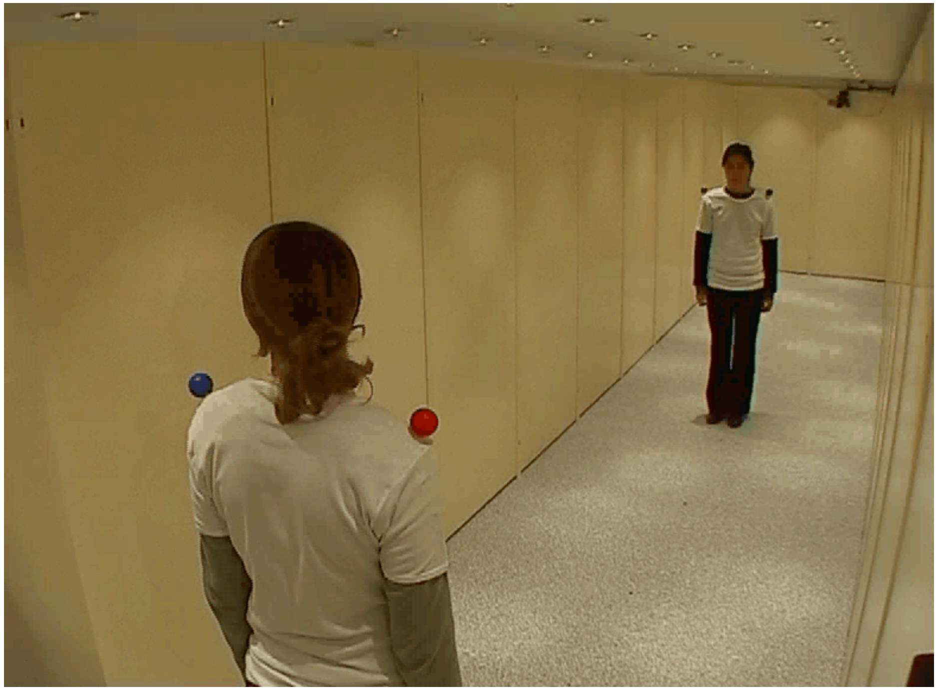
Single pedestrian's behavior



Average walking speed of single pedestrians

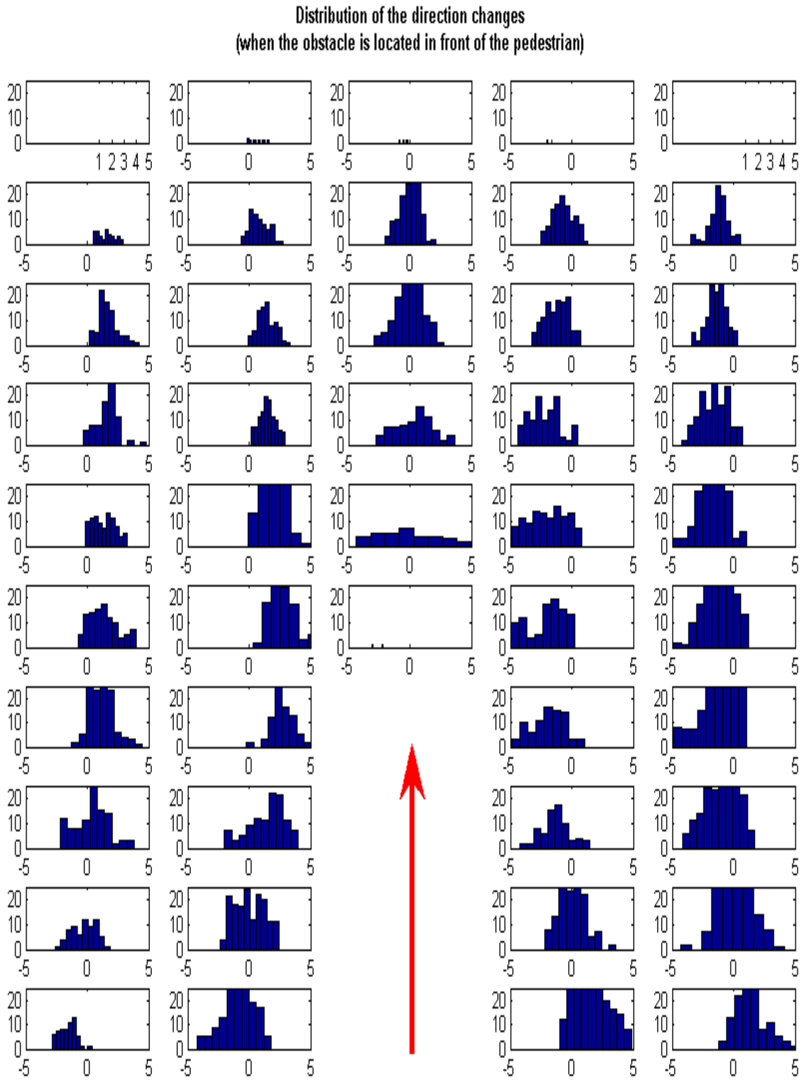
Individual Behavior

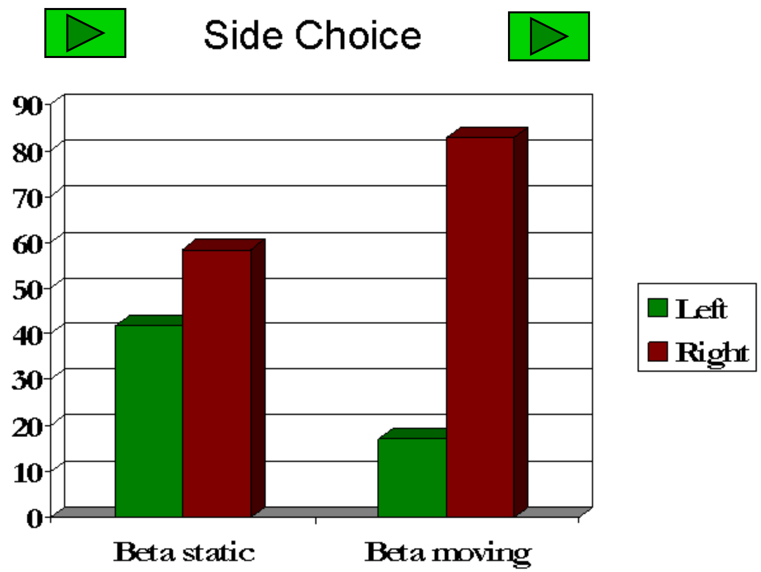
Setups 2 & 3



Avoidance of a static pedestrian

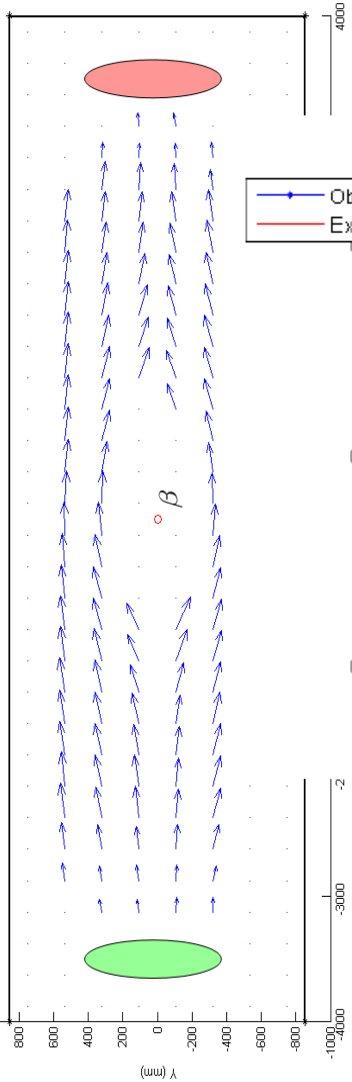
Avoidance of a moving pedestrian

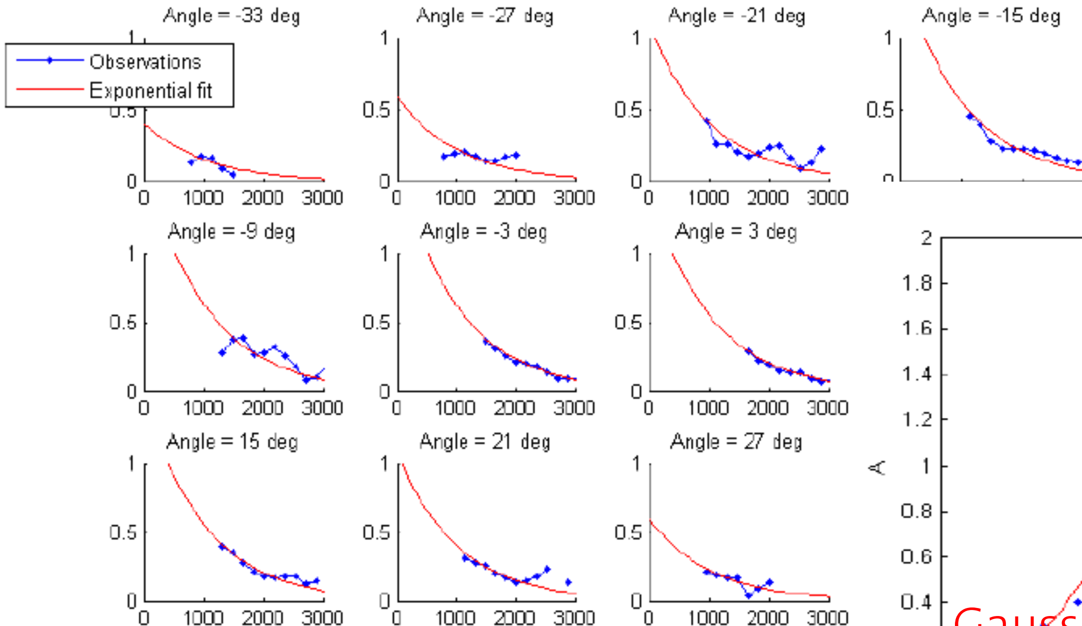

Distribution of the direction changes
(when the obstacle is located in front of the pedestrian)


Side Choice
Left
Right
Beta static
Beta moving

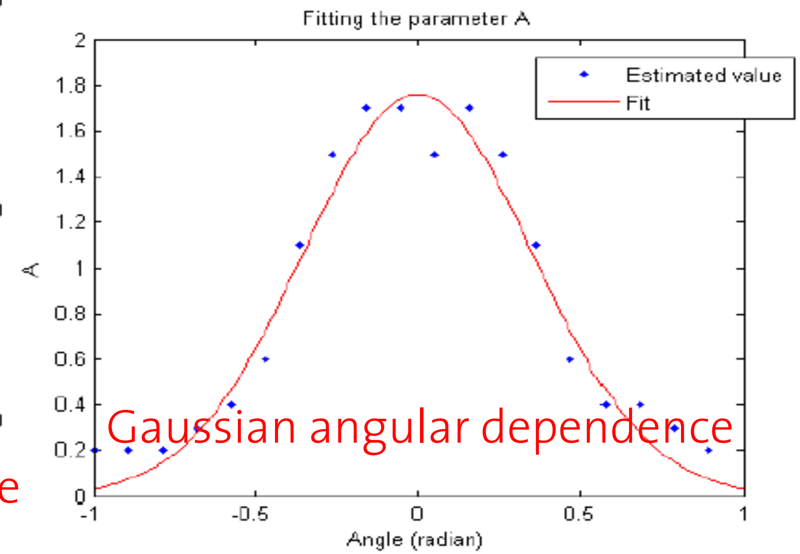
Experiments on Human Interactions in Space

Work in progress
with Guy Theraulaz
and Mehdi Moussaid





Exponential distance dependence



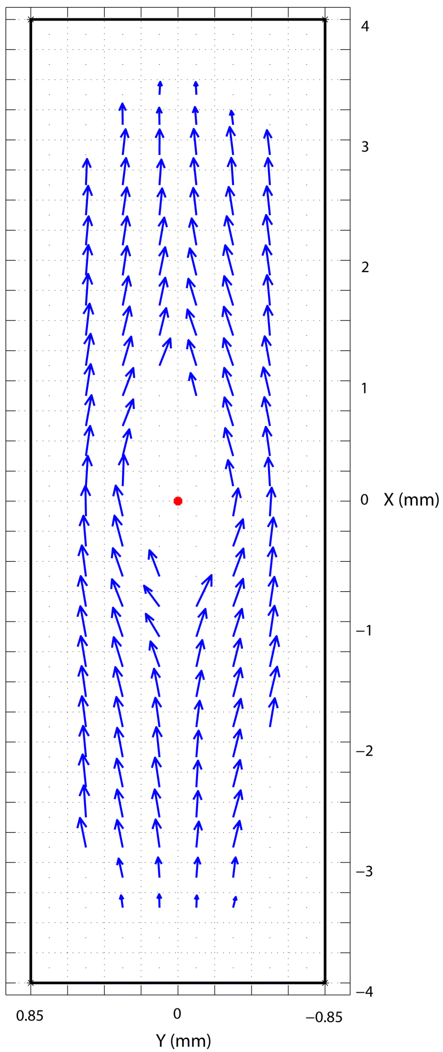
Gaussian angular dependence

$$F^{\text{int}}_{\alpha\beta} = \underbrace{F_v(d_{\alpha\beta},\varphi_{\alpha\beta})e_\alpha(t)}_{\text{velocity changes}} + \underbrace{[F_\varphi(d_{\alpha\beta},\varphi_{\alpha\beta})\xi_\alpha(\varphi_{\alpha\beta})]n_\alpha(t)}_{\text{directional changes}}$$

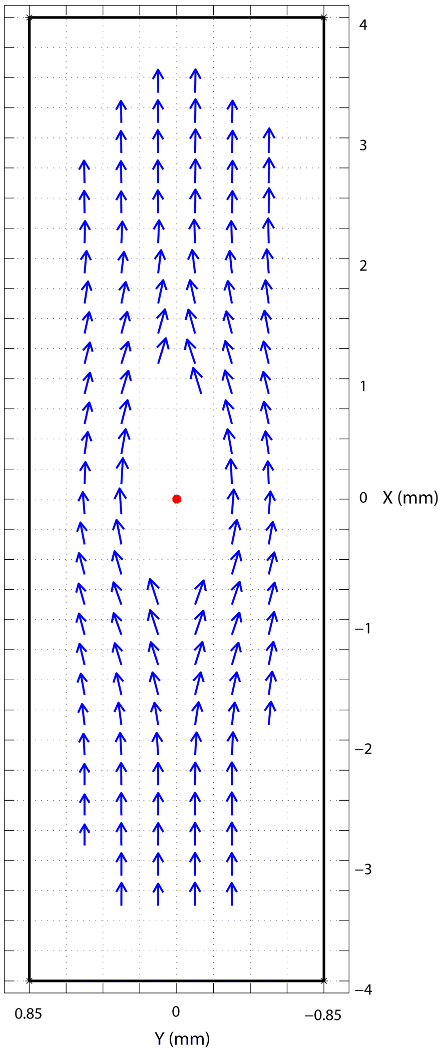
$$F_v(d,\varphi) = \mathrm{e}^{-5\varphi^2}\mathrm{e}^{-d} \qquad F_\varphi(d,\varphi) = 1.76\mathrm{e}^{-2\varphi^2}\mathrm{e}^{-d}$$

Comparison of Observations and Simulations

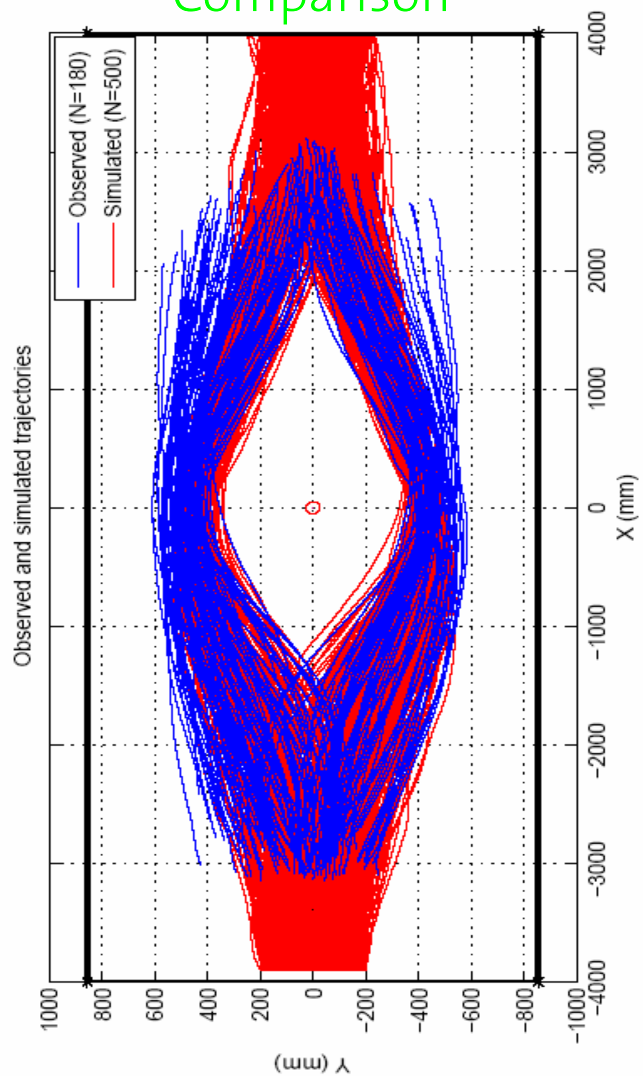
Observation



Simulation

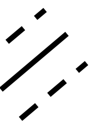


Comparison



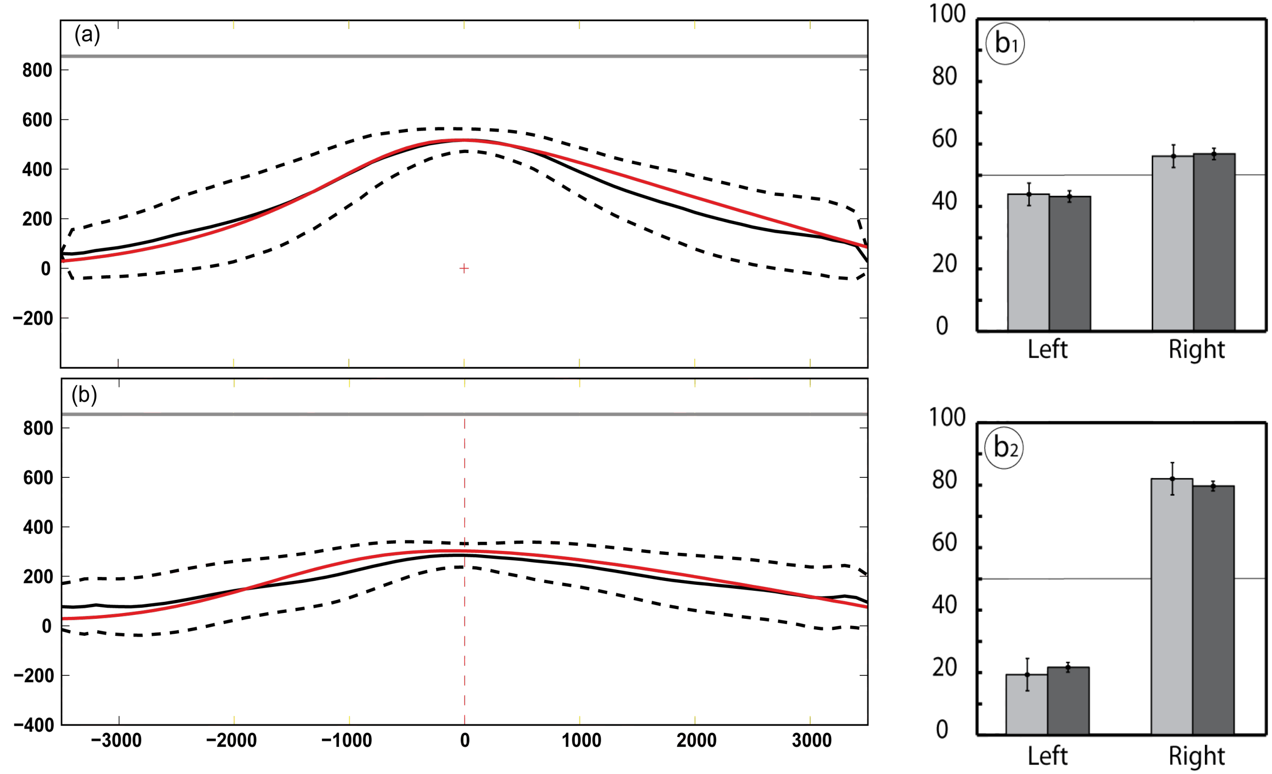
Validation 1: Corridor Experiment

- Quantitative validation

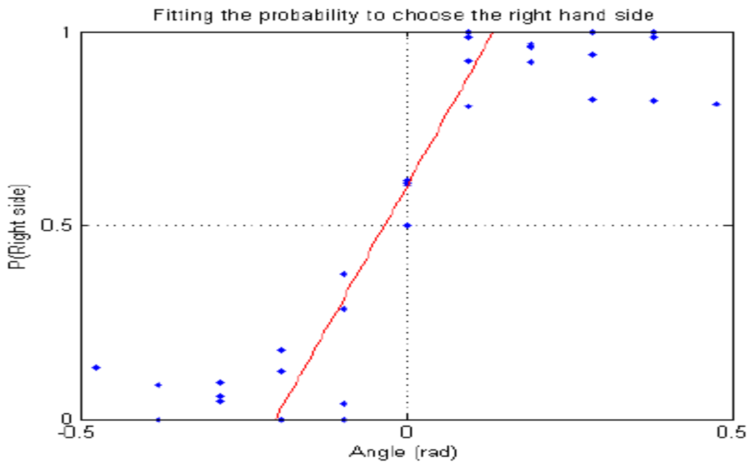


Average observed trajectory + std

Average simulated trajectory

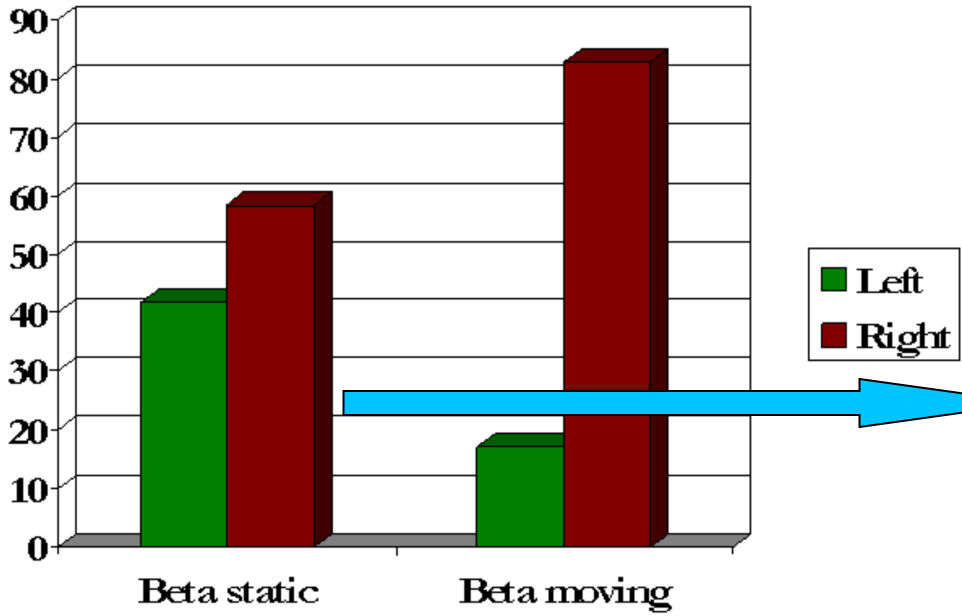


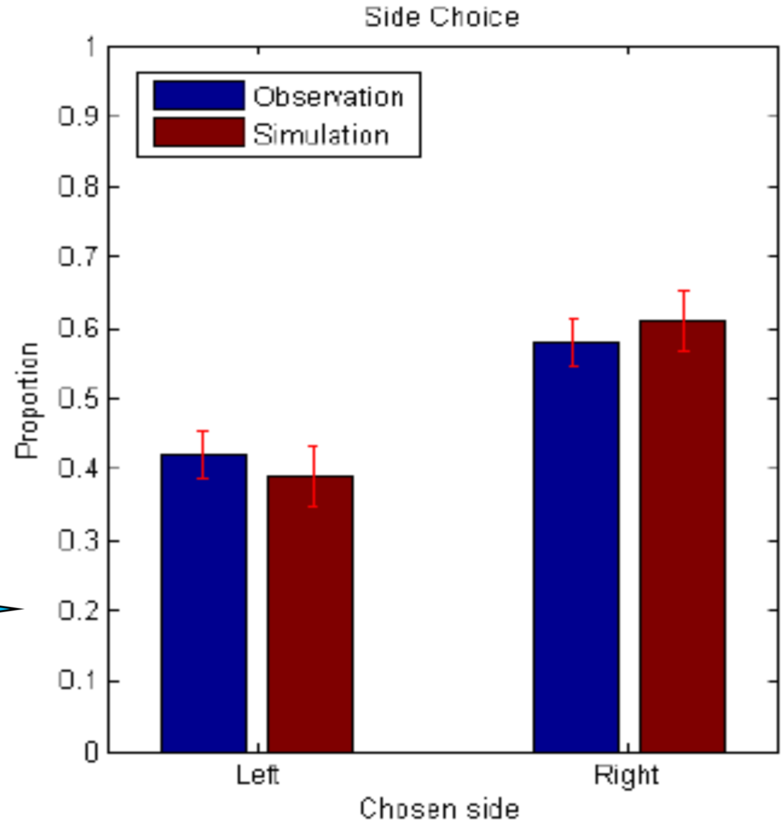
An Interactive Binary Decision Problem: Choice of Left vs. Right Side



$$\xi_\alpha = -1 \text{ with probability}$$

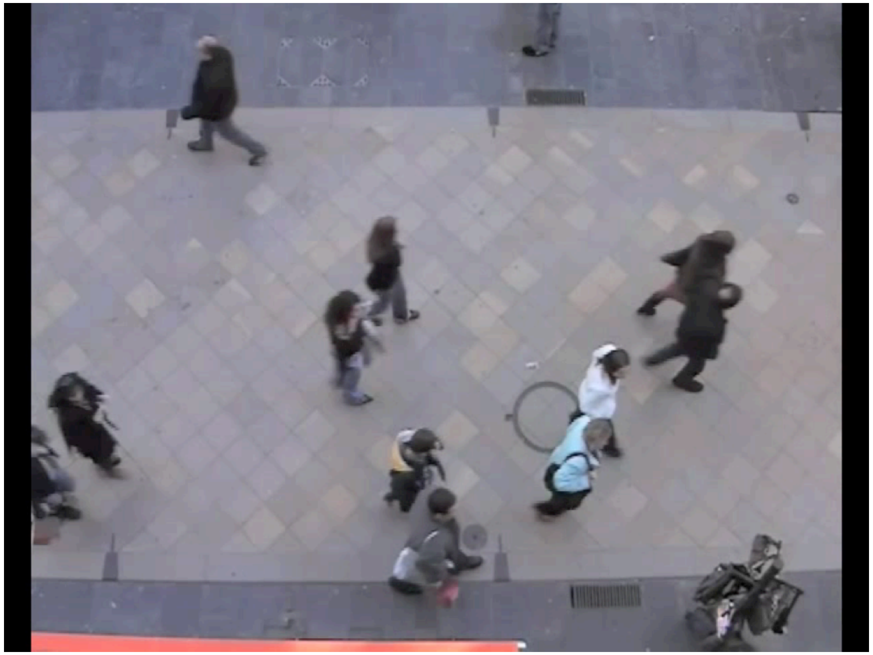
$$p_\alpha(\varphi) = \begin{cases} 0 & \text{if } \varphi < -0.2 \\ 0.57 + 2.85\varphi & \text{if } -0.2 \le \varphi \le 0.15 \\ 1 & \text{if } \varphi > 0.15 \end{cases}$$



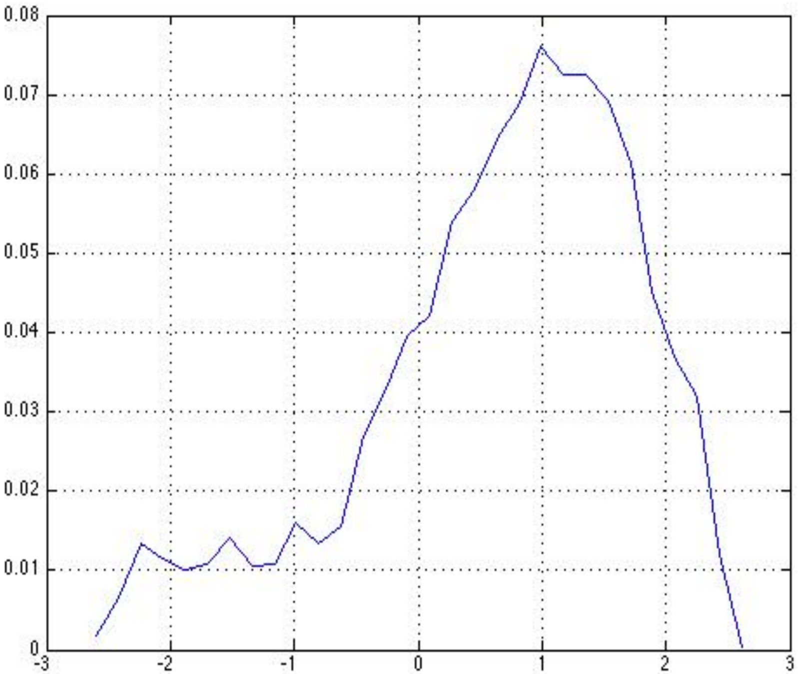


It's not just a repulsive interaction, but rather a decision problem!

Validation 2: Collective Dynamics

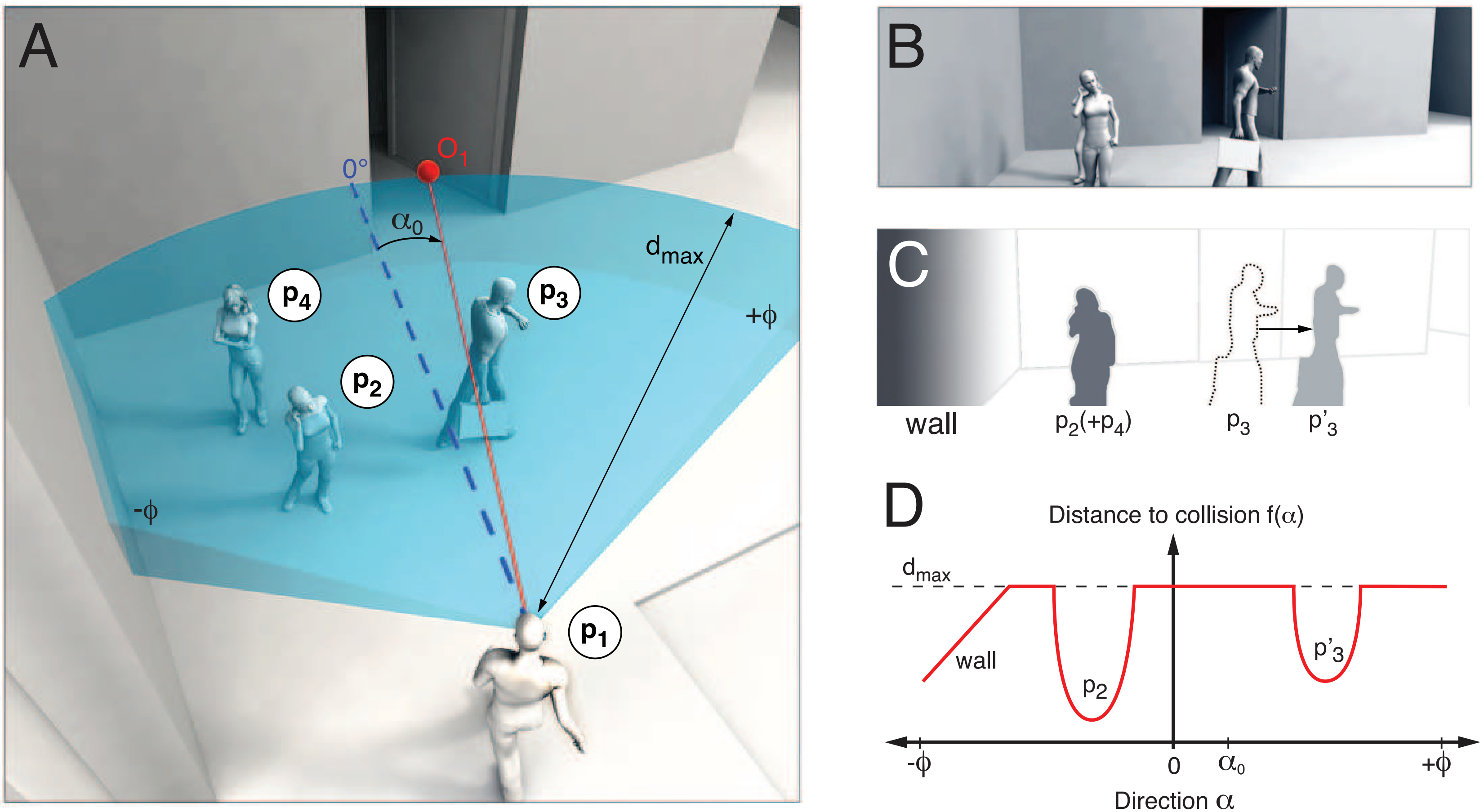


Observations in a crowded street



Asymmetry of flows (with respect to walking direction)

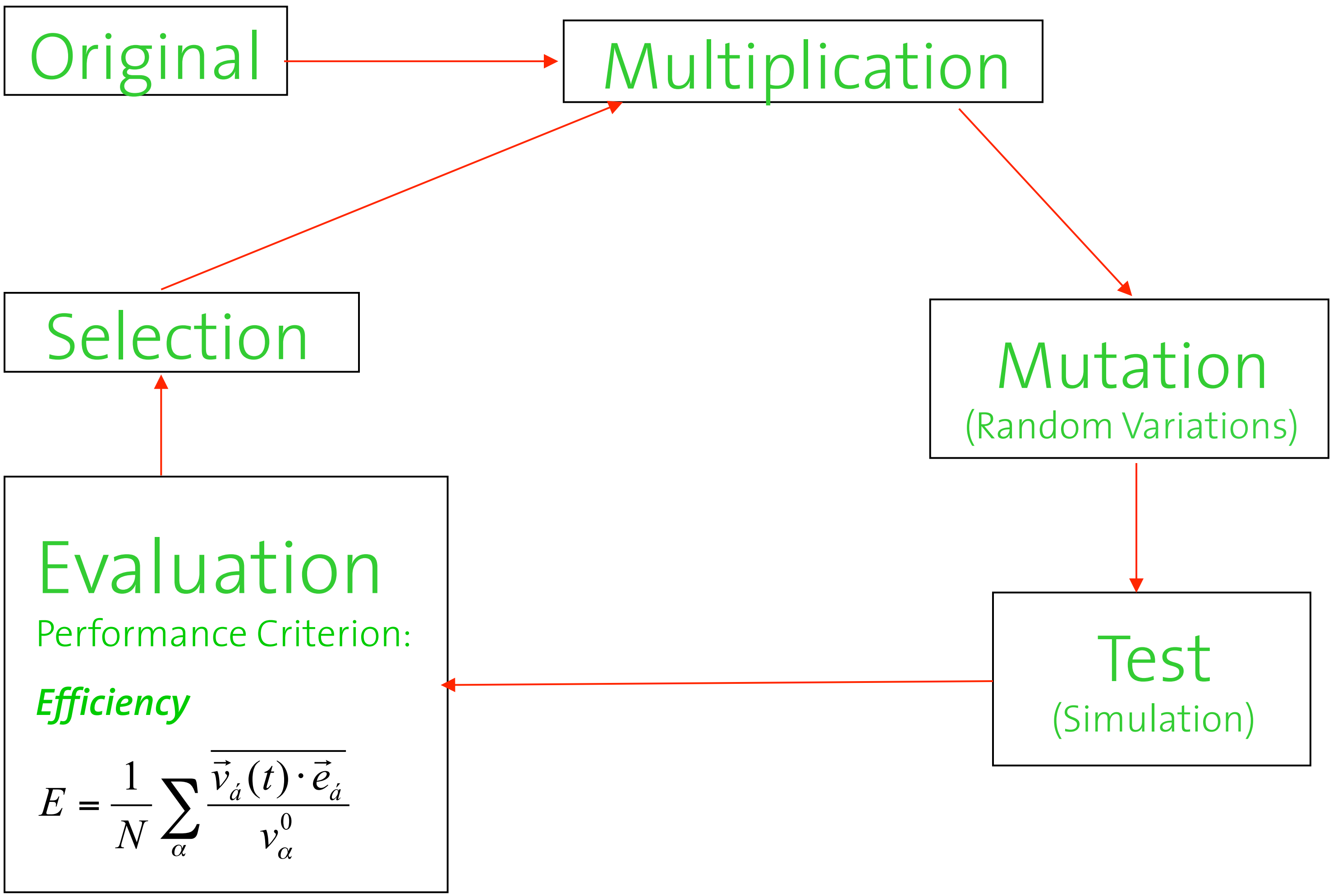
Visualization of the Cognitive (Heuristics) Model



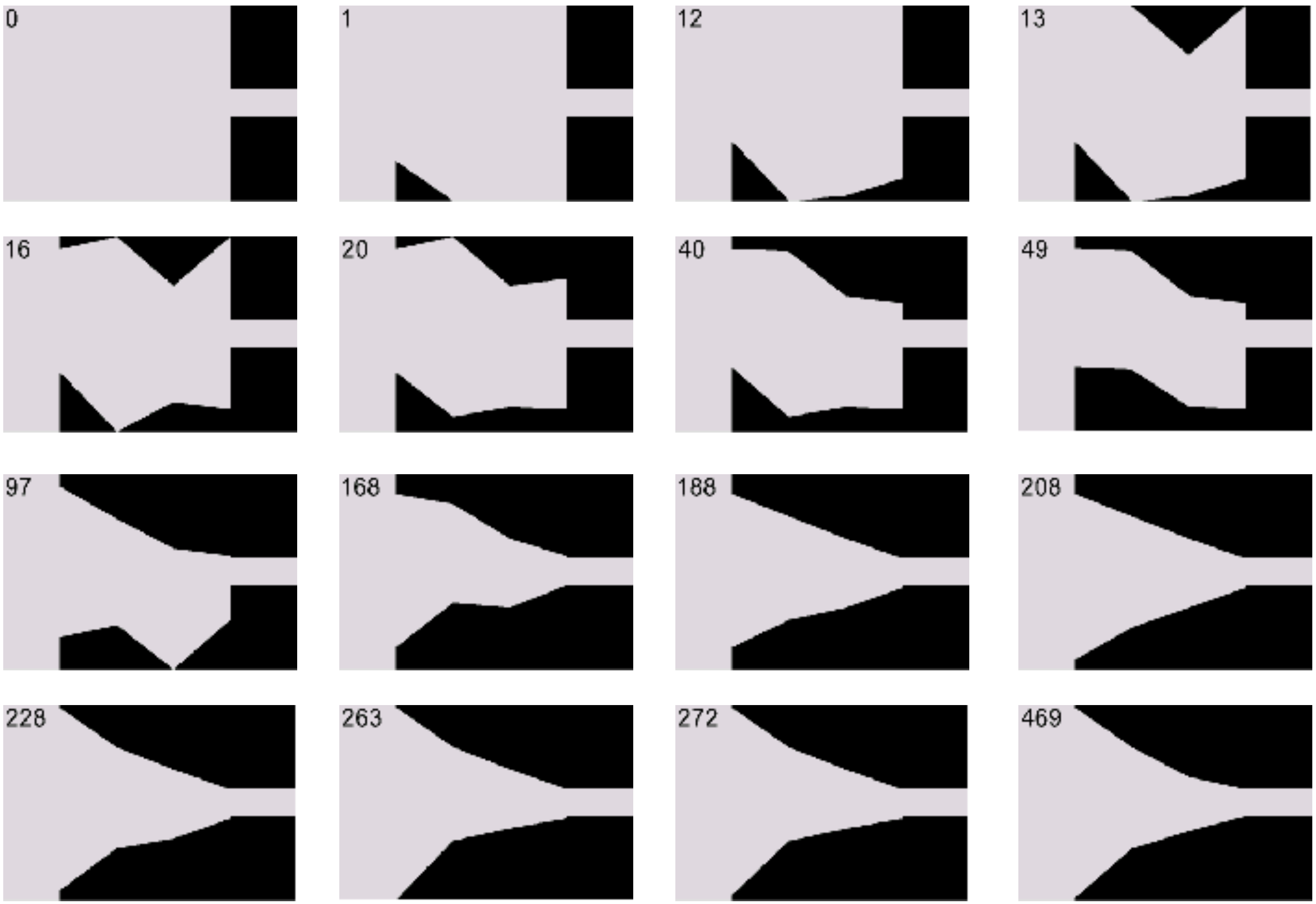
M. Moussaid et al, in PNAS

1. Walk into the least obstructed direction ("hunt for gaps")
2. Adjust speed to keep time headway constant

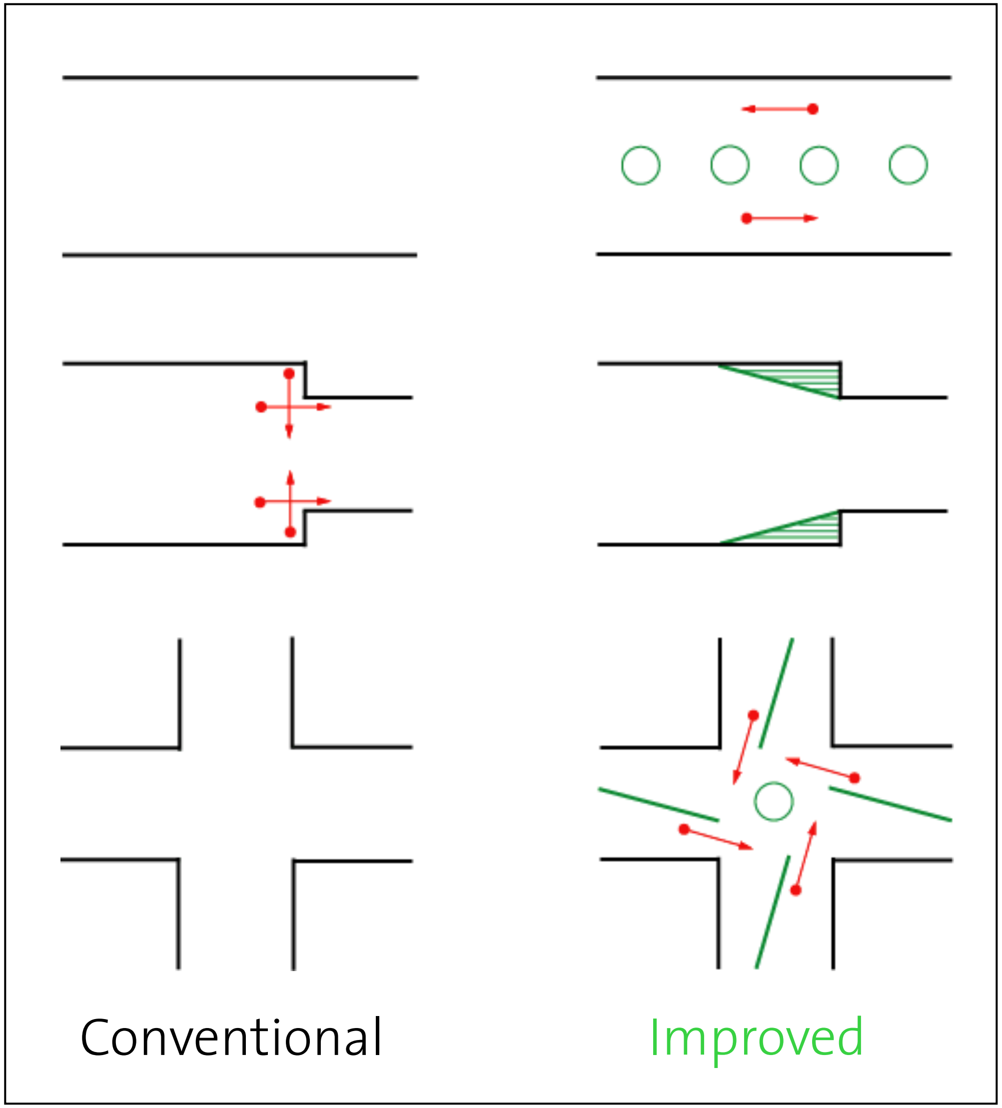
Evolutionary Optimization of Pedestrian Facilities



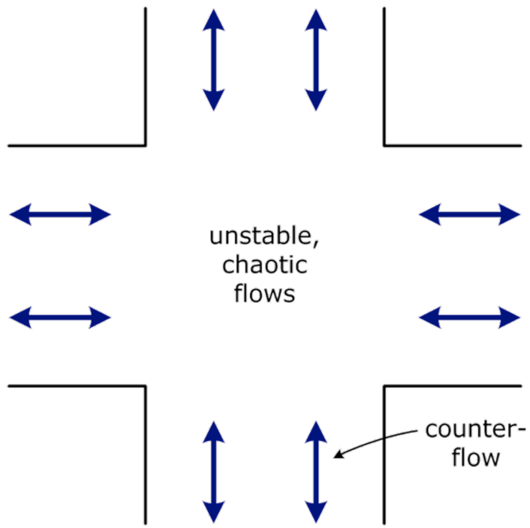
Evolutionary Optimization of a Bottleneck

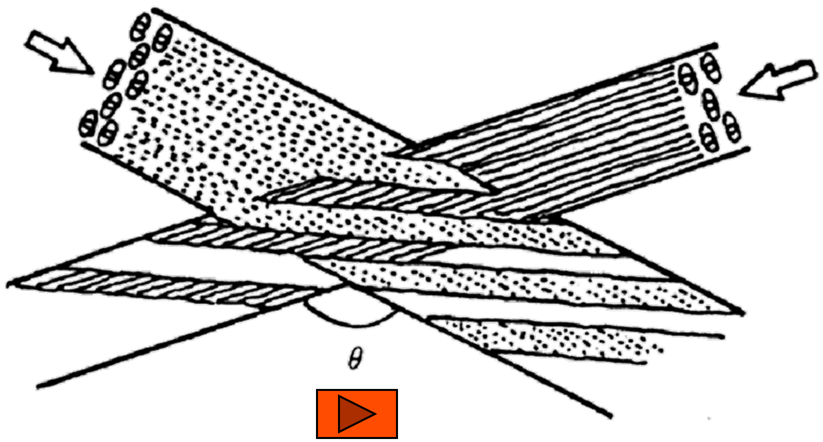


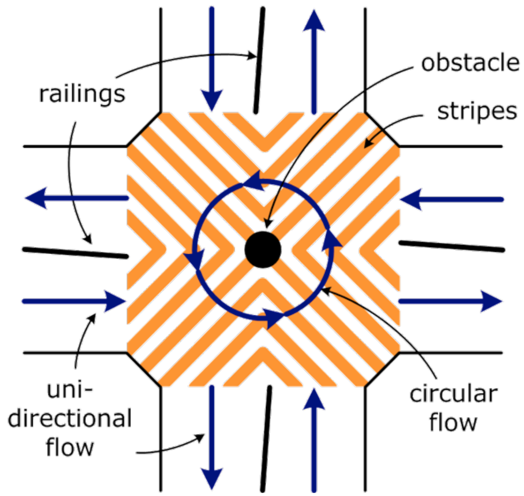
How to Optimize Pedestrian Facilities

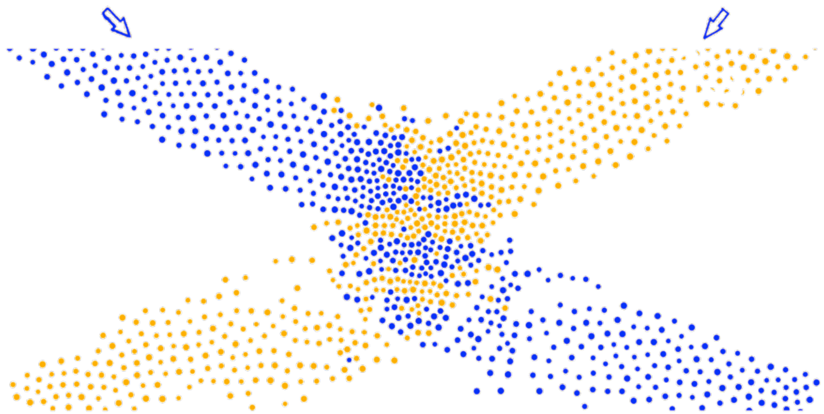


Self-Organization and Optimization of Intersecting Flows

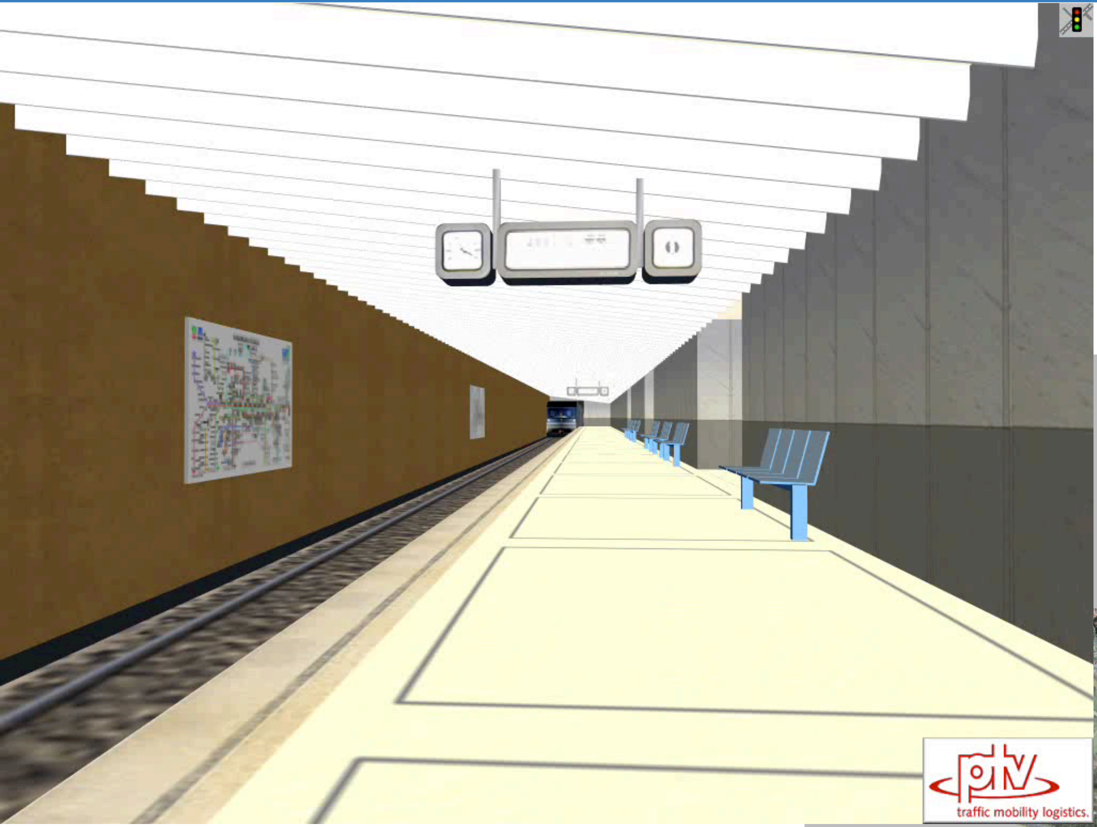


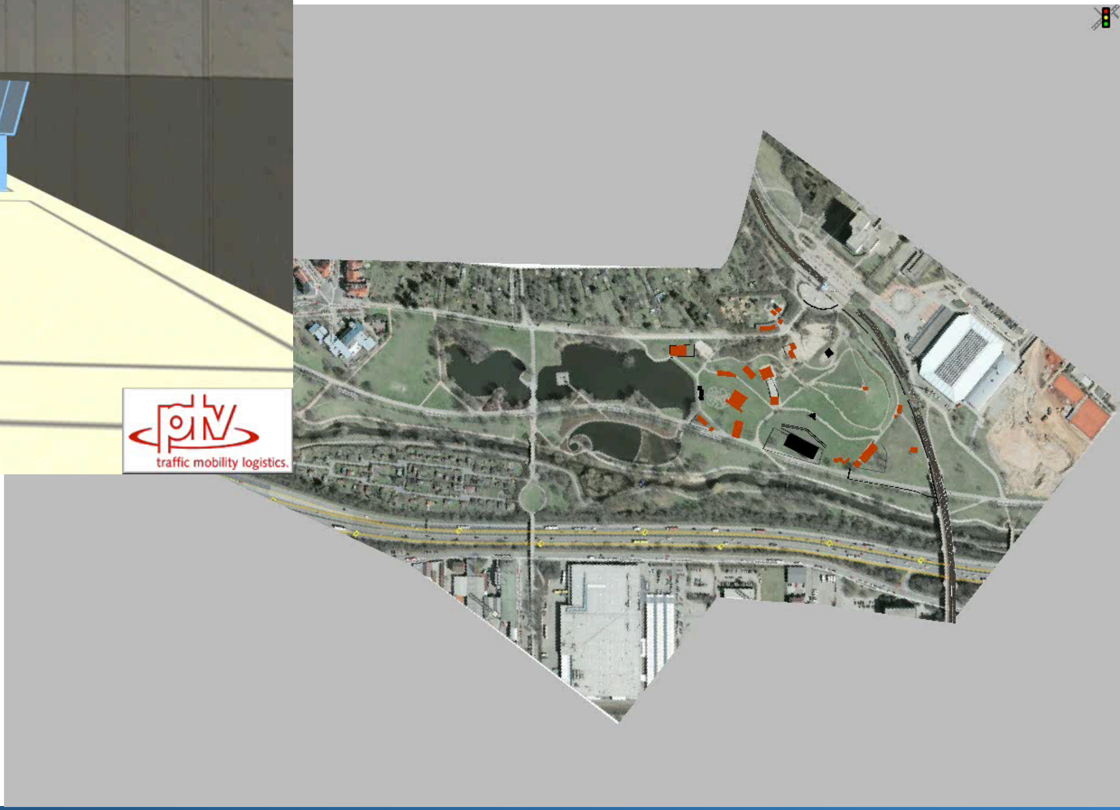




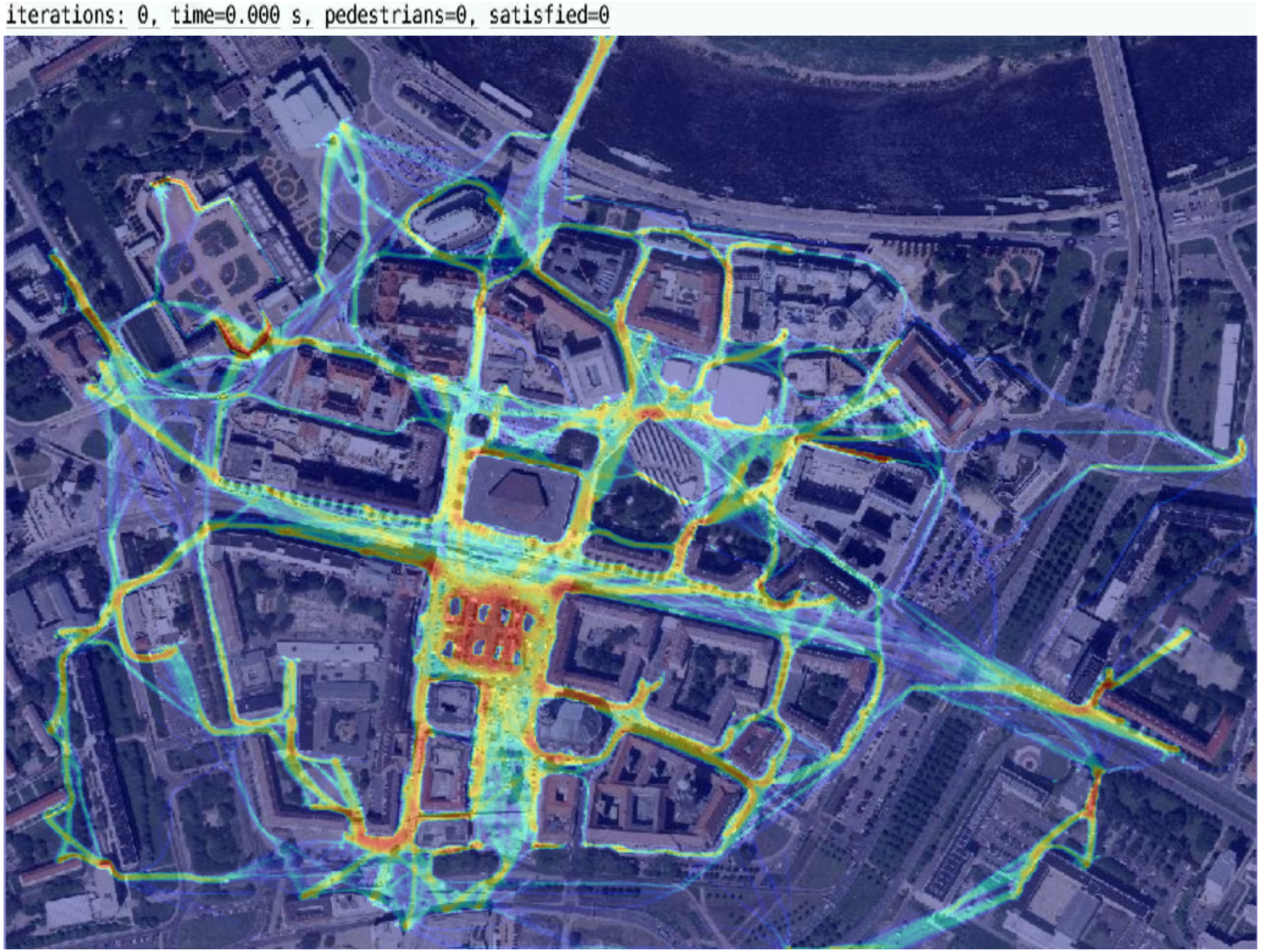


Social Force Model – Putting It All Together





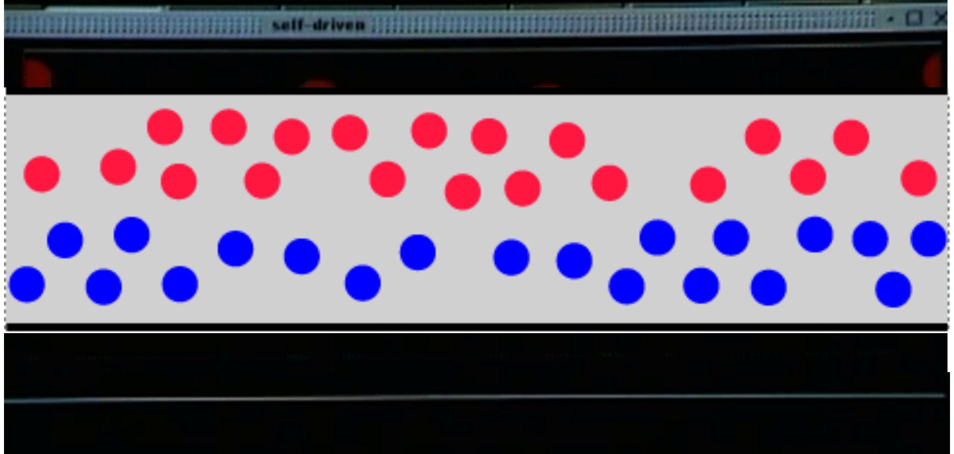
Large-Scale Simulation of Mass Events and Urban Areas



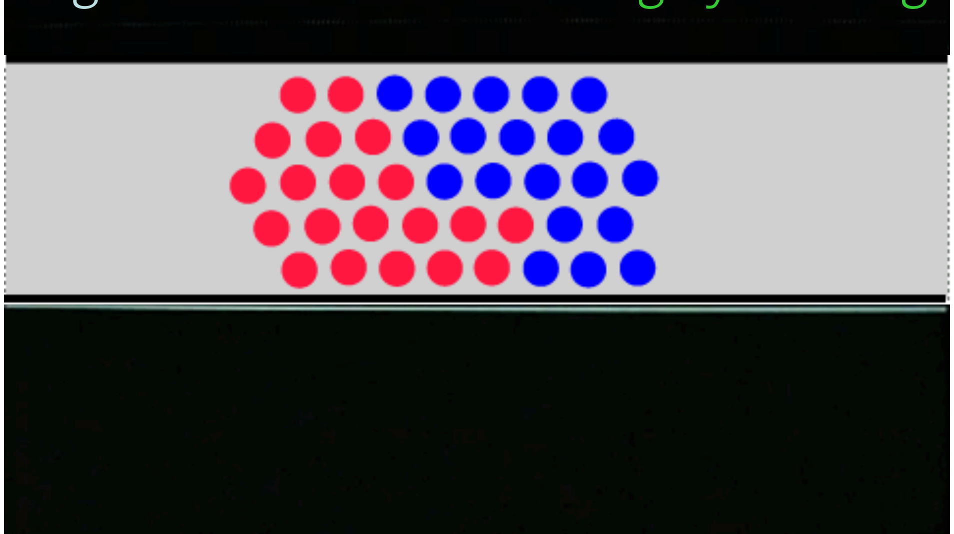
Dense Crowds and Crowd Disasters

Role of Fluctuations

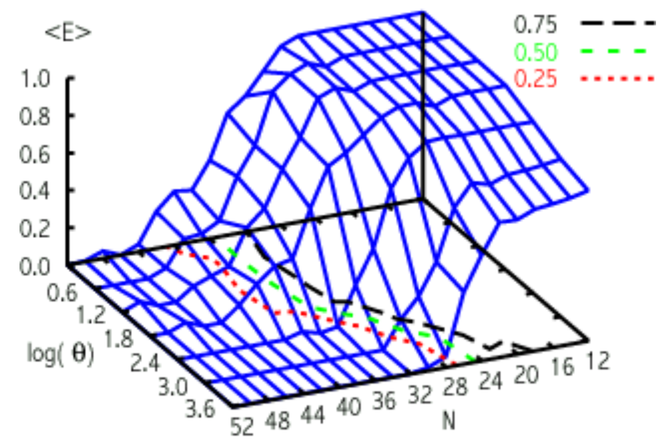
Small Fluctuations: Lane Formation



Large Fluctuations: "Freezing by Heating"



Ensemble-Averaged Efficiency

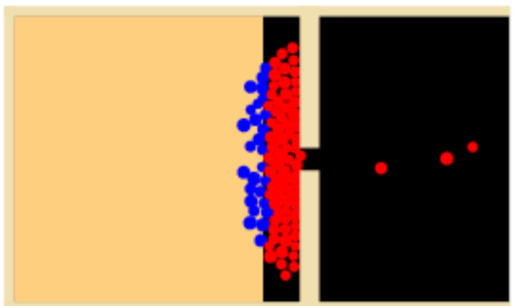


Reminder:
The temperature is proportional to the velocity variance.

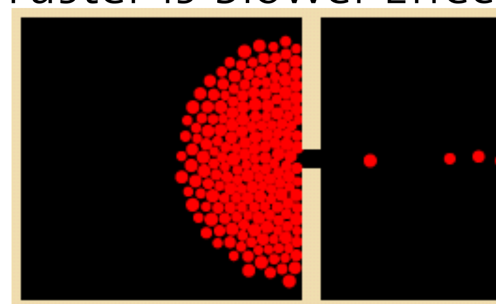
D.H., I. Farkas, T. Viscek, *Phys. Rev. Lett.* **84**, 1240 (2000).

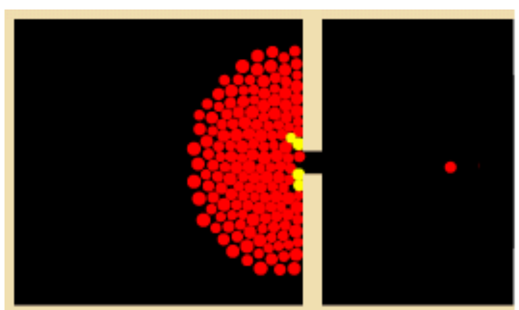
Clogging at Bottlenecks and "Faster-is-Slower Effect"

Physical Interactions and Friction Effects due to Uncontrolled Rush and Pushy Behavior

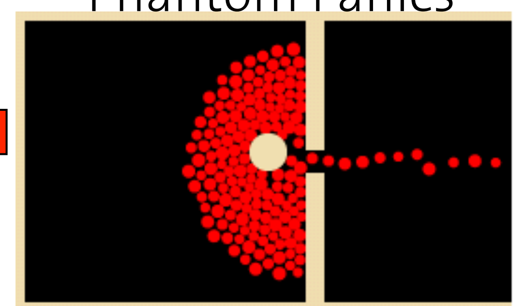


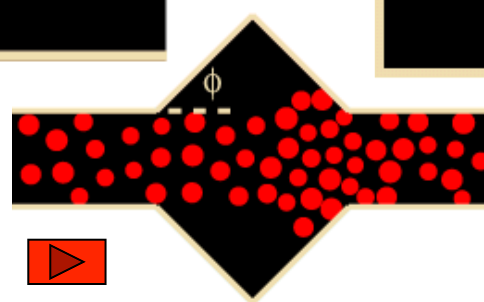
Faster-is-Slower Effect



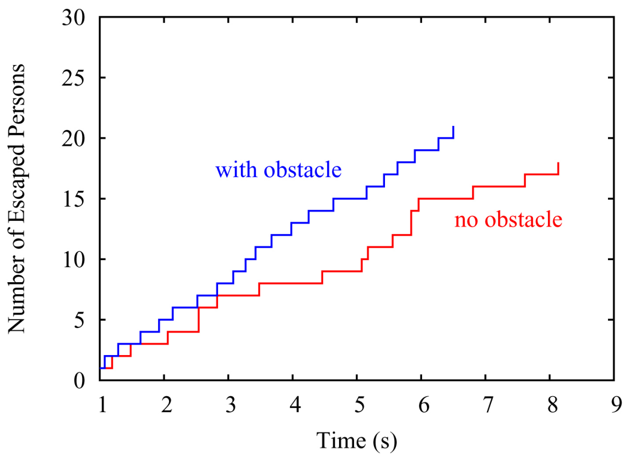


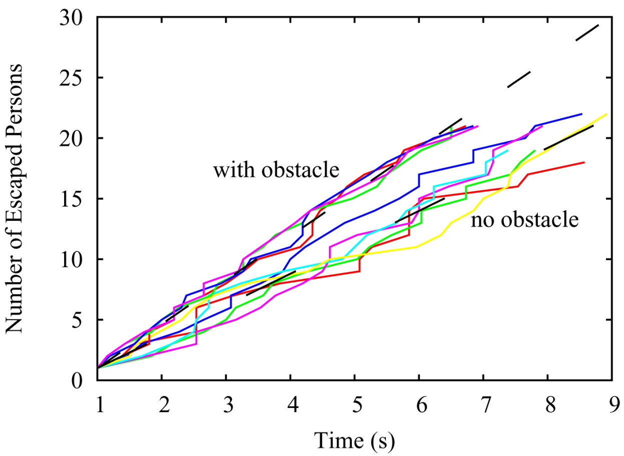
Phantom Panics





Practical Implications and Design Solutions



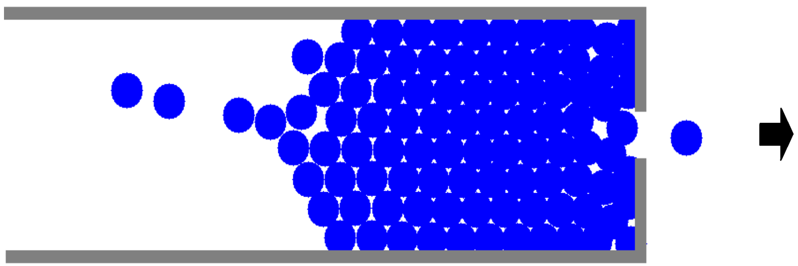


Without an obstacle one can observe clogging effects and a tendency of people to fall in panic situations (left).

The clogging effect can be significantly reduced by a suitable obstacle, which increases the efficiency of escape and diminishes the tendency of falling (right).

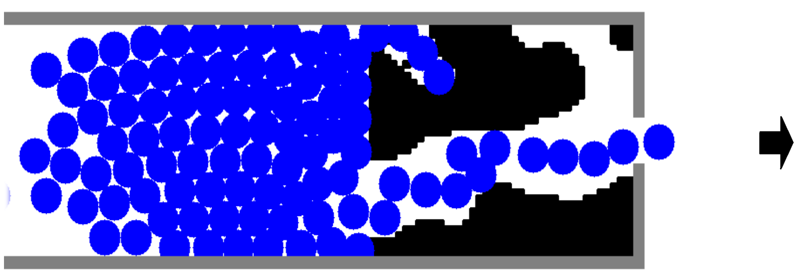
Typical Evolutionary Designs (Preliminary)

Snapshot; without obstacles



Zig-zag shape (fitness 1.78)

Snapshot; with obstacles

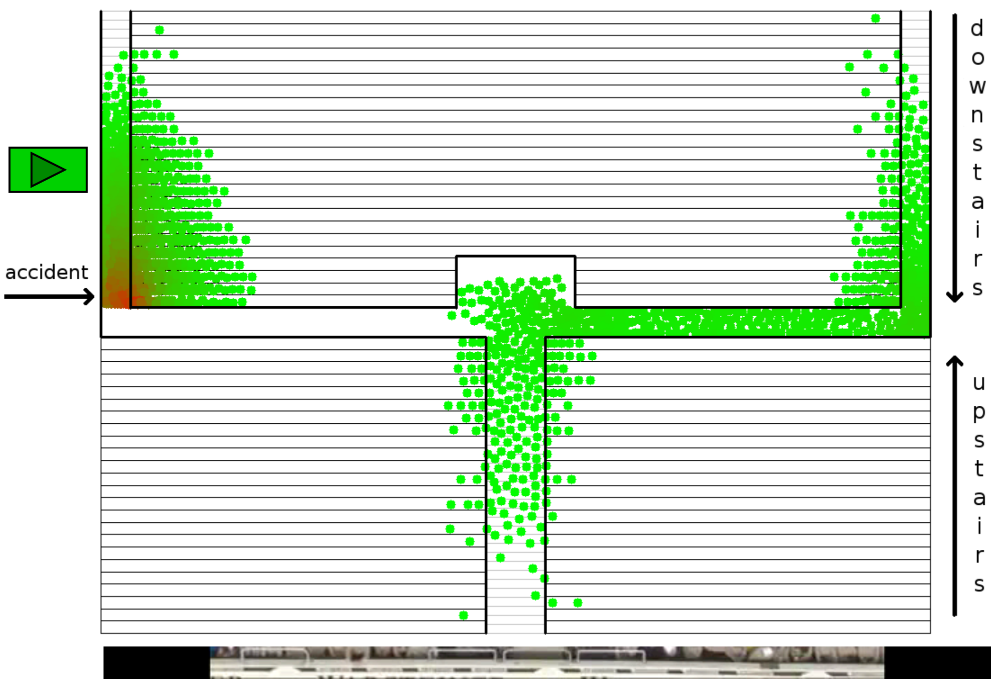


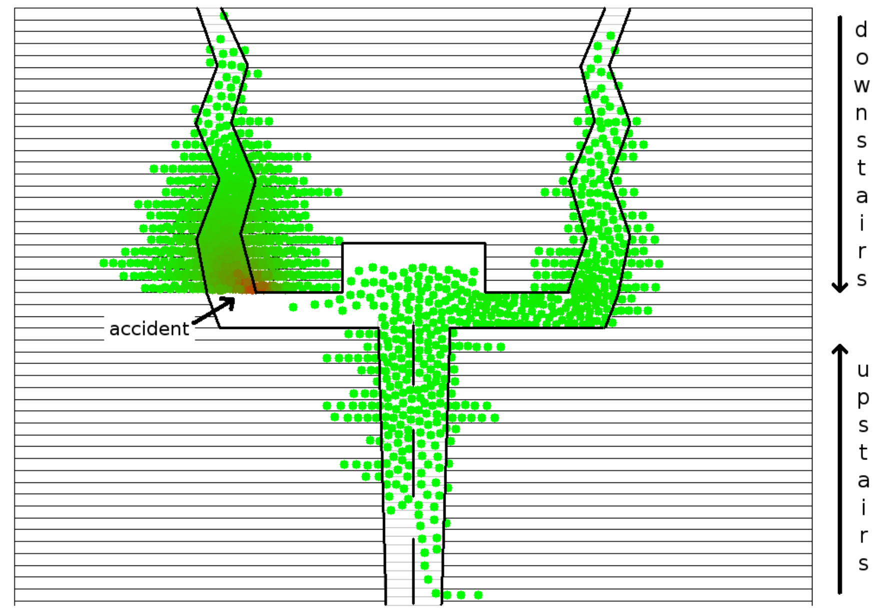
Funnel shape (fitness 1.99)

Safety Assessment of Architectural Designs

Conventional

Improved

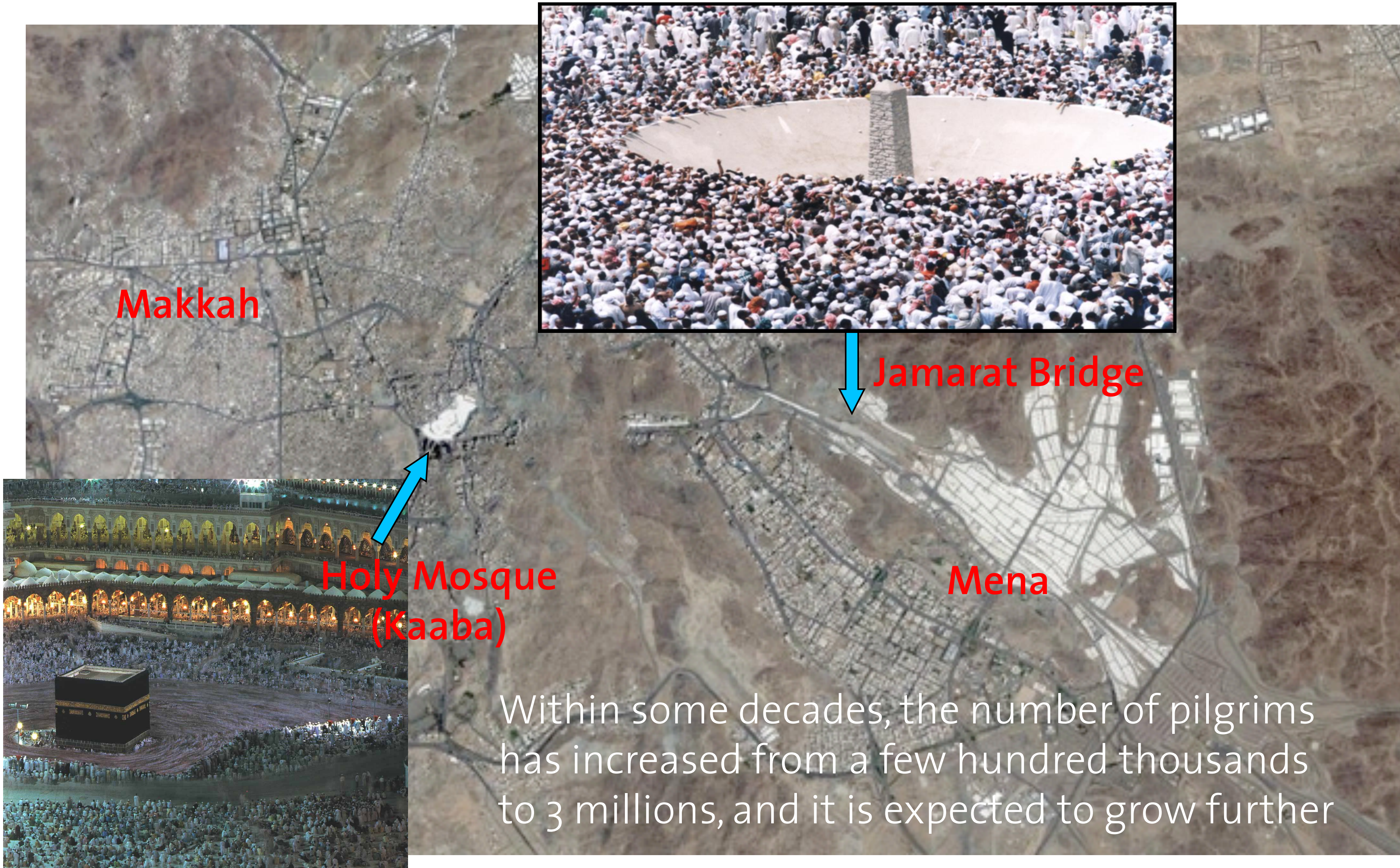




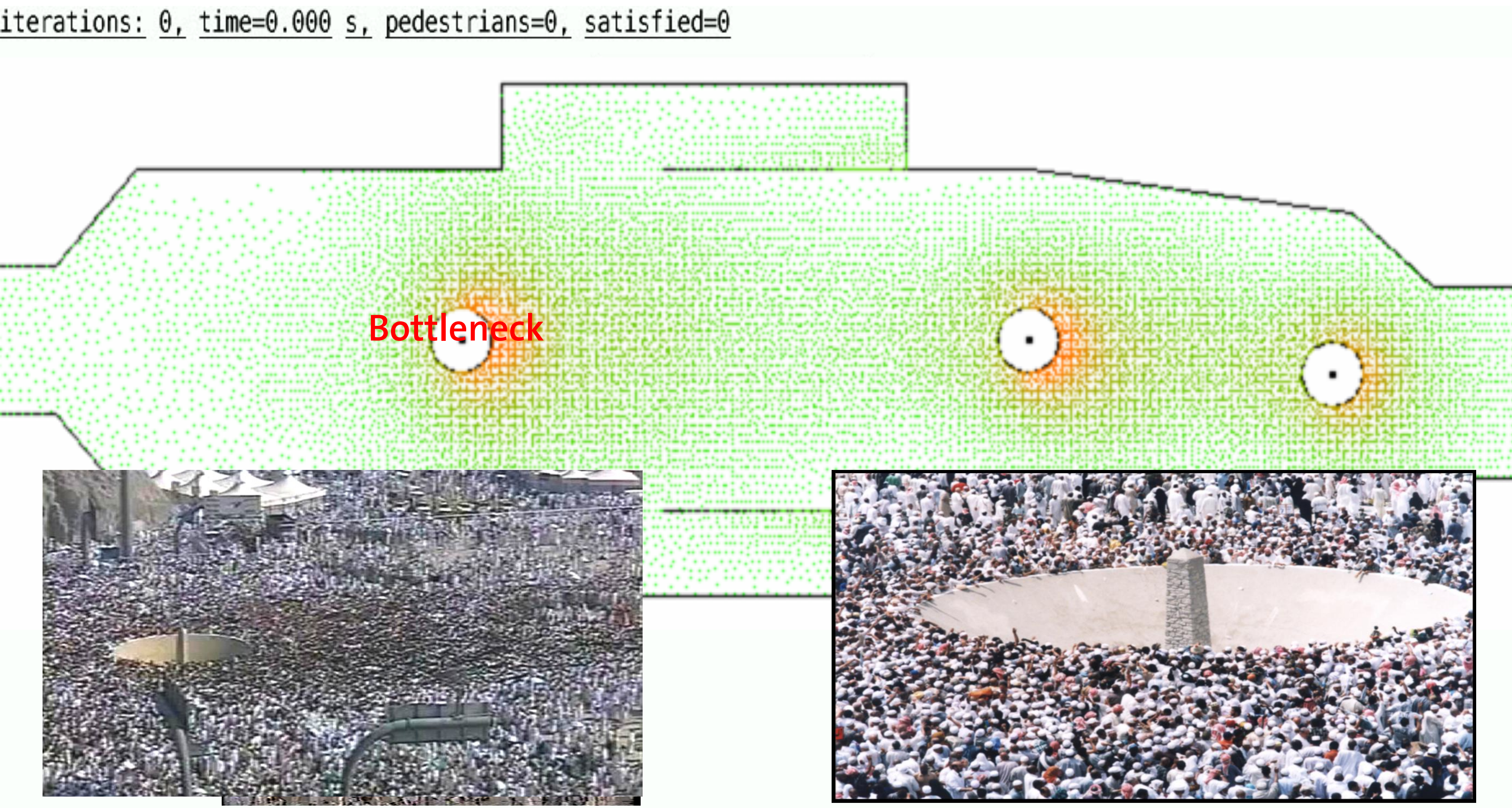
The Coliseum in Rome

- Up to 73,000 visitors
- 76 enumerated entrances
- Numbers of entrance, number, and seat indicated on each ticket
- Exit through the entrance gate
- Evacuation possible within 5 minutes
- Special building code for stadiums

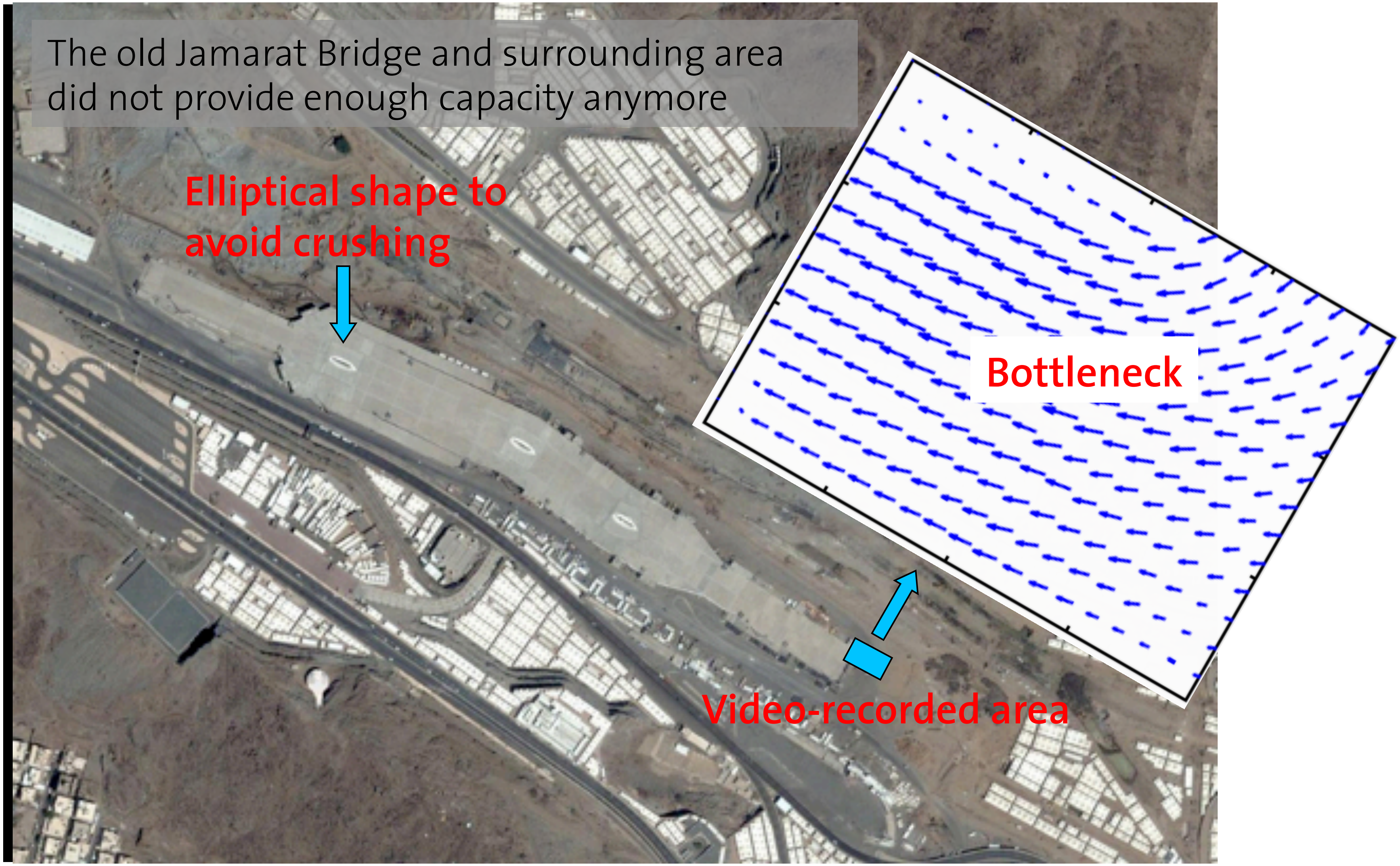
Supporting Believers Who Want to Perform their Religious Duties



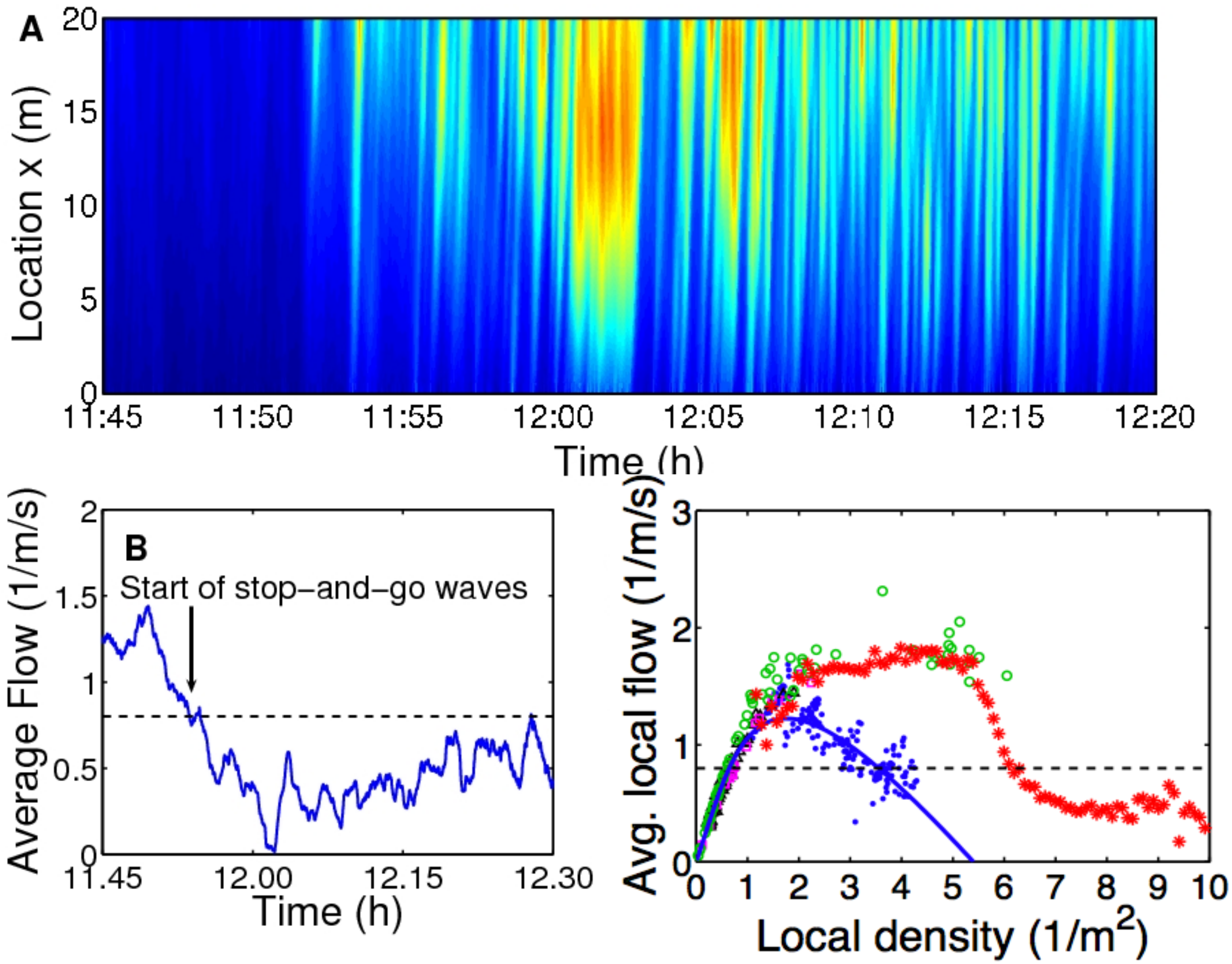
Stoning-the-Devil Ritual on the Jamarat Bridge



The Jamarat Bridge (as of January 2006)



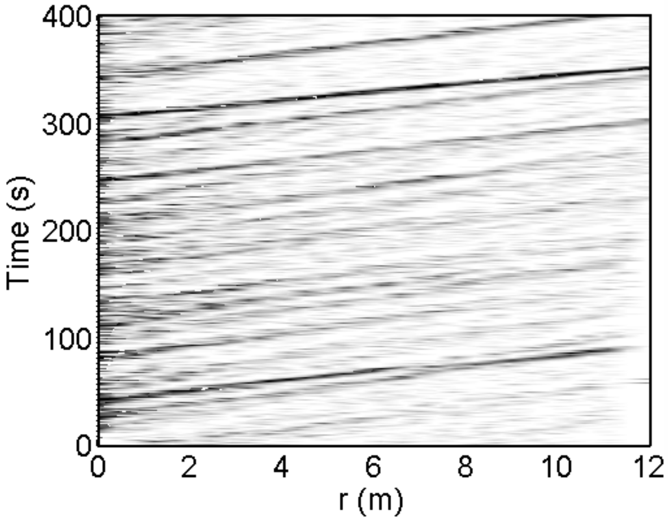
Transition from Smooth to Stop-and-Go Flow

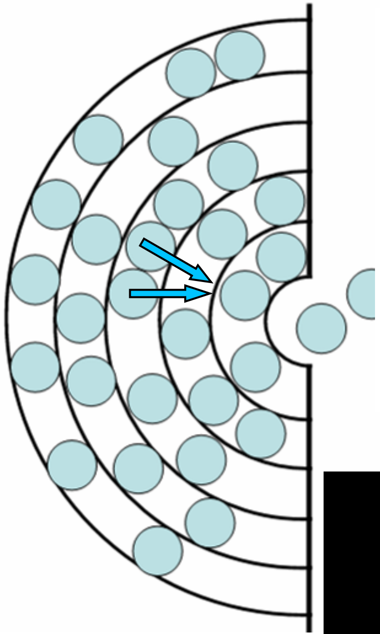


Mechanism is very different from vehicle traffic!

Modeling the Transition from Smooth to Stop-and-Go Flow

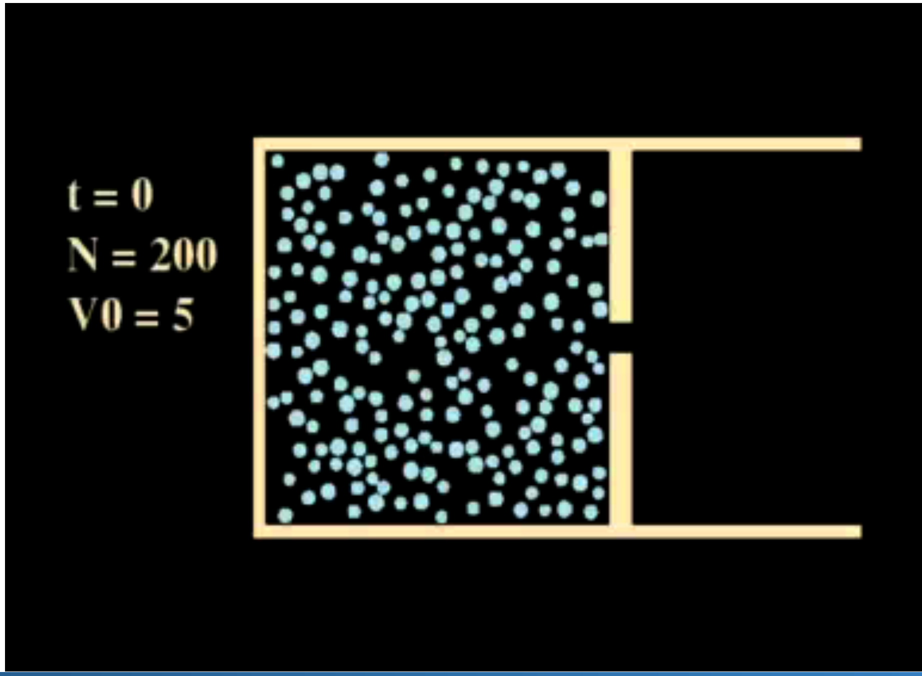
Competition for a scarce resource, here: space.



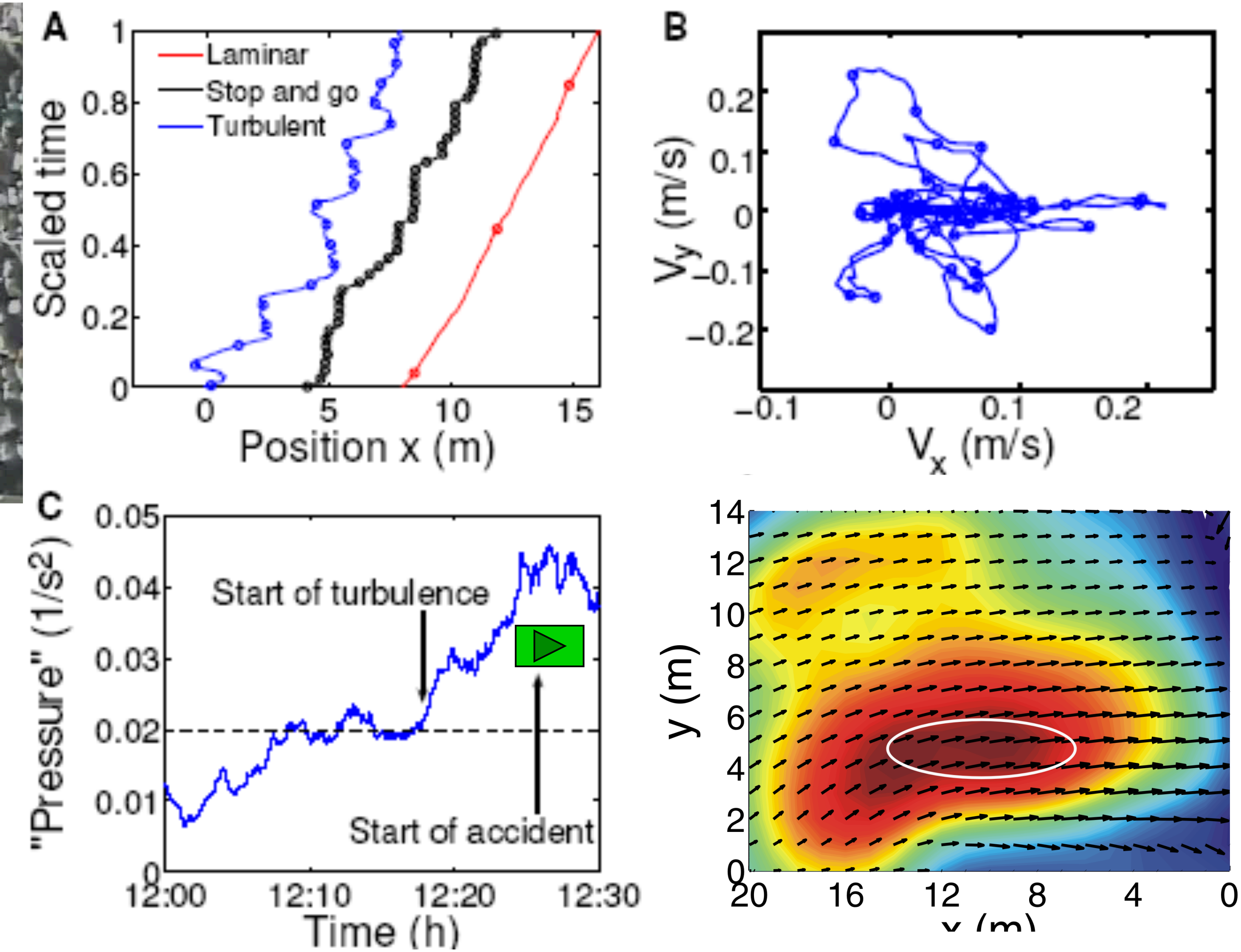


At high densities, several people may compete for the same gap and block each other. This constitutes a conflict and causes an alternation between downstream pedestrian and upstream gap propagation.

This leads to intermittent outflows with periods of no outflow. High-density clusters break up irregularly. The sizes of groups leaving the bottleneck together vary largely. Stop-and-go waves are a result.



Breakdown of Coordination: Stop-and-Go and Turbulence Flow



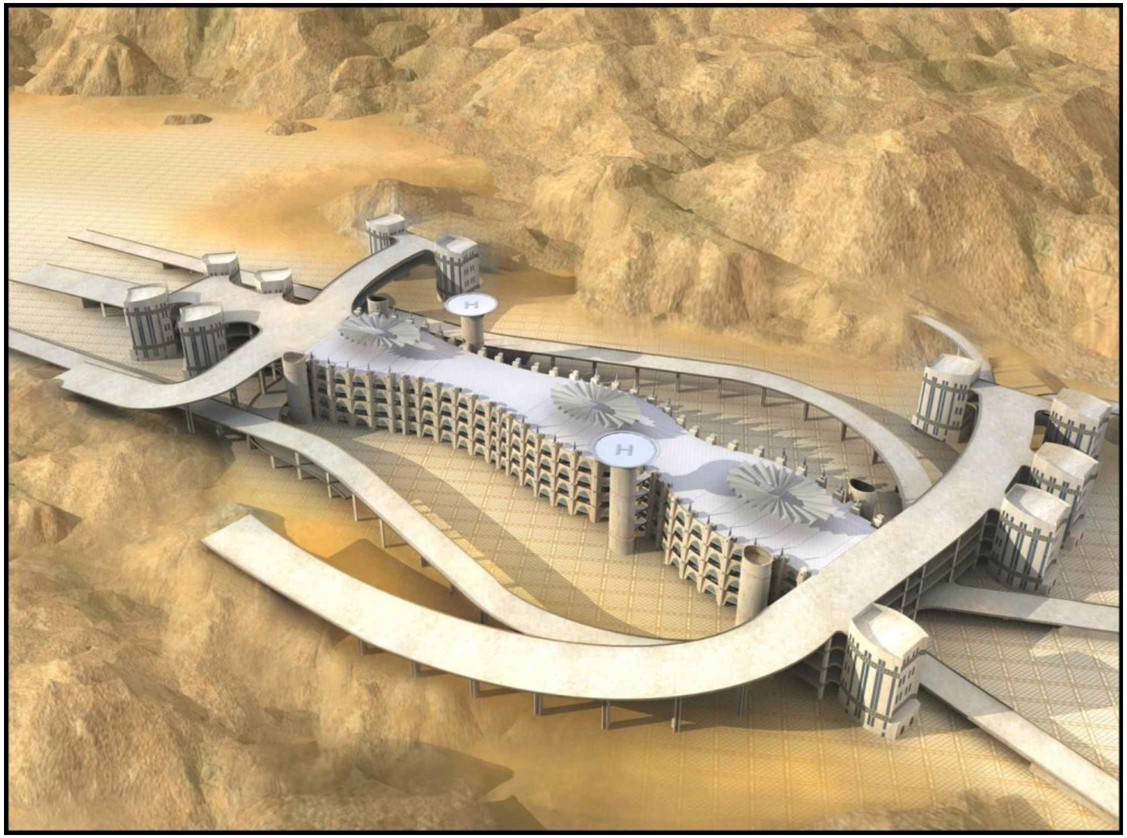
The density times the variation in speeds constitutes the hazard! Pressure fluctuations cause turbulent motion and potentially the falling and trampling of people.

Increased driving forces occur in crowded areas when trying to gain space, particularly during "crowd panic"

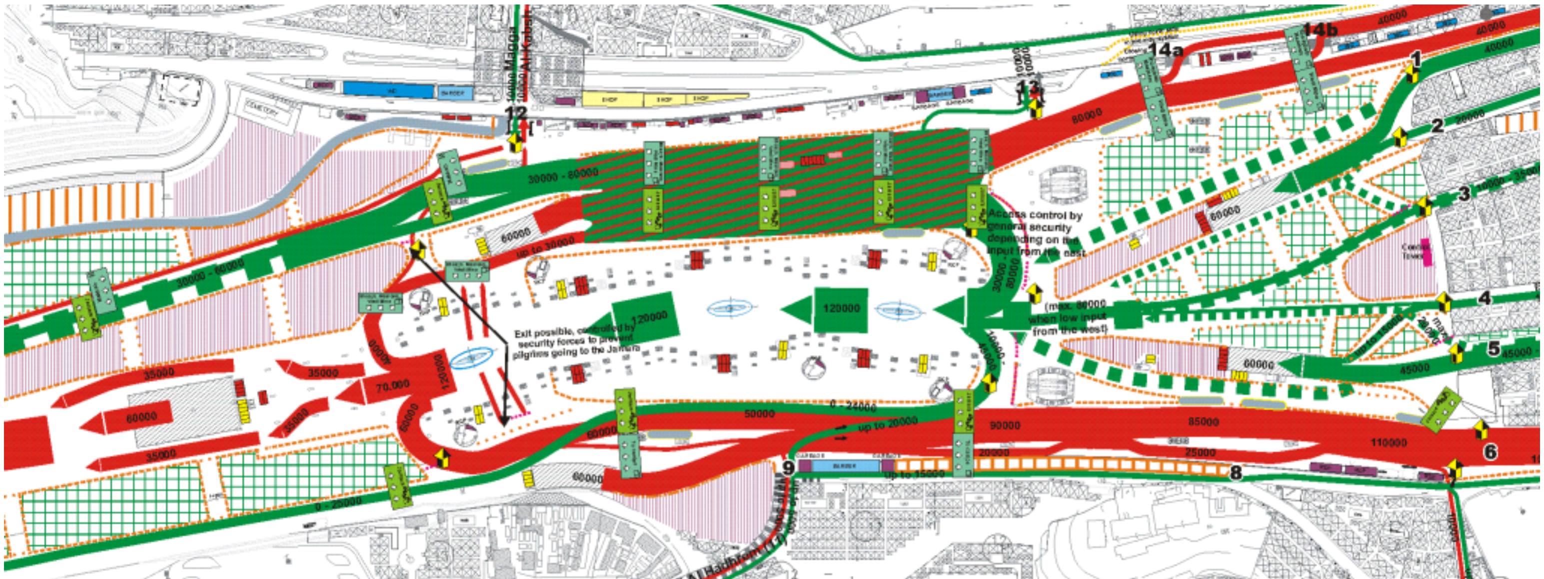
The New Jamarat Bridge and Its Advantages

In conjunction with appropriate management, the proposed new Jamarat Bridge design results in meaningful improvements in safety over existing conditions, in view of the overall design approach that supports

- a segregation of pedestrian flow and vehicular traffic
- a distribution of pilgrims to several entrances and channeling from origin area via ramps
- elliptically shaped Jamarahs, which provide a greater perimeter than the current circular basin, hence better utilization, higher throughput and better opportunity for process management
- additional space and better design features in the multi-storied structure
- better provisions for service and incident relief operations.



One-Way Plaza Organization



Source: D. Serwill, IVV Aachen

The pilgrims liked and supported this system!

The Change in Organization from 2006 to 2007

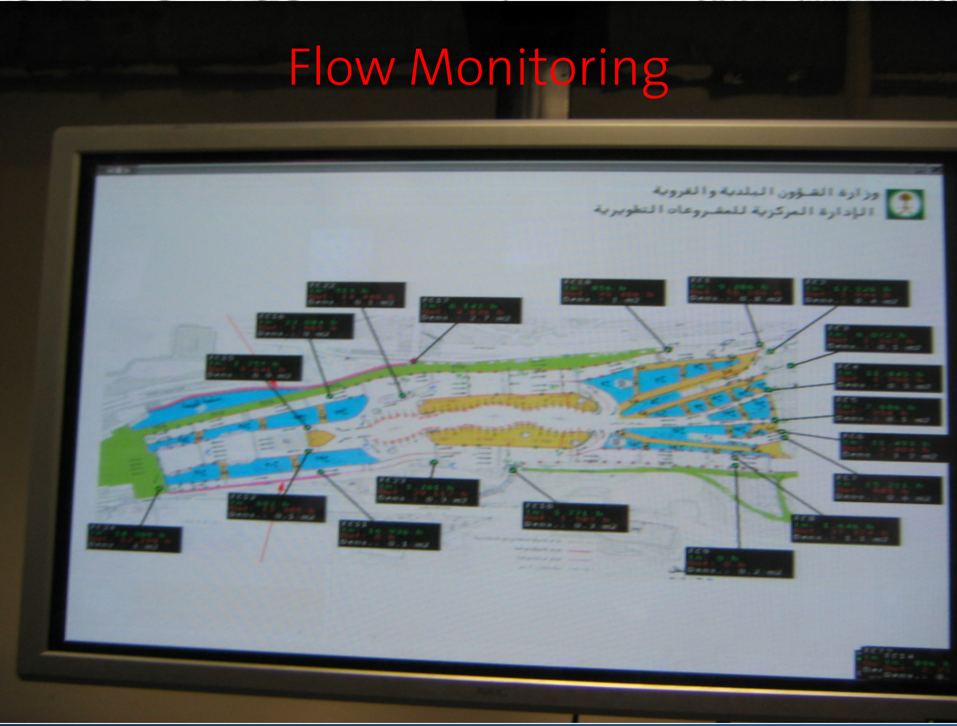
2007: Unidirectional and smooth flows. Pilgrims liked and supported the new organization.

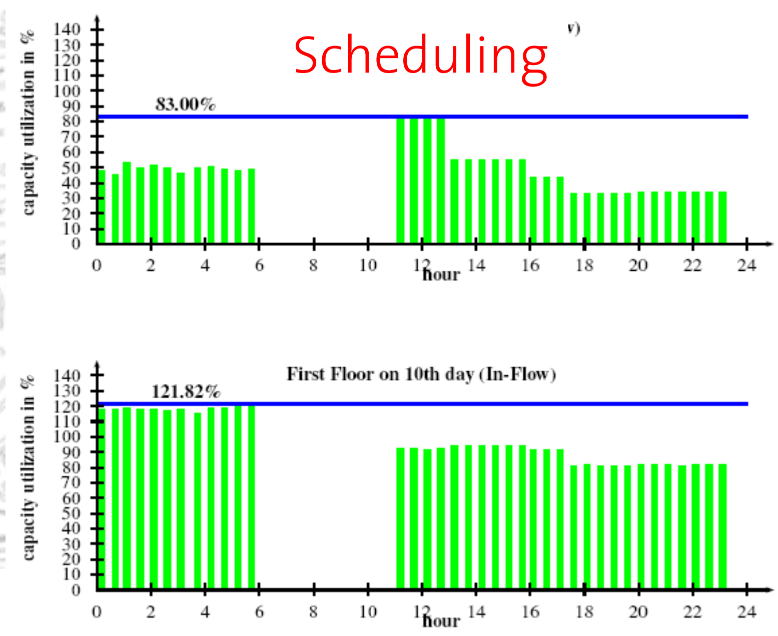
2006: Large accumulations, dense crowds, and long exposure times to intensive sun.

ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Scheduling, Flow Monitoring and Adaptive Rerouting

I would like to thank for the good scientific cooperation with many international experts and various government authorities



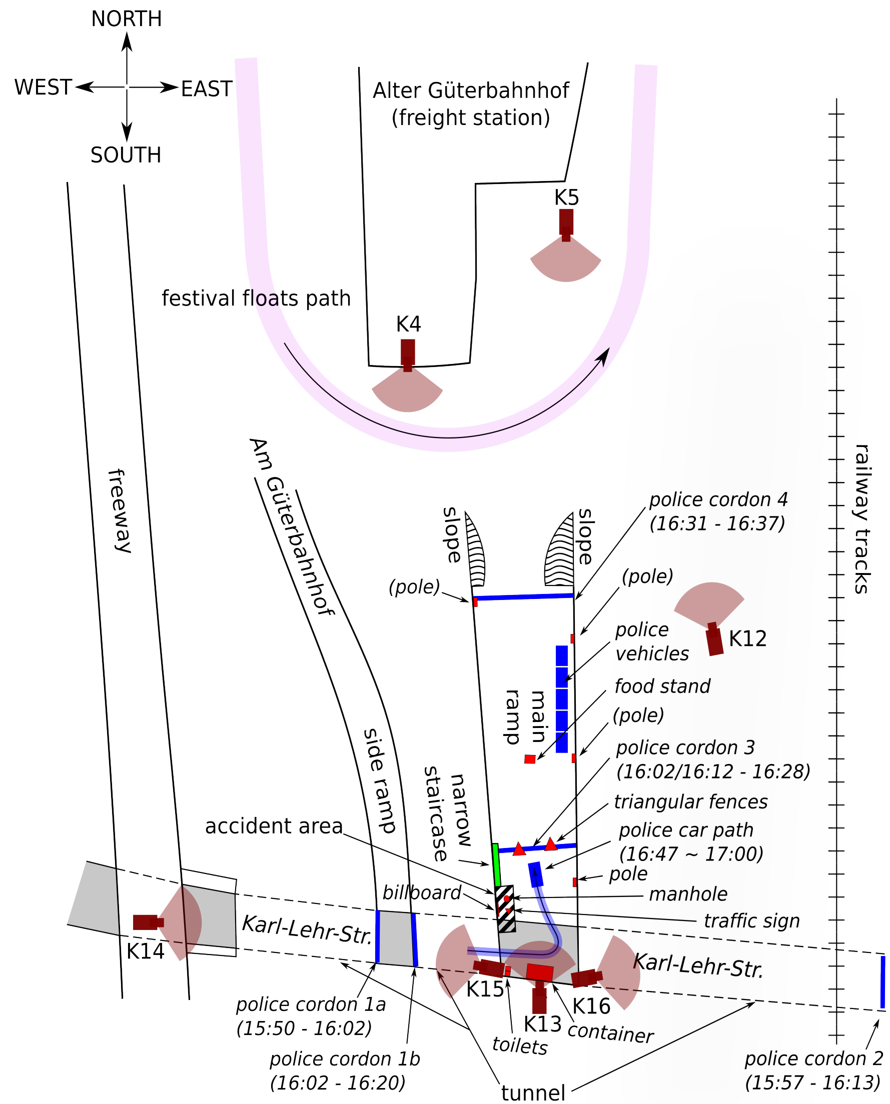


Application Example for Counting Software

Everyone Was Happy with the Result

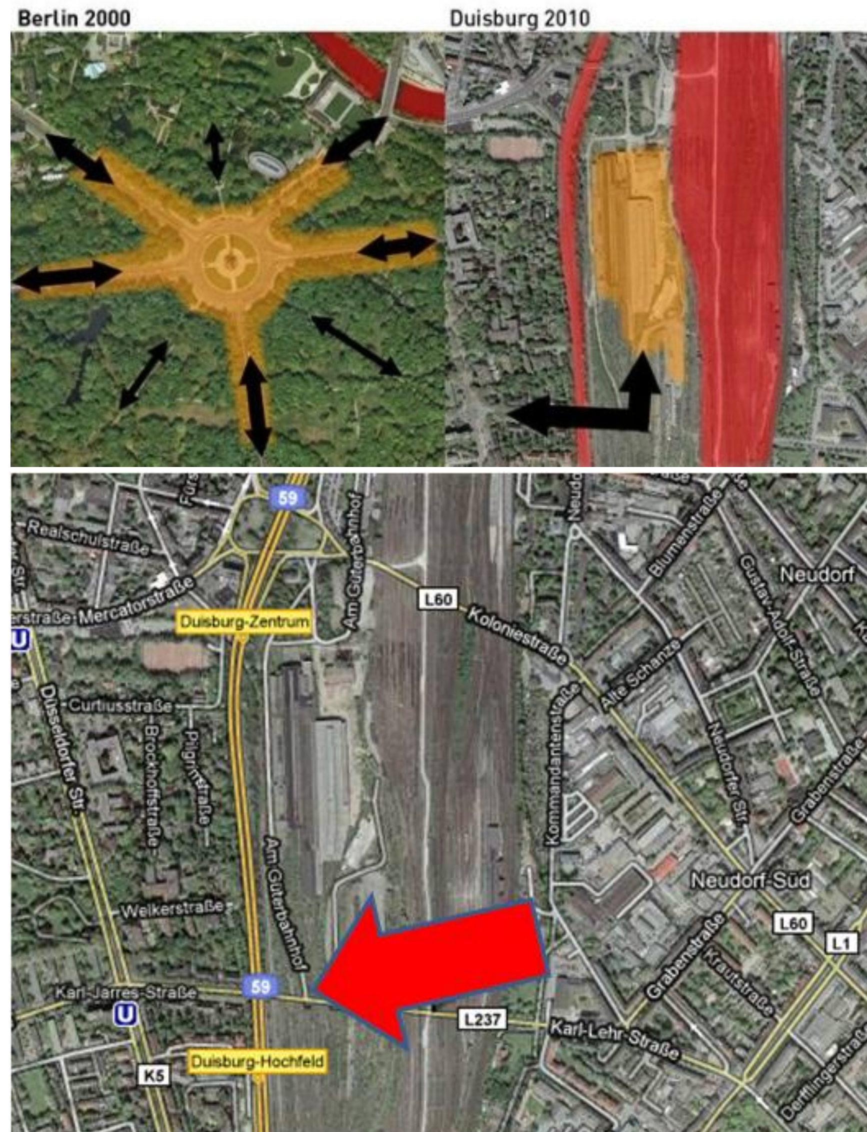
The Love Parade Disaster in Duisburg

The Festival Area

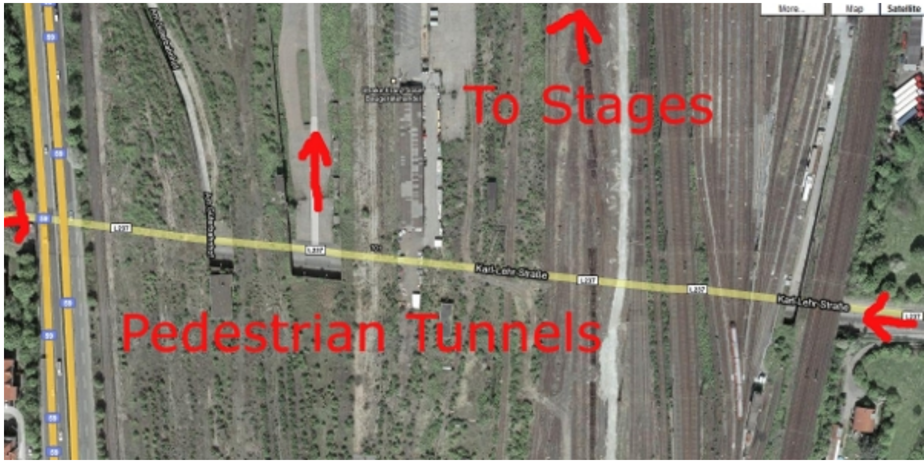


Decisions Went Wrong From the First Moment

- Berlin rejects to host the Loveparade. Other cities take over. The Loveparade moves from city to city, which creates new organizational challenges each time in more difficult locations than Berlin had offered with its wide roads and expansion areas
- Wuppertal has to cancel its Loveparade in 2009, because it cannot manage the security challenges
- Duisburg/Essen is elected to be Europe's cultural metropolis 2010. It is under pressure (also from the side of the federal state) to come up with an attractive cultural program.
- City and organizer push through the approval of the event despite of security concerns from different sides- The responsible police chief officer is forced to quit his post



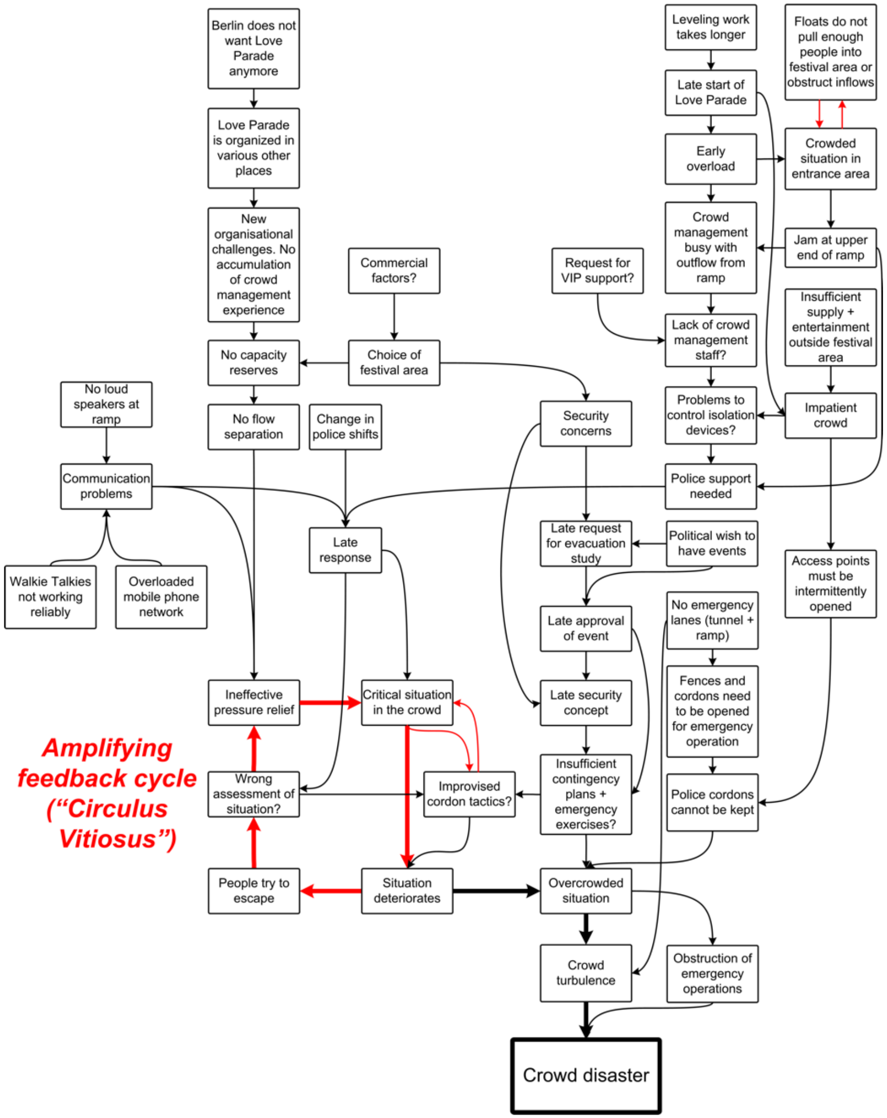
- To overcome security regulations, an evacuation study is ordered that allows to make exceptions. The scenarios are restricted to evacuation situations and miss out the situation of normal entering and exiting the area.
- To avoid overcrowding, the assumed number of participants is adjusted by a factor of six (from 1.4 millions to 250.000)
- The security concept is finished last minute. It is not well coordinated with the police forces.
- In- and outflows are not well separated, bottlenecks and abrupt directional changes are not suitably avoided or mitigated

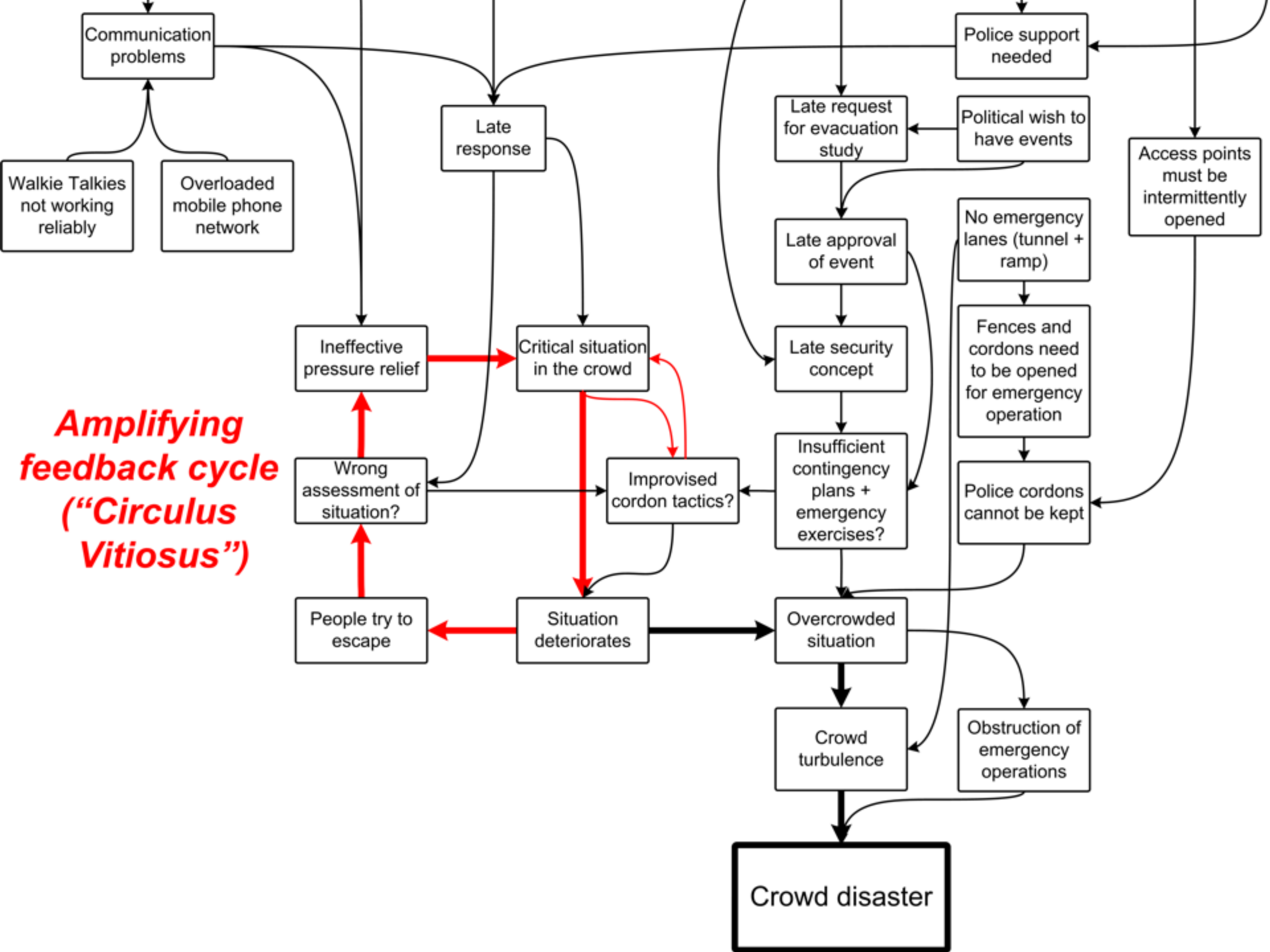


The Course of Events

- People can enter the Loveparade area later and return earlier than expected
- Hours later, the organizers cannot control the inflow anymore and ask the police for help
- There is no strategy to entertain people who have to wait or cannot enter the area, and to provide them with water.
- The police chains interrupting the inflows cannot be maintained. The situation gets out of control, and the area becomes seriously overcrowded.
- The police underestimates the criticality of the situation, reacts to late, and not in a suitable way (looks rather like a strategy to fight anarchists than an attempt to protect the health and save the lives of peaceful people). Police is not prepared to take over responsibility from the organizers (no walkie talkies, no megaphones, not suitable strategy, flow is interrupted in the wrong way, no suitable pressure relief strategies are applied)
- The coordination between organizers and police fails. There is no sufficient feedback between the situation, the crowd management, and the crowd. Suitable communication means are missing or not used.
- The evacuation of the critical area is improvised and inefficient.

Crowd Disasters as Systemic Failures





Communication problems
Walkie Talkies not working reliably
Overloaded mobile phone network
Late response
Late request for evacuation study
Police support needed
Political wish to have events
Access points must be intermittently opened
Late approval of event
No emergency lanes (tunnel + ramp)
Fences and cordons need to be opened for emergency operation
Ineffective pressure relief
Critical situation in the crowd
Late security concept
Amplifying feedback cycle ("Circulus Vitiosus")
Wrong assessment of situation?
Improvised cordon tactics?
Insufficient contingency plans + emergency exercises?
Police cordons cannot be kept
People try to escape
Situation deteriorates
Overcrowded situation
Crowd turbulence
Obstruction of emergency operations
Crowd disaster

Possible Measures to Prevent Crowd Disasters in Future

- Implement ways to stop too much political pressure. It should not be possible to ignore qualified minorities. Contradictory voices must be recorded and replied to/addressed in a substantial way.
- Evacuation studies must work with realistic numbers and should not be restricted to special cases (e.g. evacuation scenarios). First, an analysis of the expected inflows and outflows (and, hence, number of participants) needs to be done, considering the possibility of large variations in numbers. A bottleneck analysis must follow, before the required simulation scenarios are specified. The commissioned engineering office must be encouraged to point out critical issues (even beyond the scope of the commissioned analysis).
- The crowd management and security concept must consider sufficient safety margins (at least 30 percent) and contingency plans in case of possible problems
- Bottlenecks must be avoided or mitigated, and dense counter-flows or intersecting flows are to be avoided
- Unavoidable bottlenecks or confluence points are to be monitored with suitable video analysis software. Security forces and emergency units must be in the immediate neighborhood. Contingency plans must have been exercised. Communication between different teams of officials (organizers, police, emergency, people) must be ensured (walkie-talkies, megaphones, etc.).
- Local organizing teams should be supported by experienced national or supernational professional teams