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

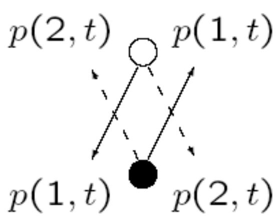
with Anders Johansson, Wenjian Yu, Mehdi Moussaid,

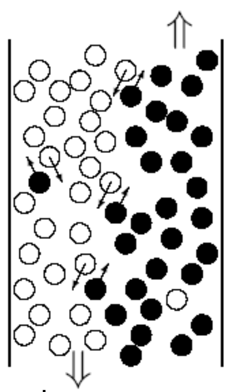
Illes Farkas, Peter Molnar, Tamas Vicsek and others

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.





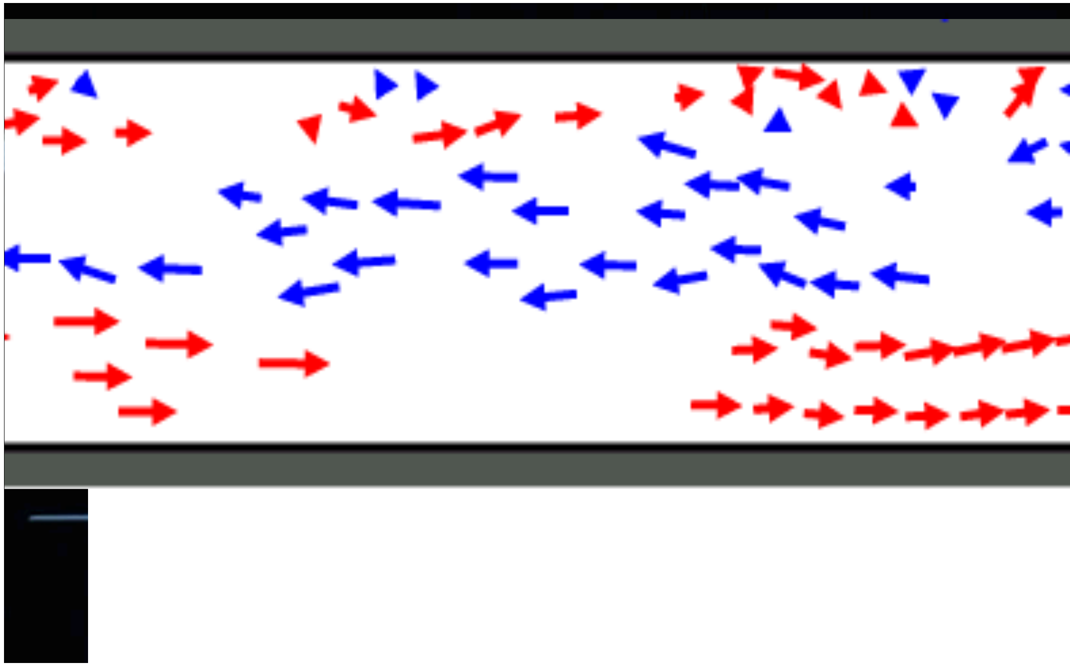
Do pedestrians behave as individuals or social beings?

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)

Lane Formation in Pedestrian Counter Flows

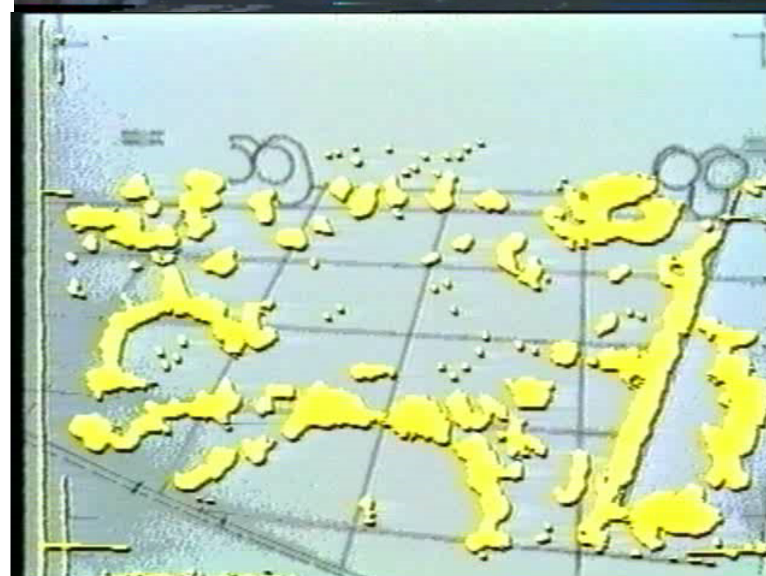
Emergence of Coordination in Pedestrian Counterflows

Acts like Adam Smith's "invisible hand"

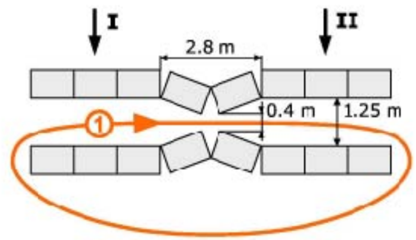


Based on individual interactions, lanes of uniform walking directions emerge in pedestrian crowds by self-organization. This constitutes a „macroscopic" social structure. Nobody orchestrates this collective behavior, and most people are not even aware of it. A behavioral convention „institutionalizes"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

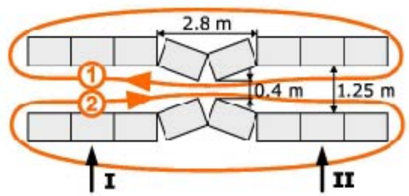
Underlying Mechanisms?



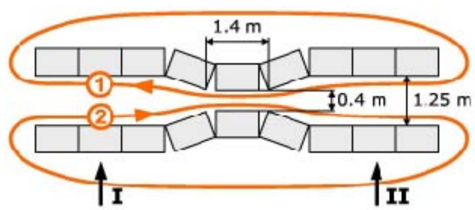
Experiments: Corridor with Bottlenecks



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

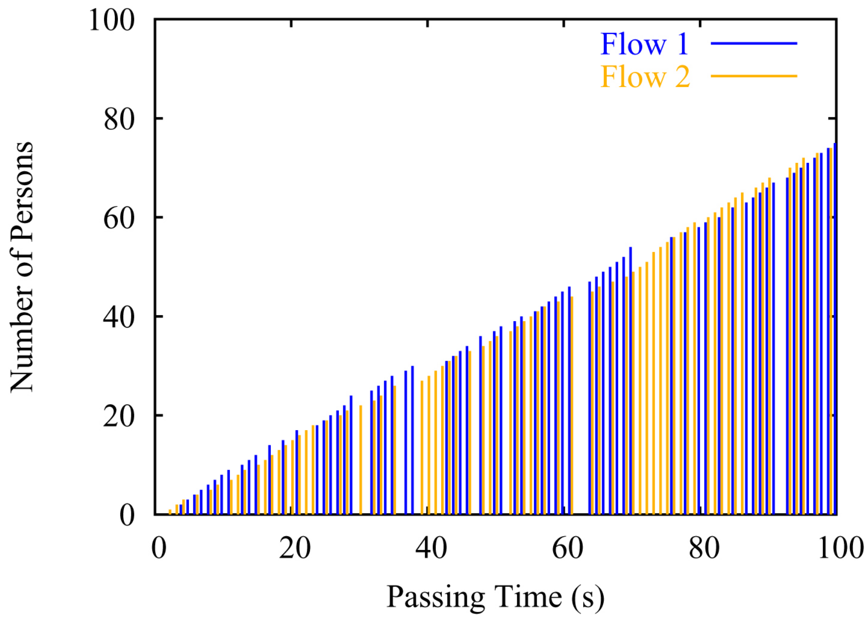


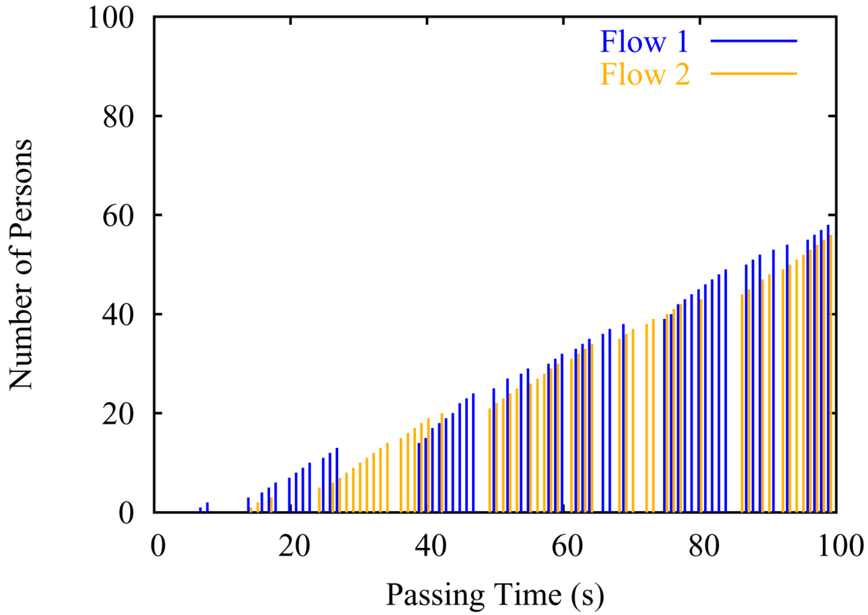
Experiment 2: Pedestrian counter-flows in a corridor with a short bottle-neck



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

Bottlenecks

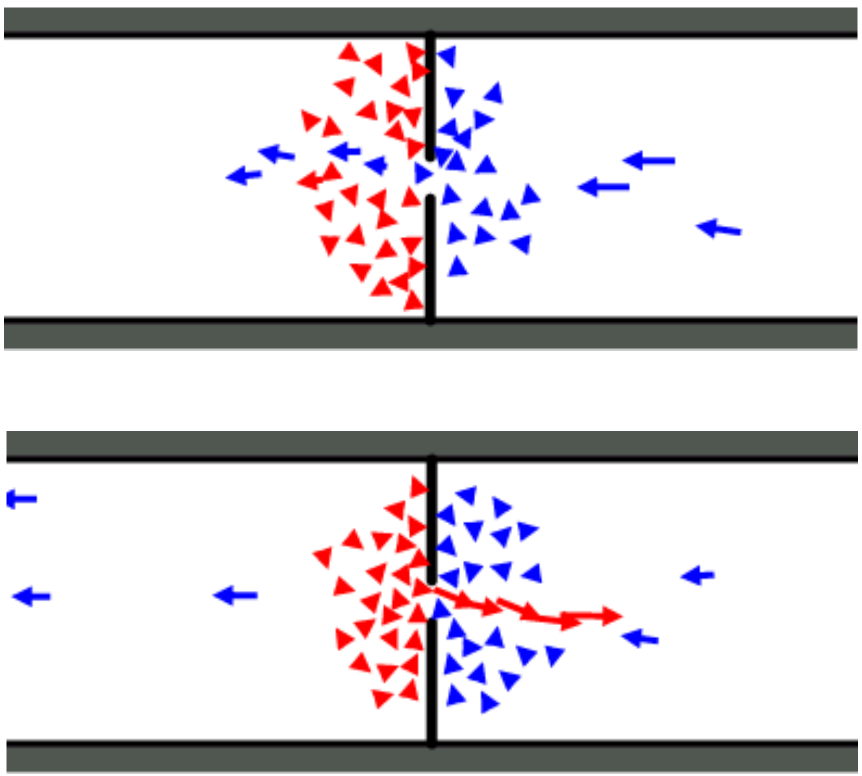




Compared to the flow through a corridor without narrowings the pedestrian flow after a short bottleneck is less regular due to oscillations in the passing direction. Pedestrians of the same direction of motion have a slight tendency to cluster (left).

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

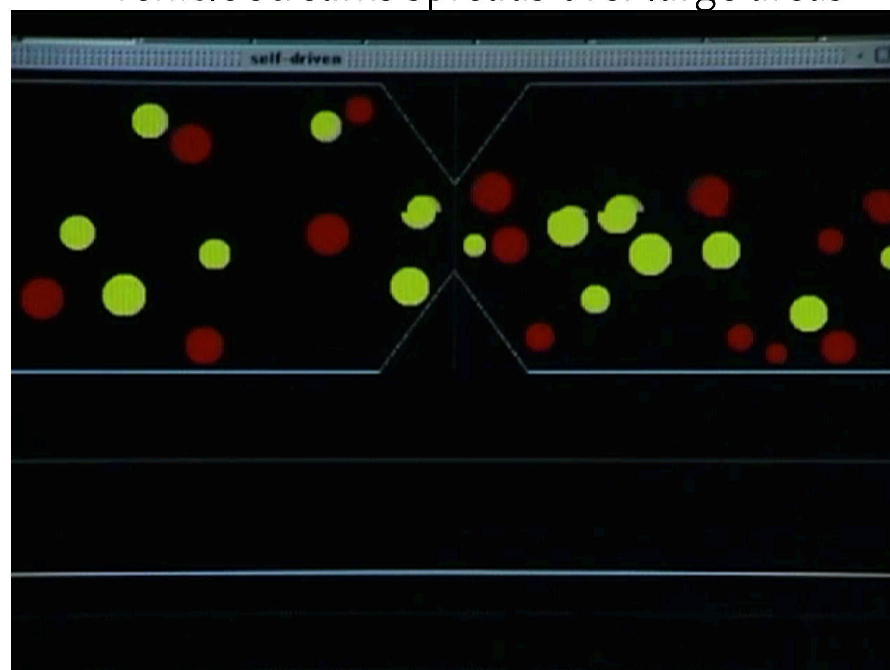


Pressure-oriented, autonomous, distributed signal control:

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

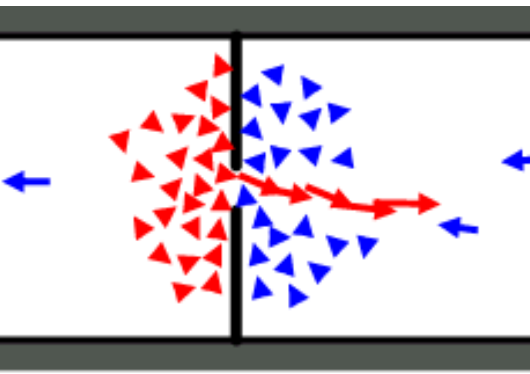
In huge street networks:

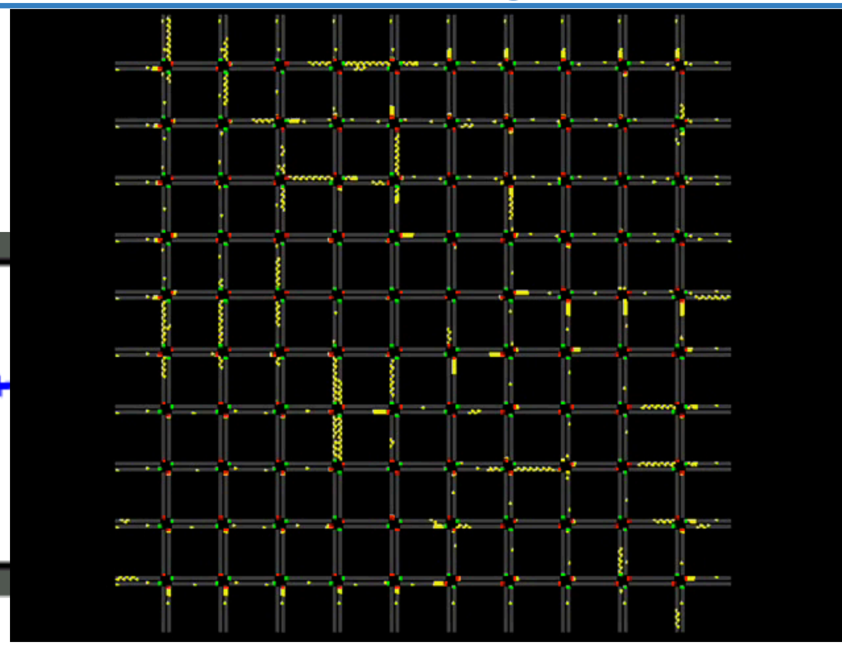
‘Synchronization’ of traffic lights due to vehicle streams spreads over large areas

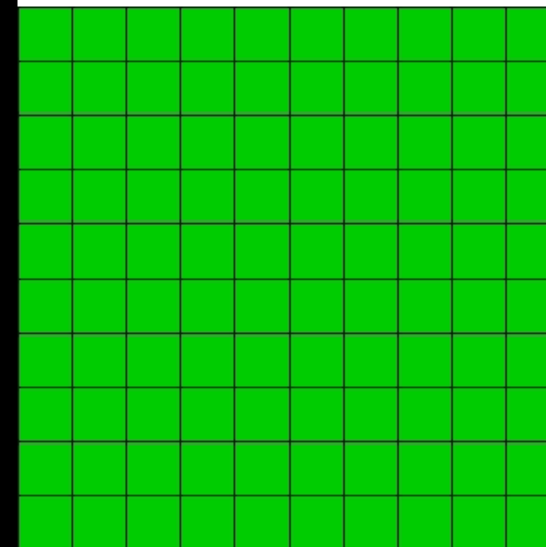


Decentralized Concept of Self-Organized Traffic Light Control

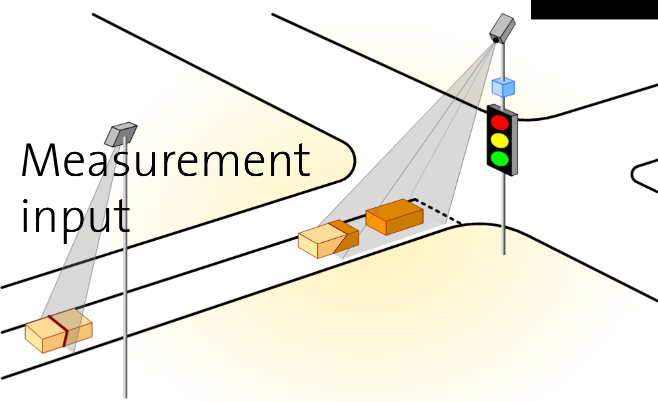
Inspiration: Self-organized oscillations at bottlenecks



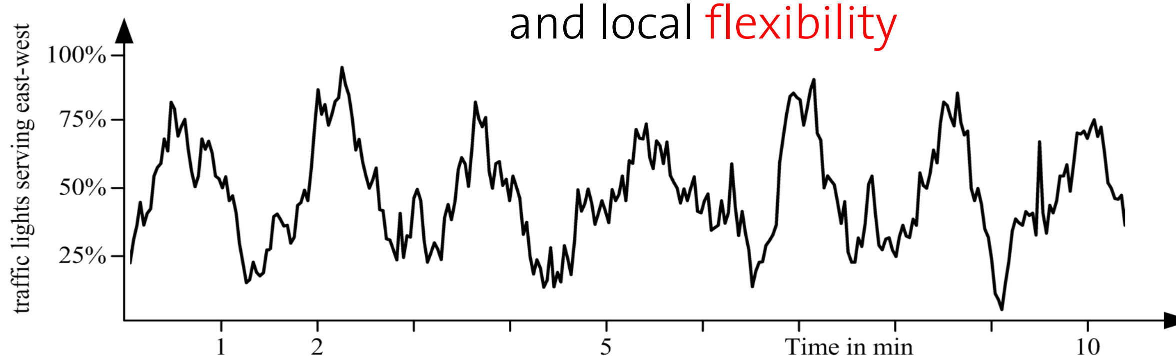




Measurement input



Optimal compromise between coordination and local flexibility

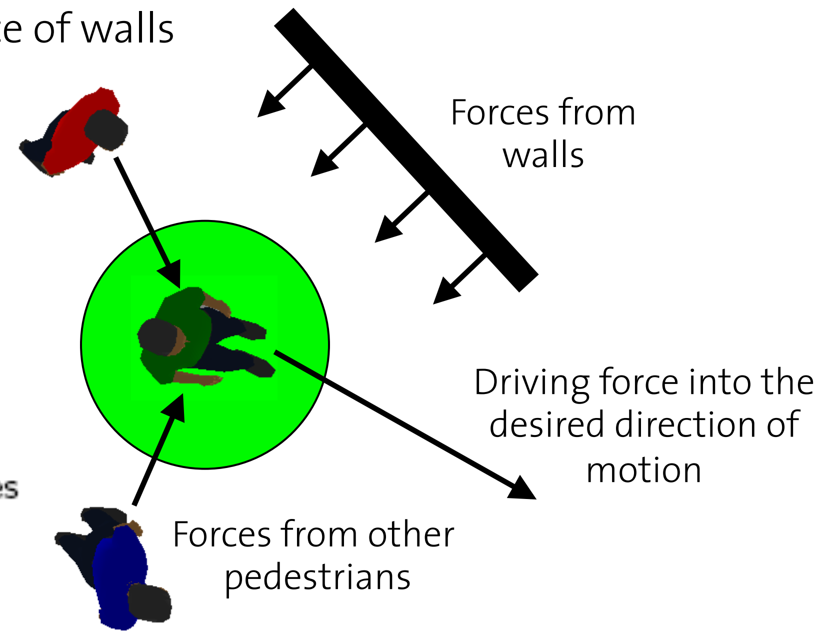


Published in *JSTAT* (2008)

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



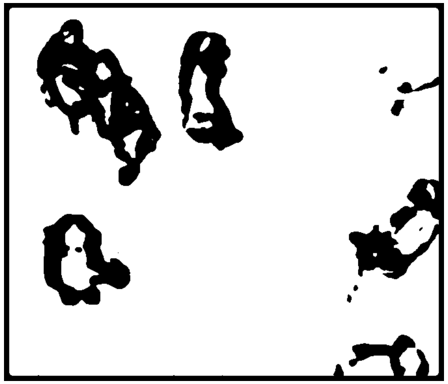
$$\frac{dx_\alpha}{dt} = v_\alpha(t)$$ (equation of motion)

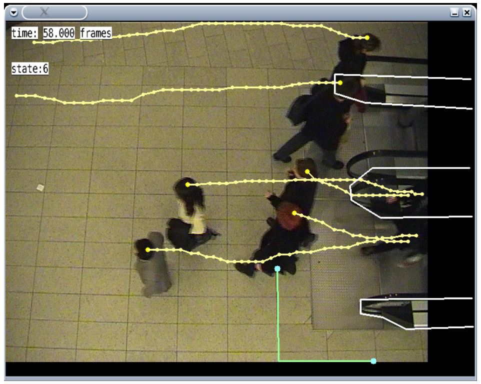
$$\underbrace{\frac{dv_\alpha}{dt}}_{\text{acceleration}} = \underbrace{\frac{1}{\tau_\alpha}(v_\alpha^0 e_\alpha^0 - v_\alpha)}_{\text{driving force}} + \underbrace{\sum_{\beta(\neq\alpha)} F_{\alpha\beta}^{\text{int}}}_{\text{interactions}} + \underbrace{F_\alpha^{\text{walls}}}_{\text{boundaries}}$$

(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.

Evaluation of Pedestrian Trajectories

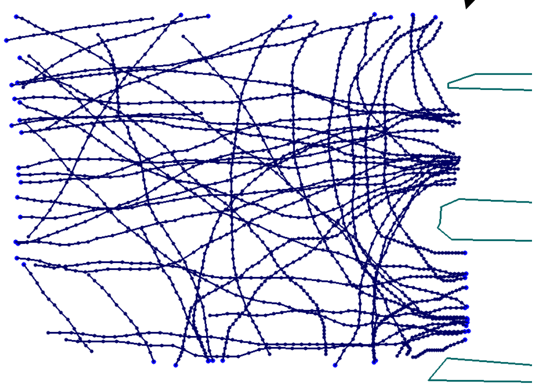




Calculate trend matrices:

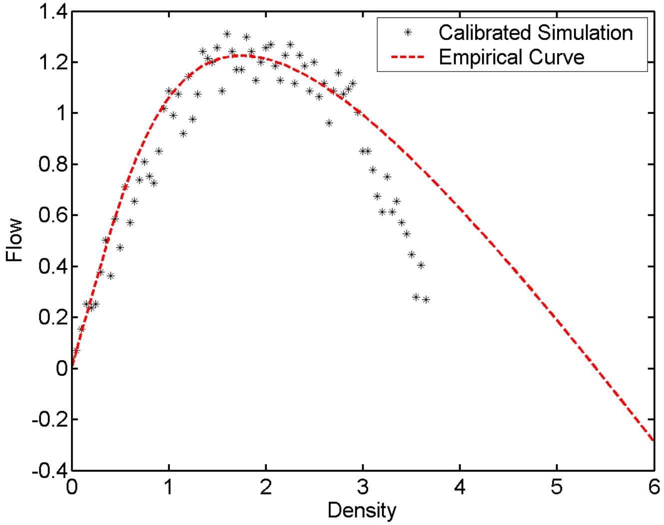
$\text{Trend}_0 = \text{Frame}_n - \text{Frame}_{n-1}$

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

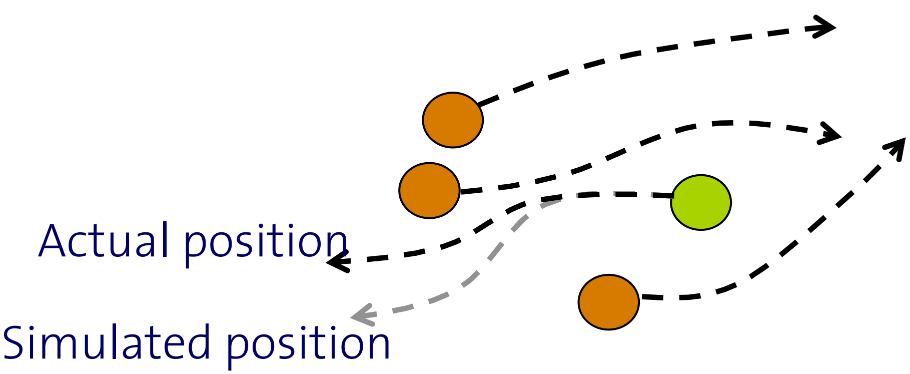


Recognize movement by searching for similarities in the local neighborhoods around each point in the trend matrices.

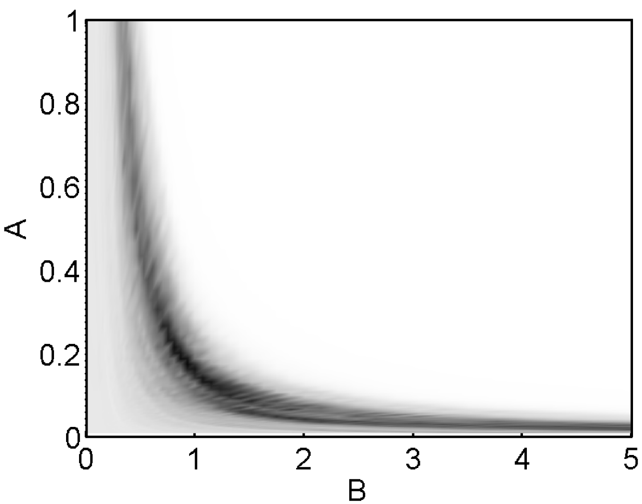
Transform the trajectory coordinates into the ground plane, by approximating each human to be 170 cm high.



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.

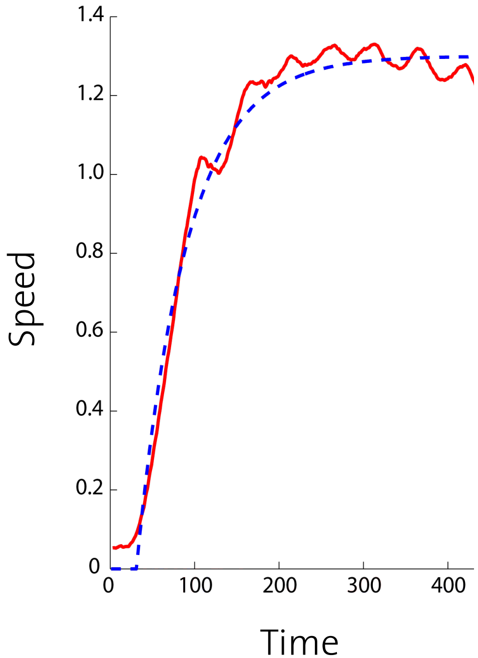


Model	A	B	λ	Fitness
Circular	0.11 ± 0.06	0.84 ± 0.63	1	-0.65
Elliptical I	1.52 ± 1.65	0.21 ± 0.08	1	-0.67
Elliptical II	4.30 ± 3.91	1.07 ± 1.35	1	-0.47
Circular	0.42 ± 0.26	1.65 ± 1.01	0.12 ± 0.07	-0.60
Elliptical I	0.11 ± 0.01	1.19 ± 0.45	0.16 ± 0.04	-0.59
Elliptical II	0.04 ± 0.01	3.22 ± 0.67	0.06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

Individual Behavior

Setup 1

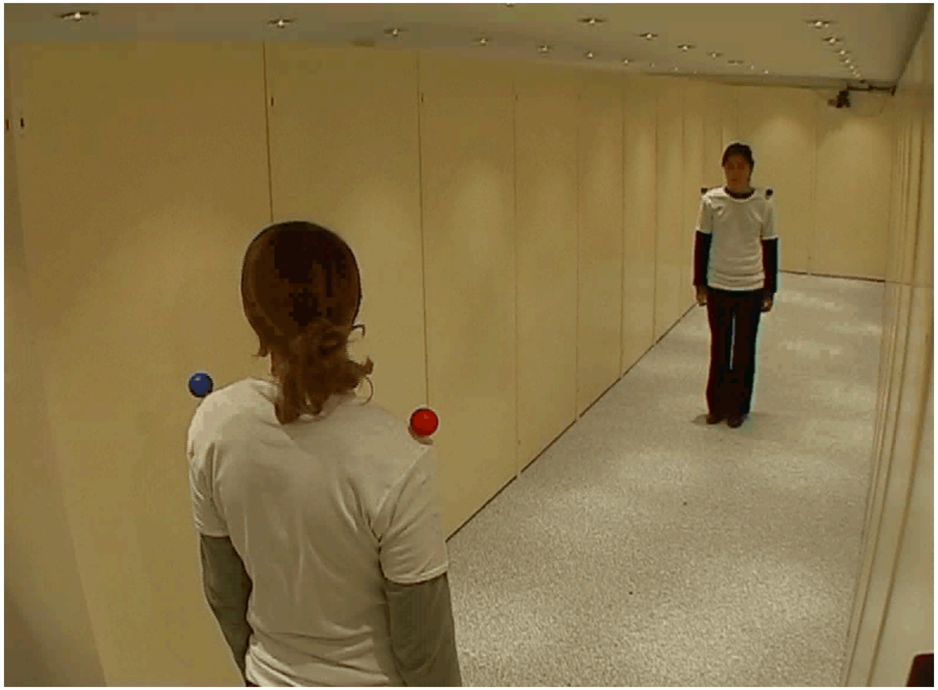
Single pedestrian's behavior



Average walking speed of single pedestrians

Individual Behavior

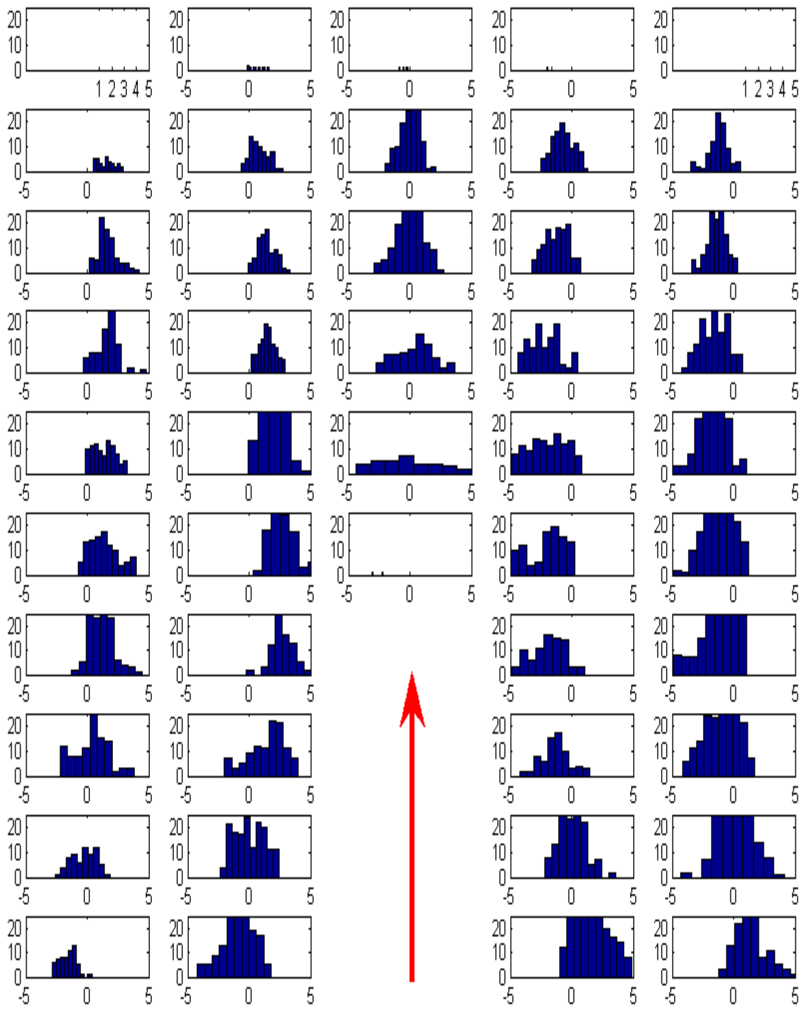
Setups 2 & 3

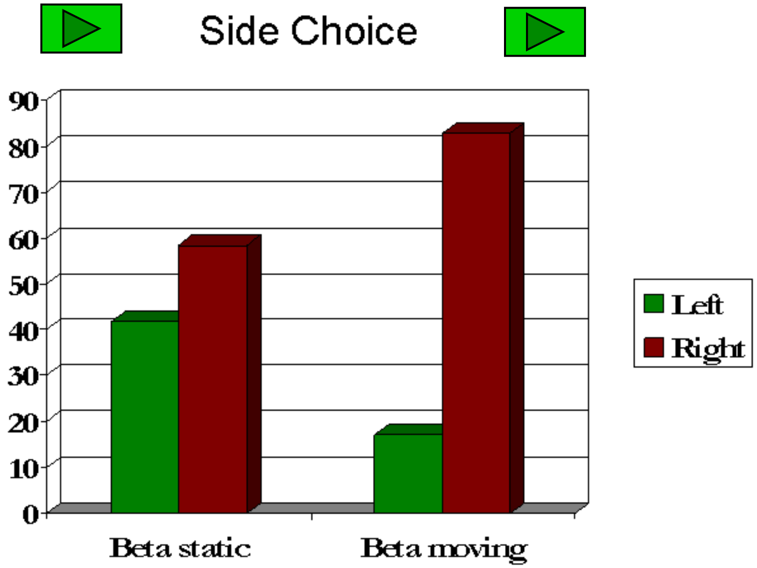


Avoidance of a static pedestrian

Avoidance of a moving pedestrian

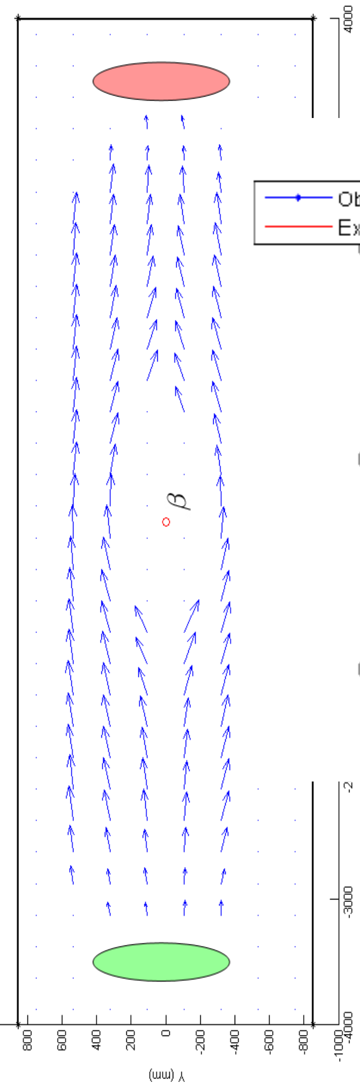
Distribution of the direction changes
(when the obstacle is located in front of the pedestrian)

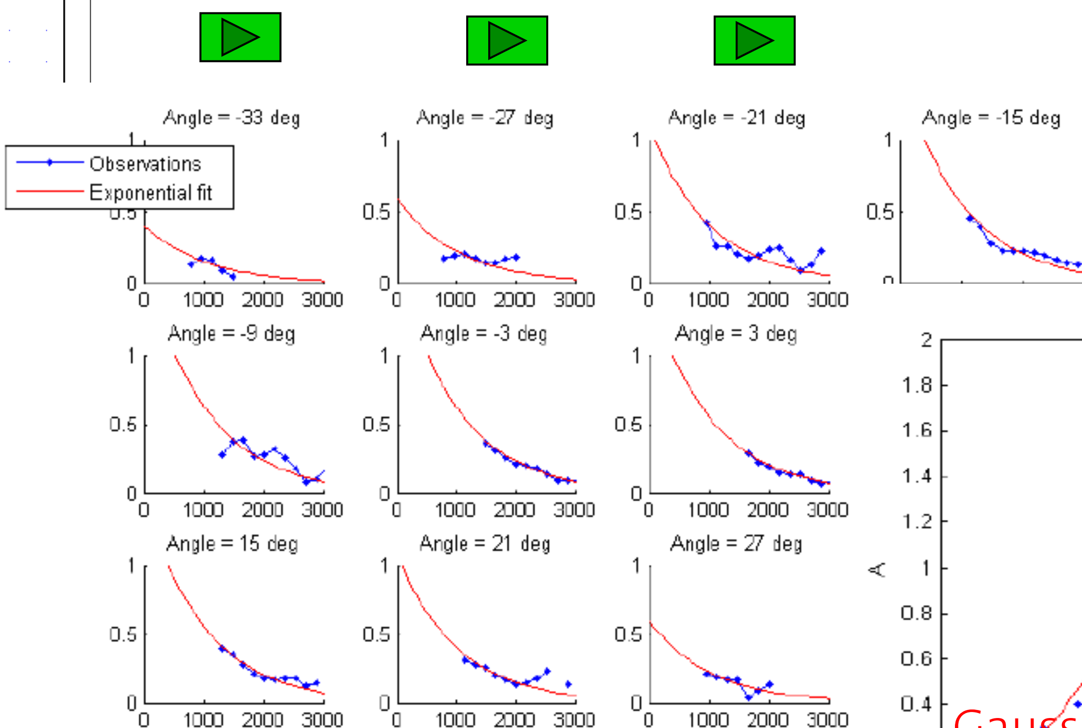




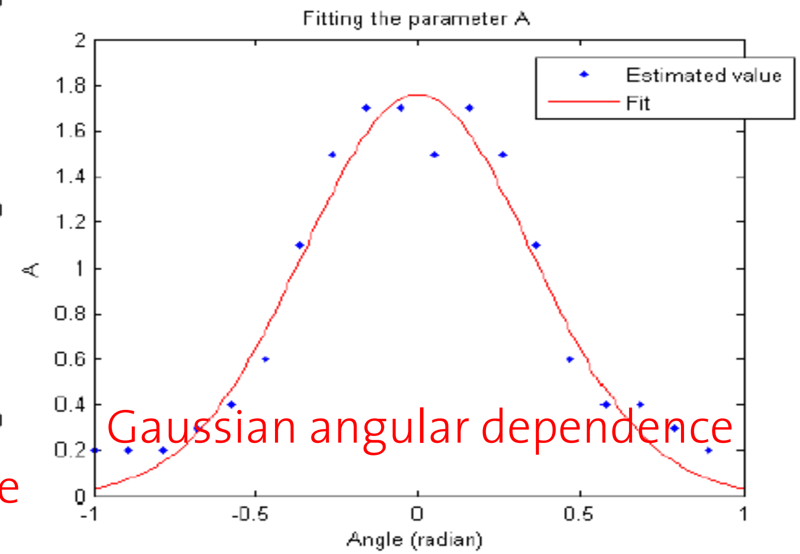
Experiments on Human Interactions in Space

Work in progress
with Guy Theraulaz
and Mehdi Moussaid





Exponential distance dependence



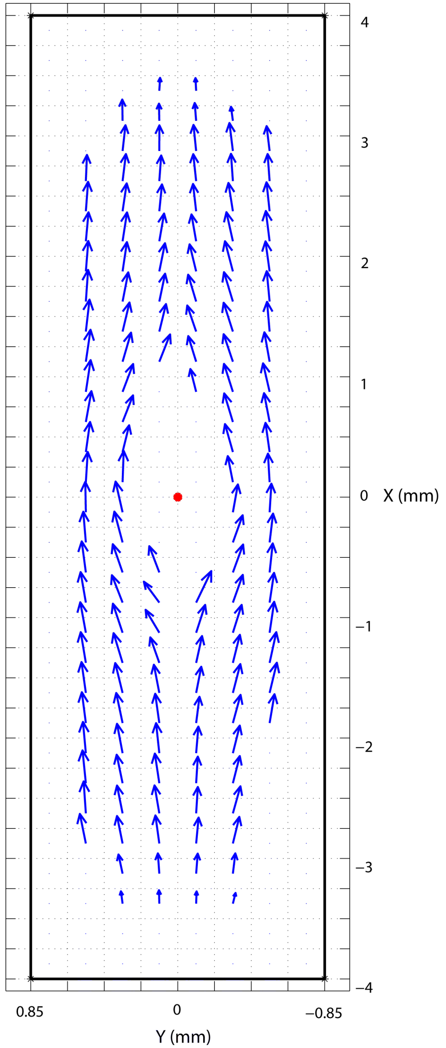
Gaussian angular dependence

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

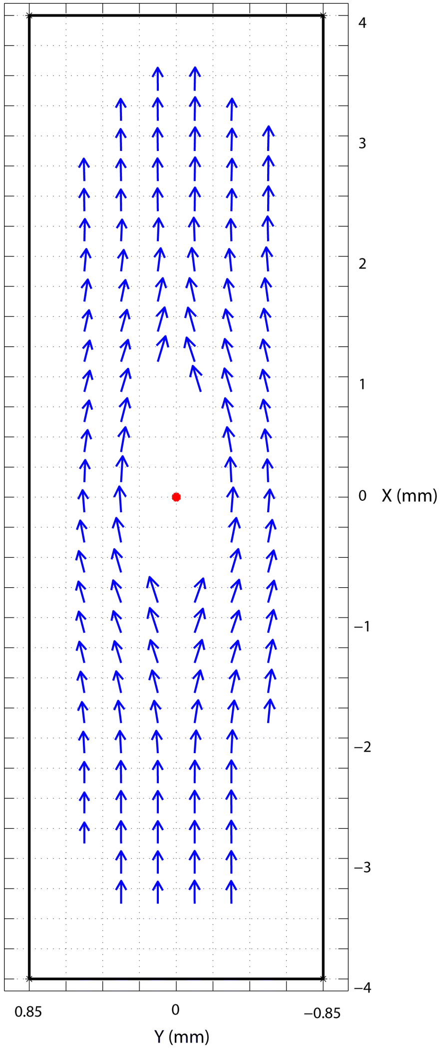
$$F_v(d, \varphi) = \mathrm{e}^{-5\varphi^2} \mathrm{e}^{-d} \qquad F_\varphi(d, \varphi) = 1.76 \mathrm{e}^{-2\varphi^2} \mathrm{e}^{-d}$$

Comparison of Observations and Simulations

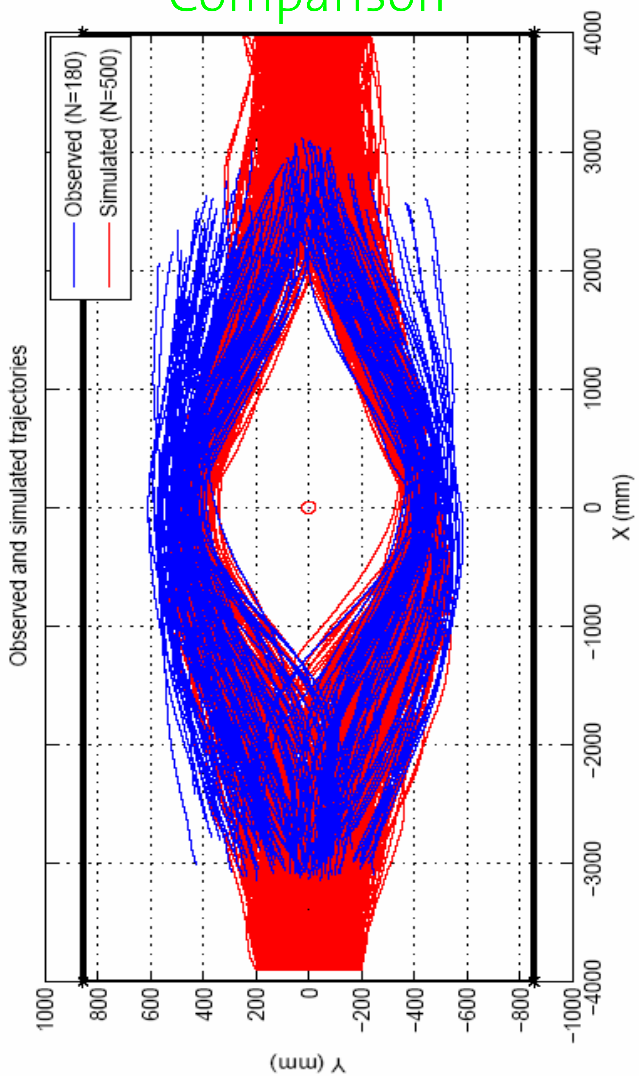
Observation



Simulation



Comparison

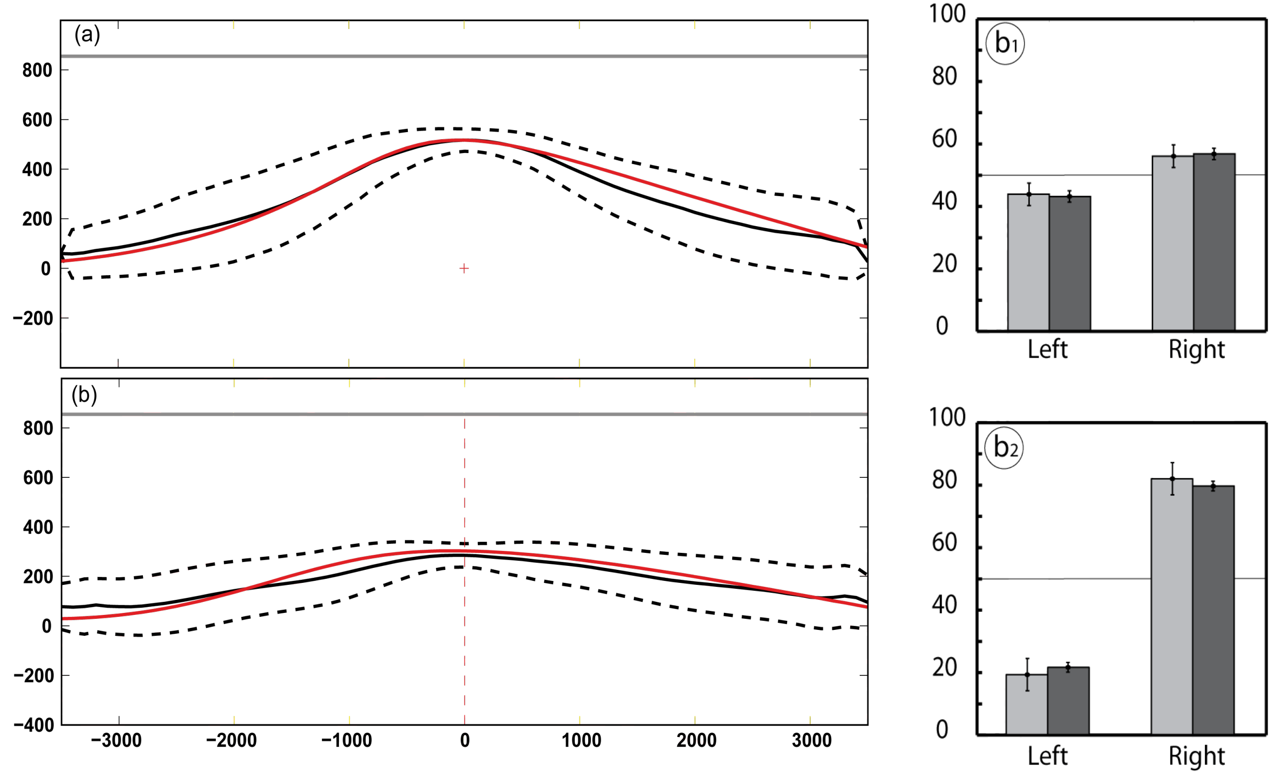


Validation 1: Corridor Experiment

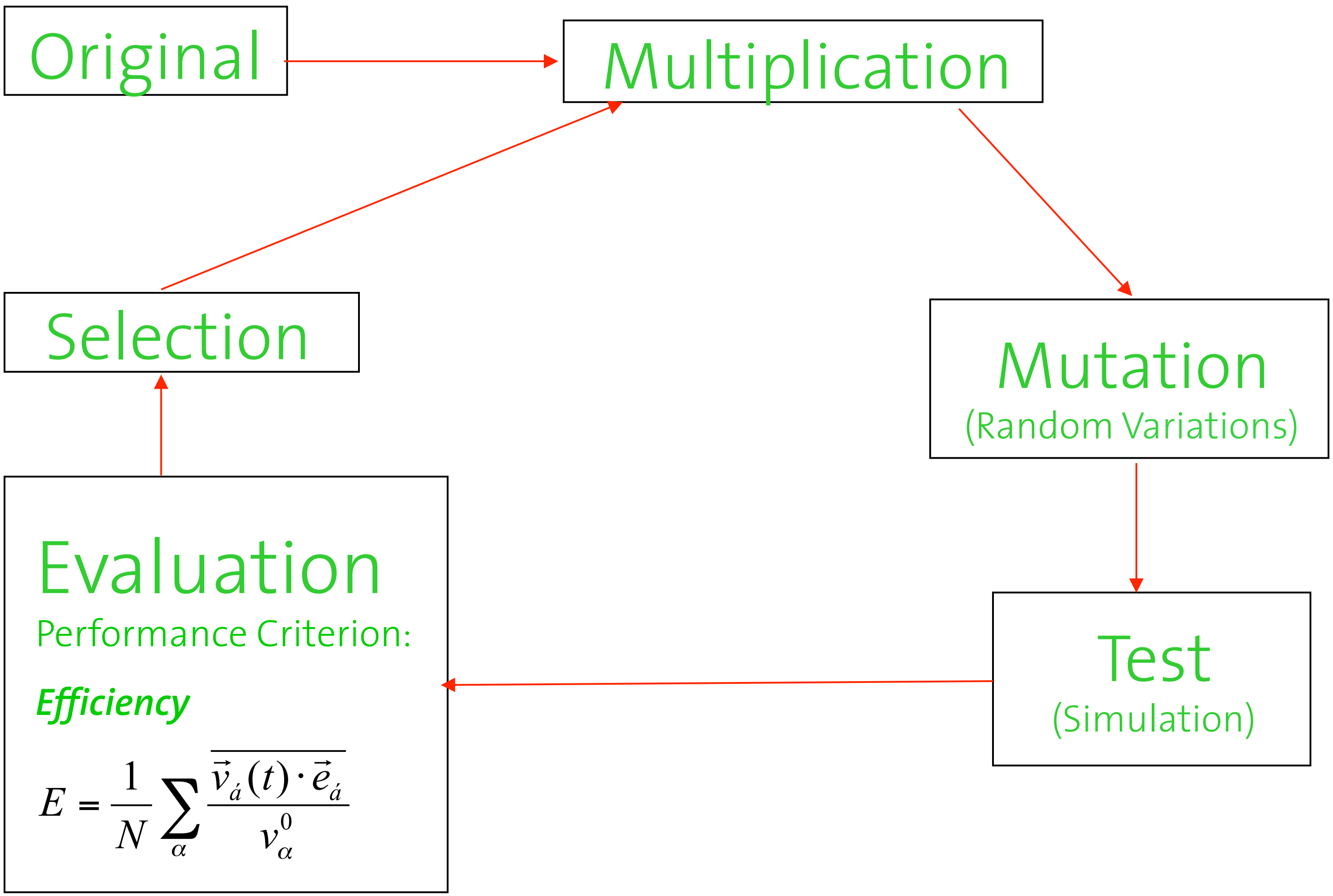
- Quantitative validation

  Average observed trajectory + std

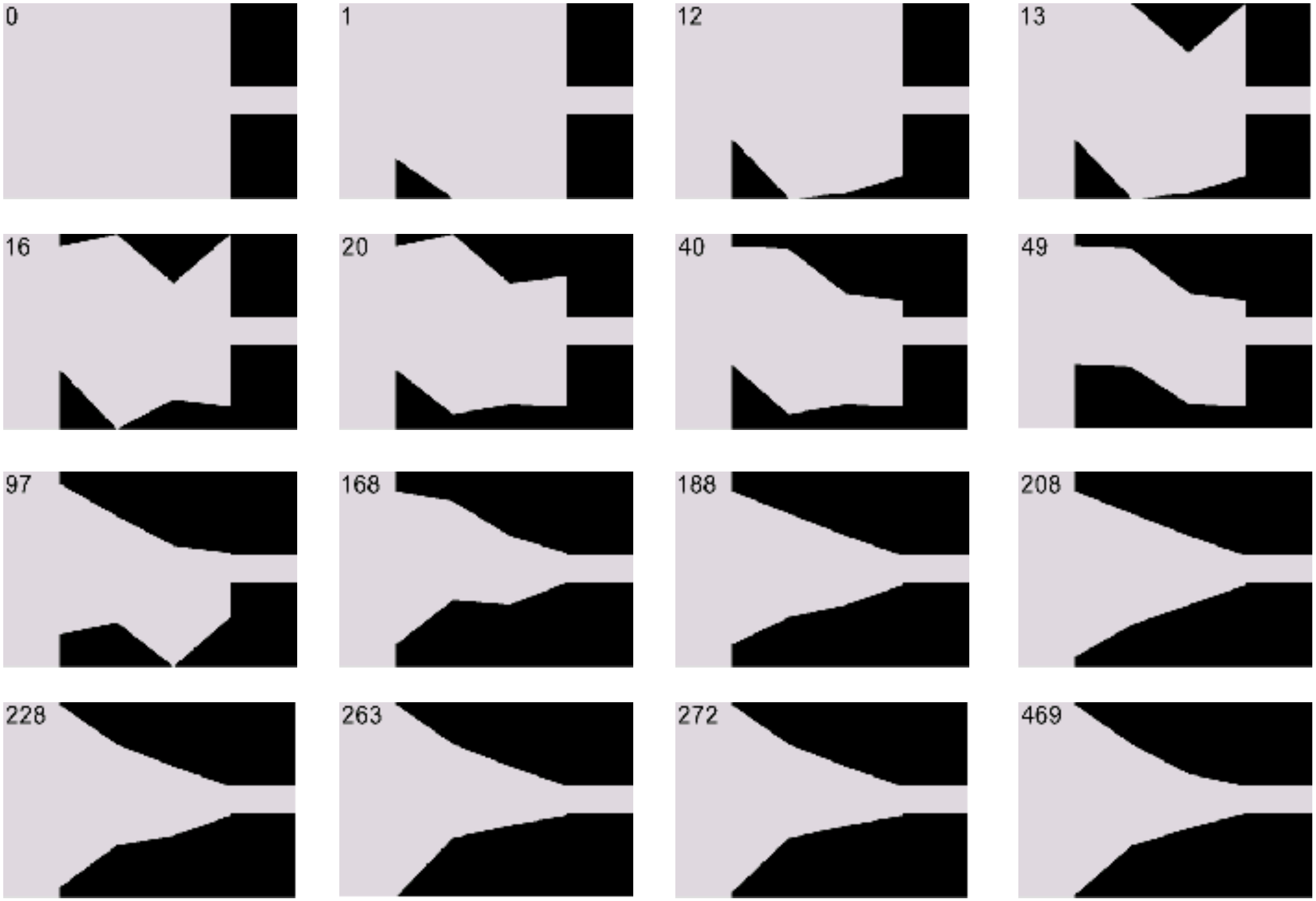
  Average simulated trajectory



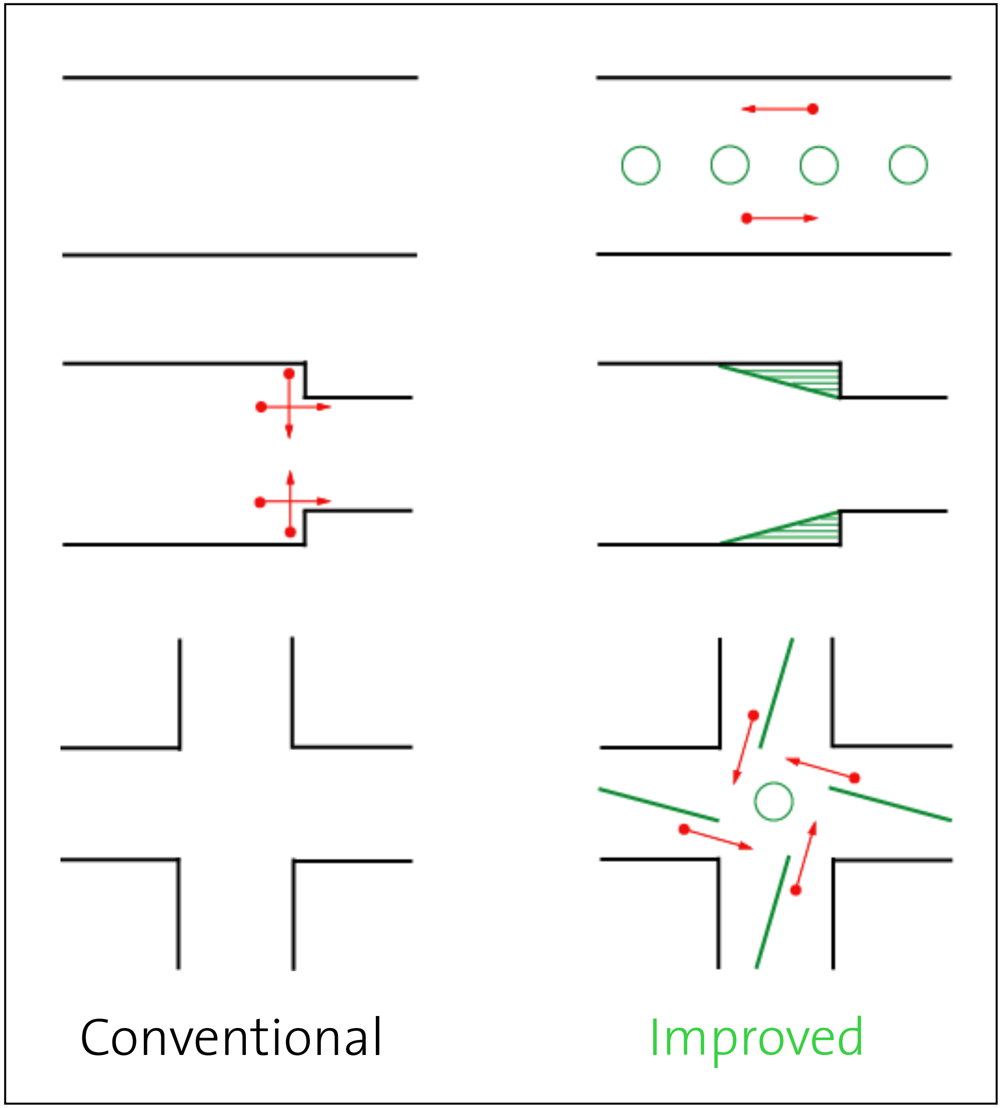
Evolutionary Optimization of Pedestrian Facilities



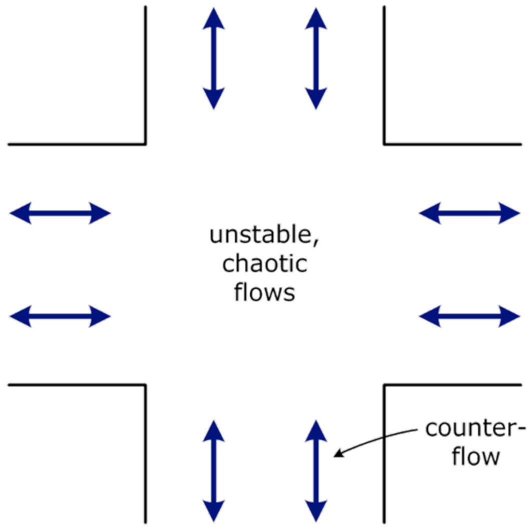
Evolutionary Optimization of a Bottleneck

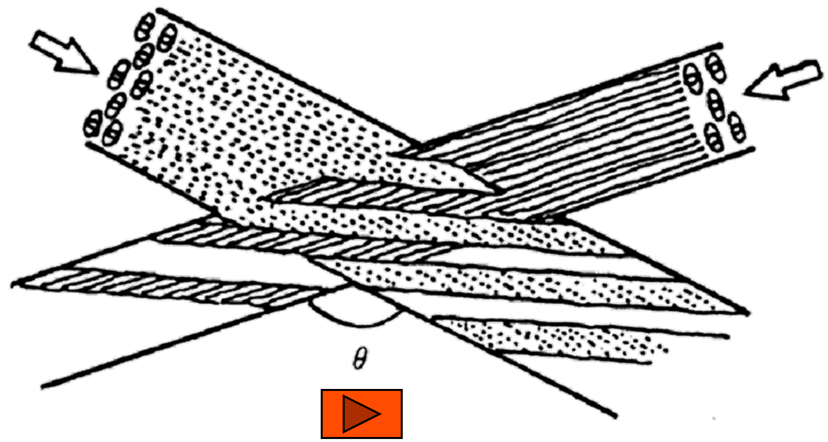


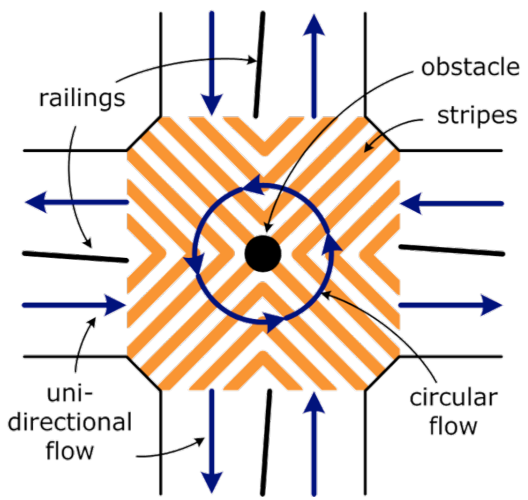
How to Optimize Pedestrian Facilities

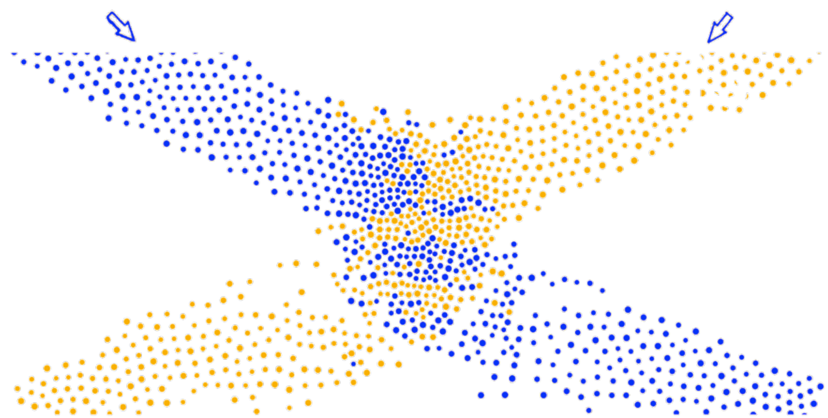


Self-Organization and Optimization of Intersecting Flows

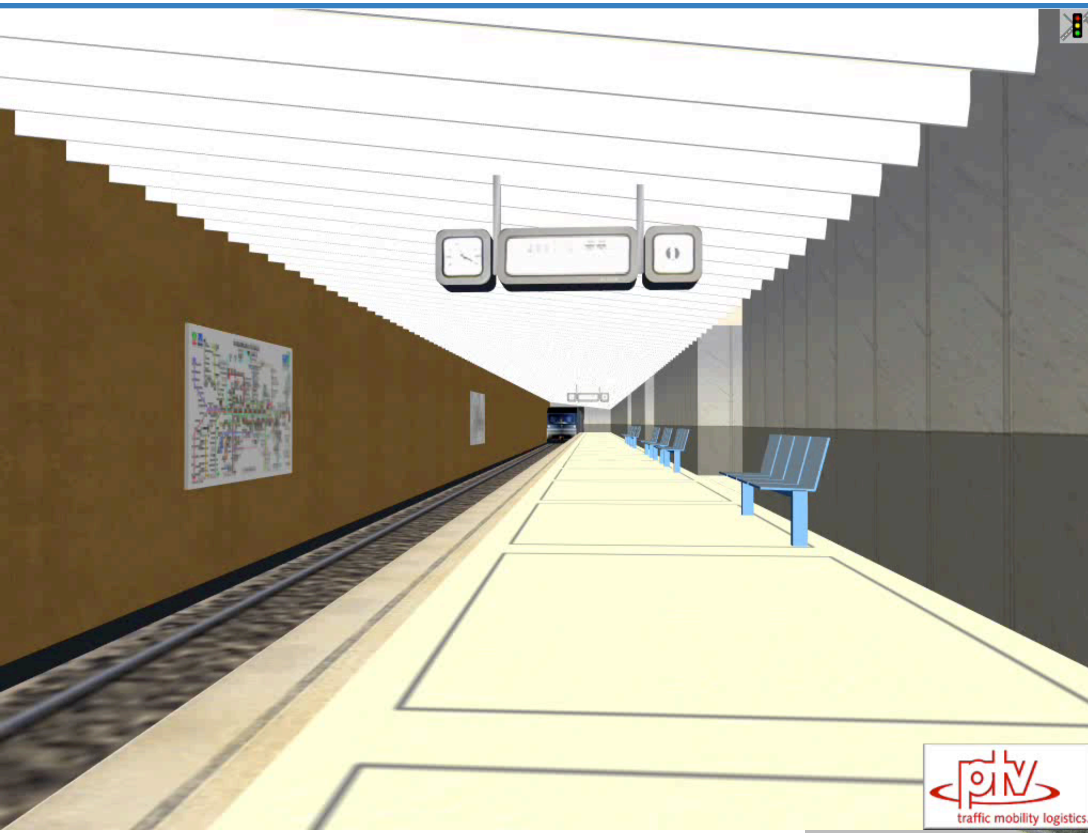






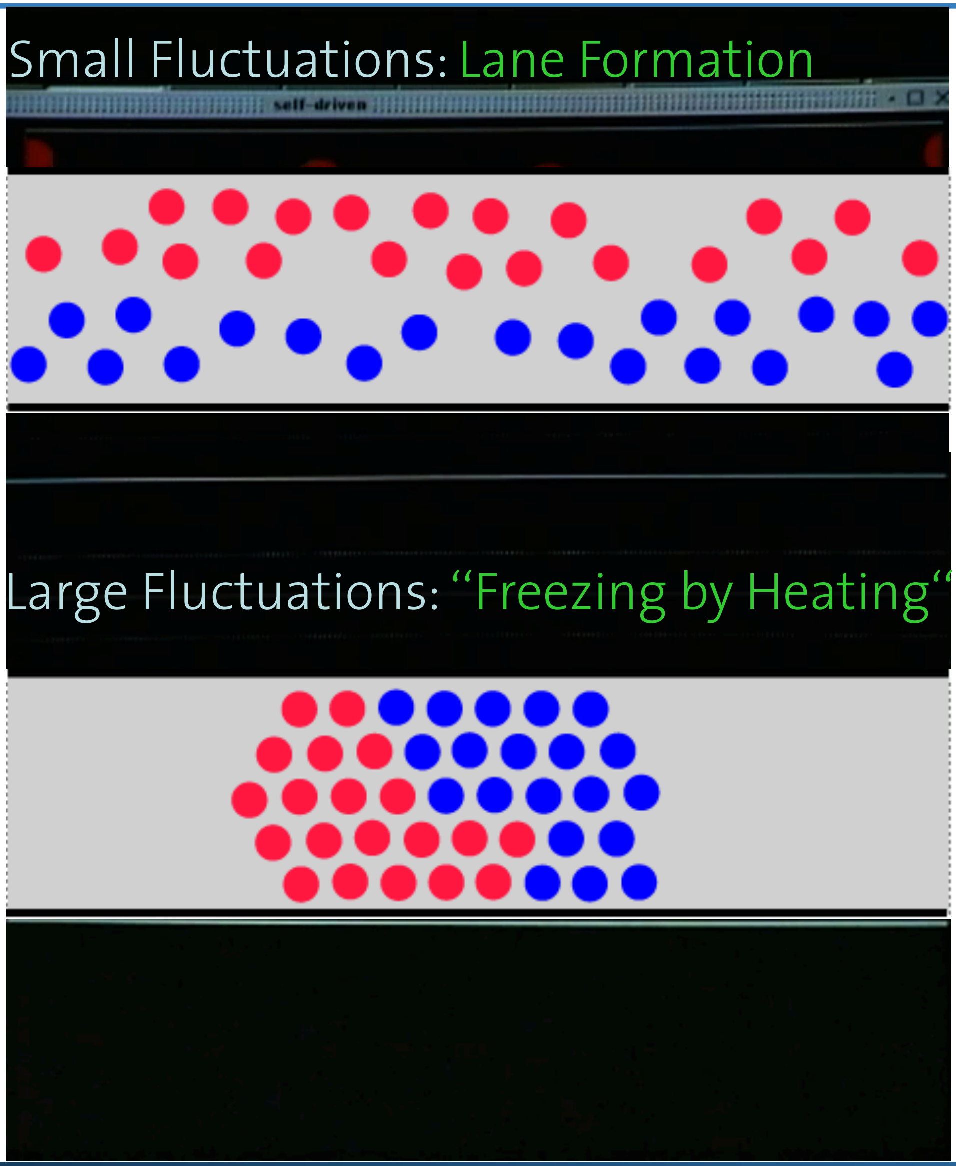


Social Force Model – Putting It All Together

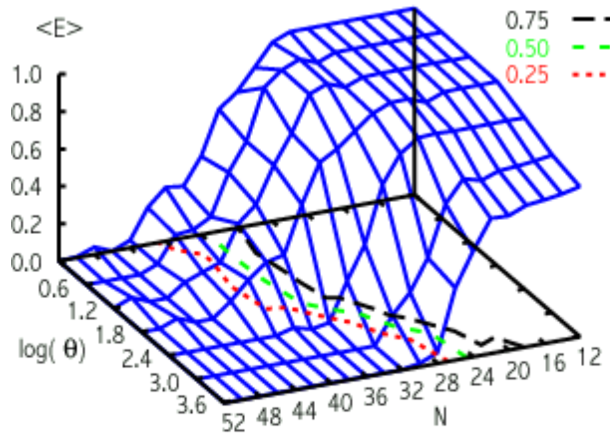


Dense Crowds and Crowd Disasters

Role of Fluctuations



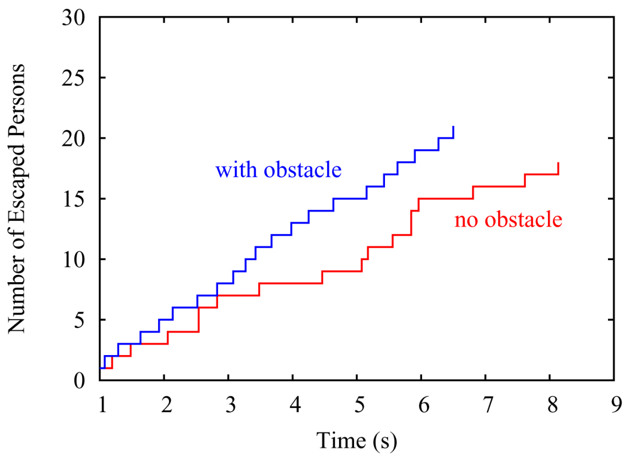
Ensemble-Averaged Efficiency

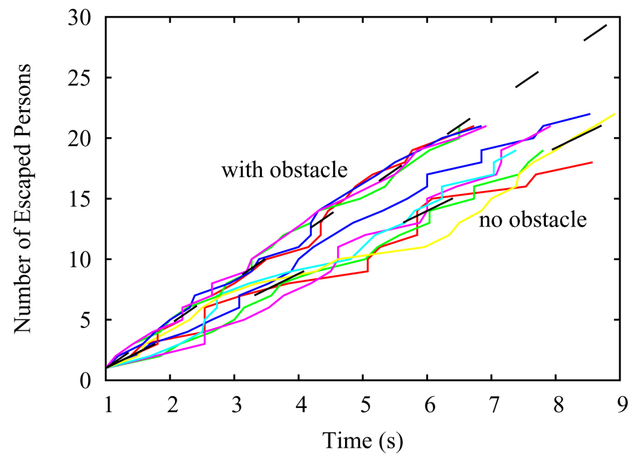


Reminder:
The temperature is proportional to the velocity variance.

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

Practical Implications and Design Solutions



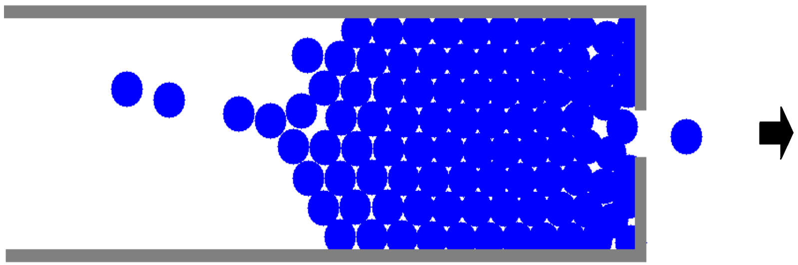


Without an obstacle one can observe clogging effects and a tendency of people to fall in panic situations (left).

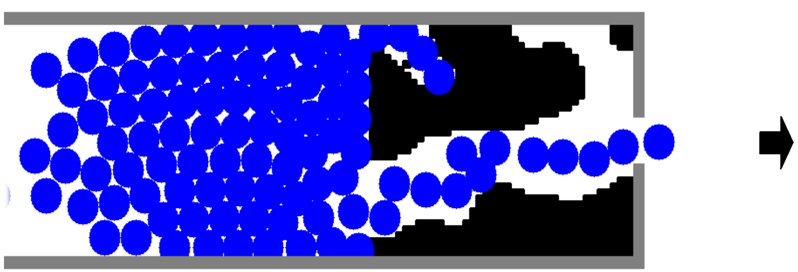
The clogging effect can be significantly reduced by a suitable obstacle, which increases the efficiency of escape and diminishes the tendency of falling (right).

Typical Evolutionary Designs (Preliminary)

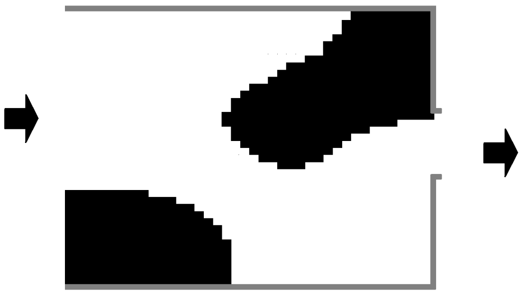
Snapshot; without obstacles



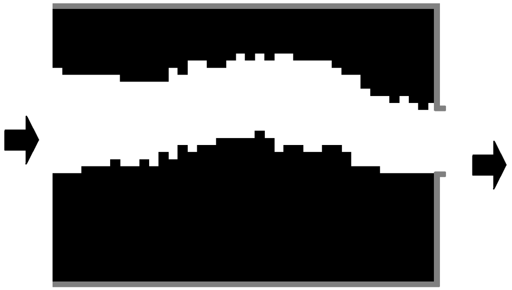
Snapshot; with obstacles



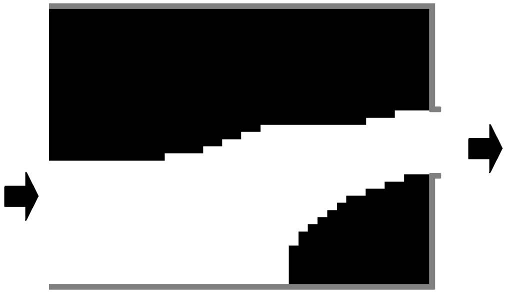
Compartment shape (fitness 0.83)



Zig-zag shape (fitness 1.78)

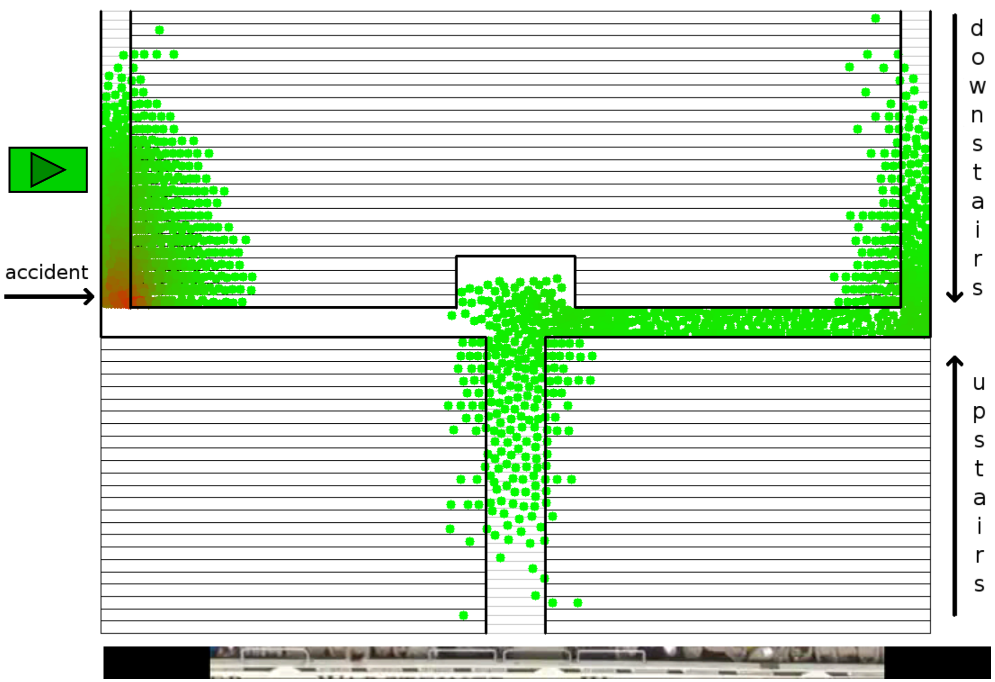


Funnel shape (fitness 1.99)

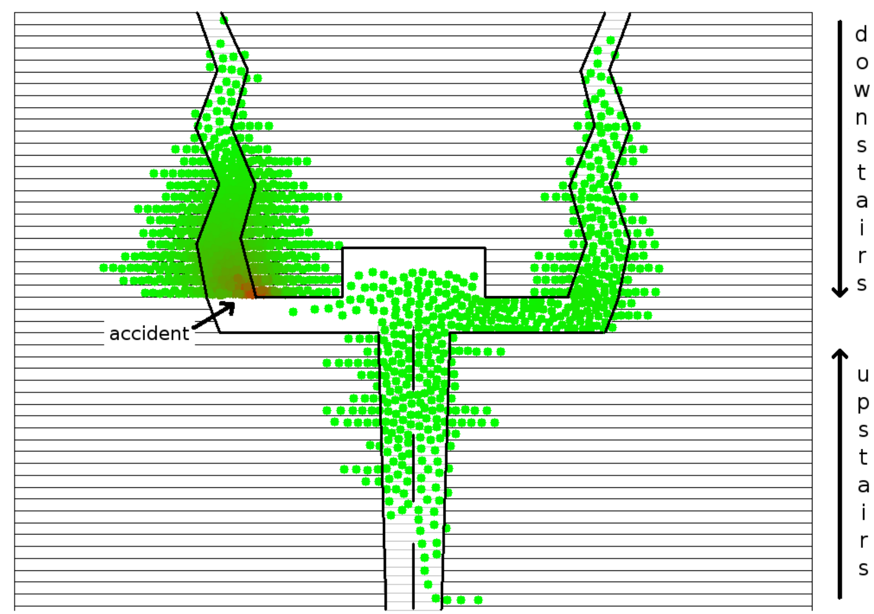


Safety Assessment of Architectural Designs

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

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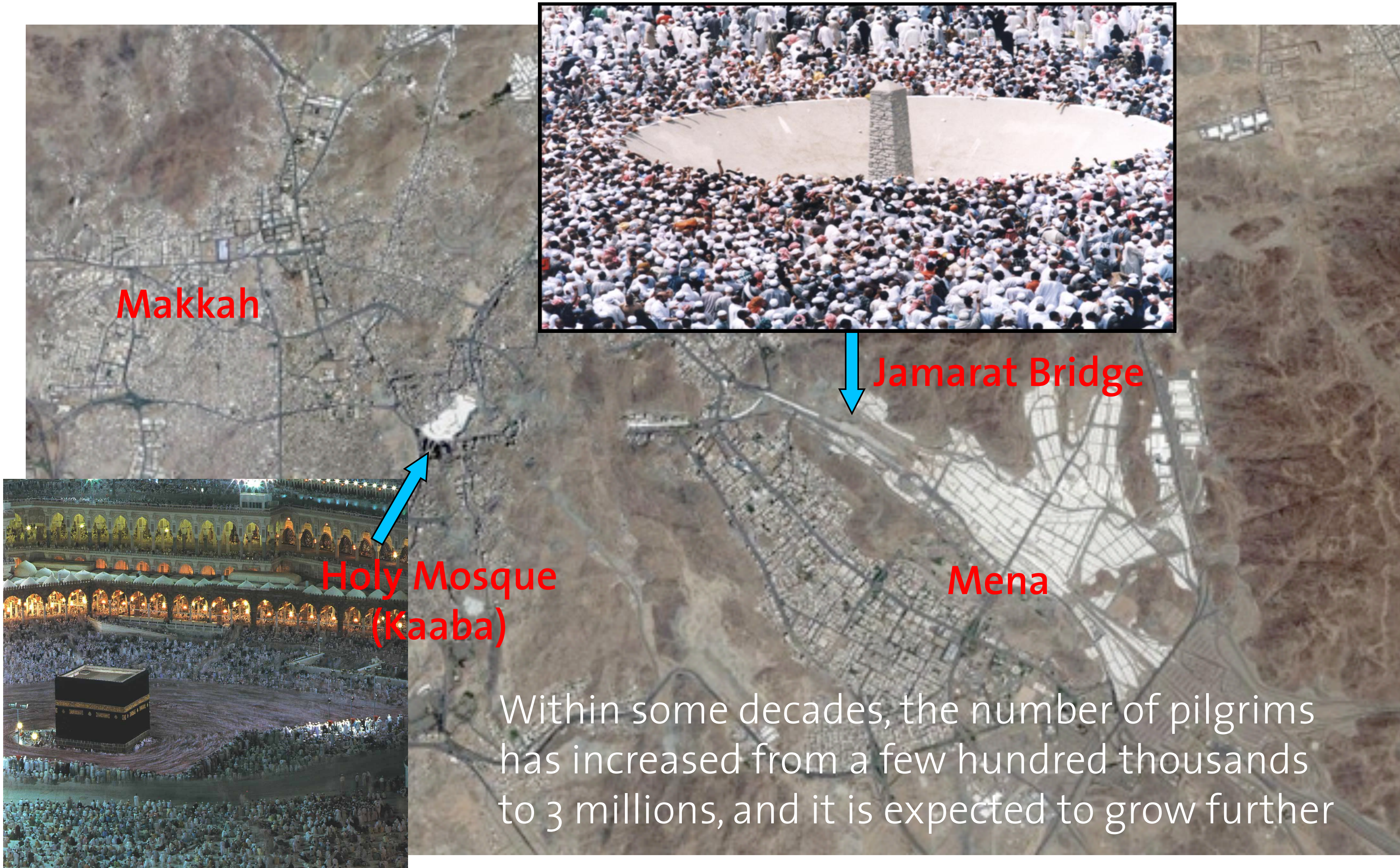
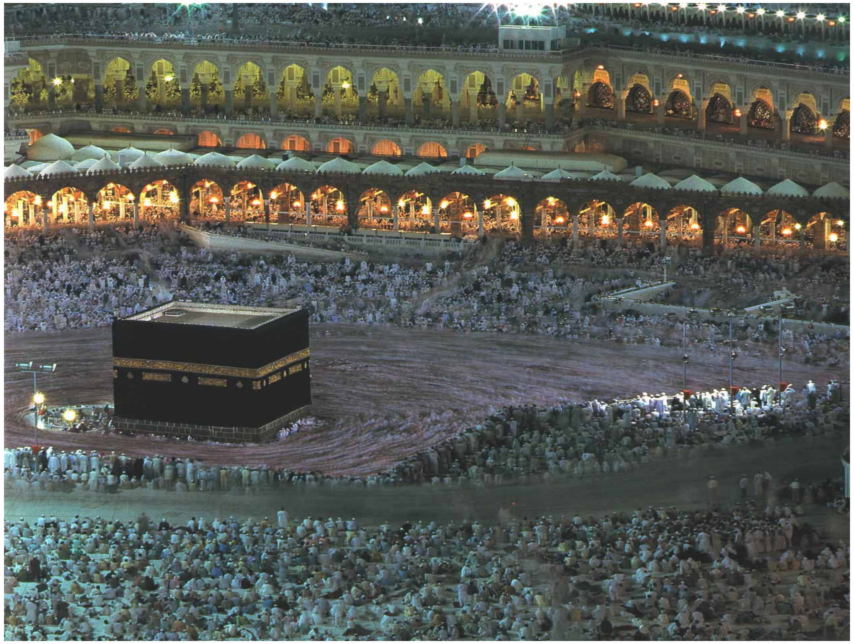
Supporting Believers Who Want to Perform their Religious Duties



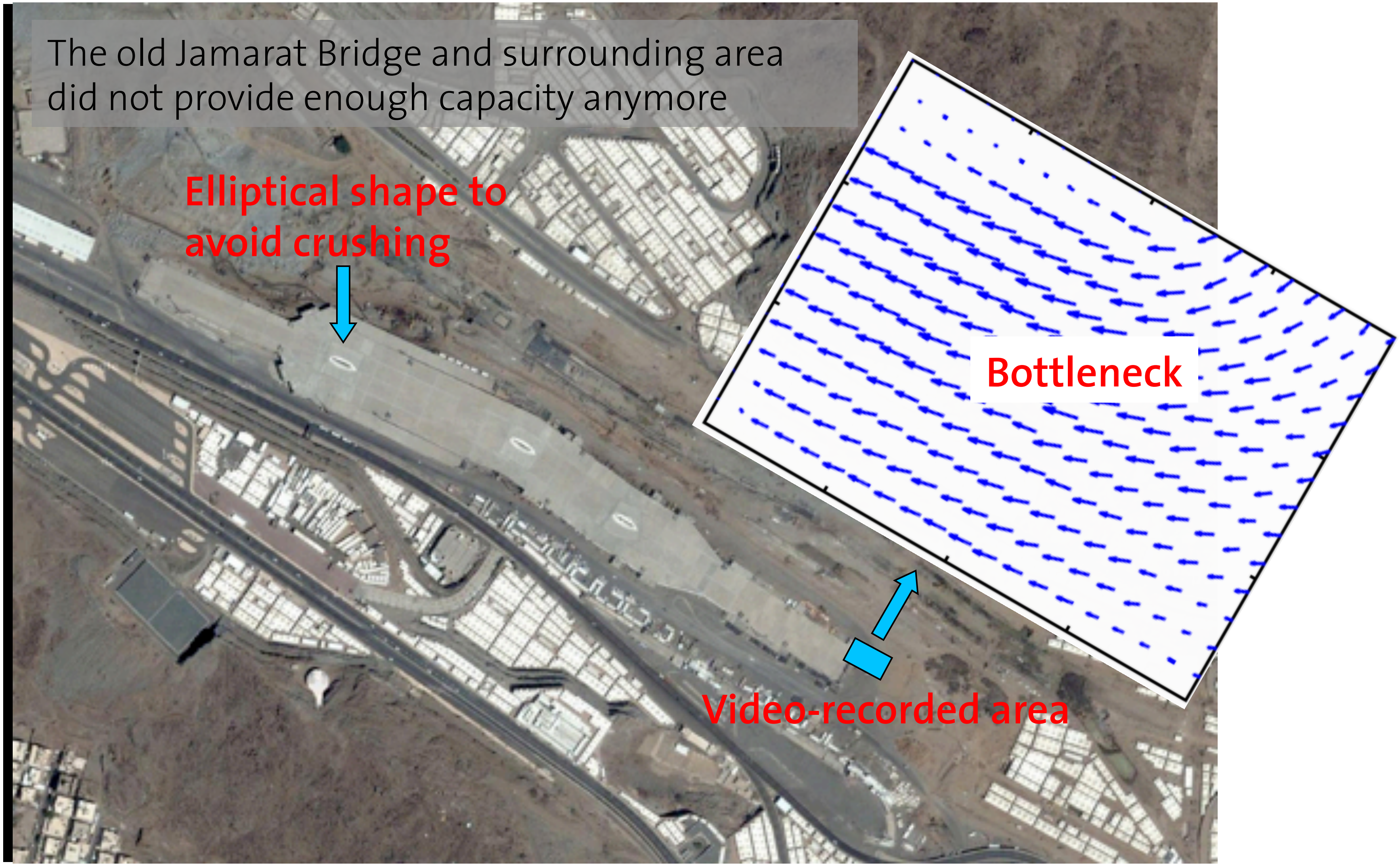
Within some decades, the number of pilgrims has increased from a few hundred thousands to 3 millions, and it is expected to grow further

Annual Pilgrimage in Makkah

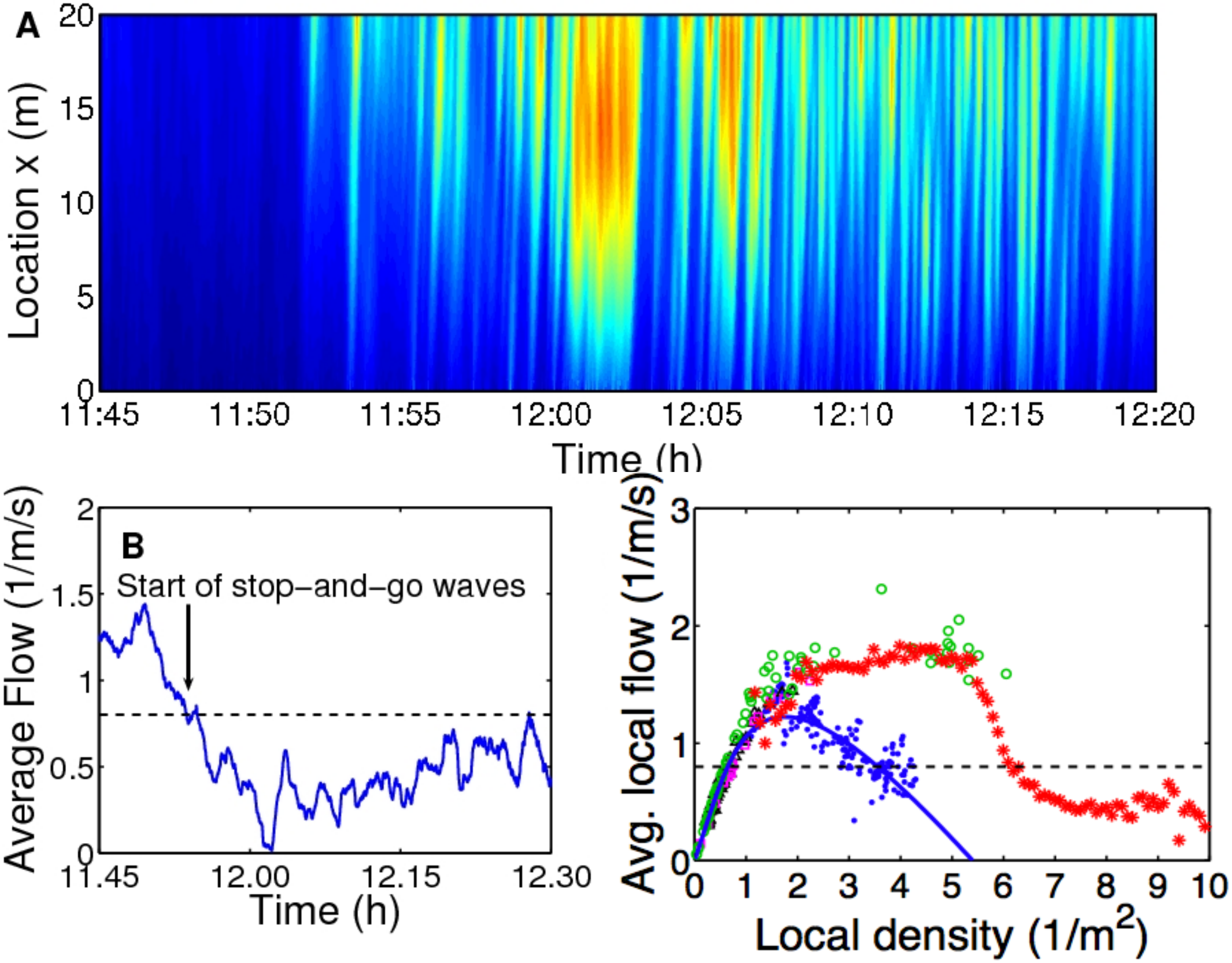
Orderly behavior is supported by social norms and imitation.



The Jamarat Bridge (as of January 2006)



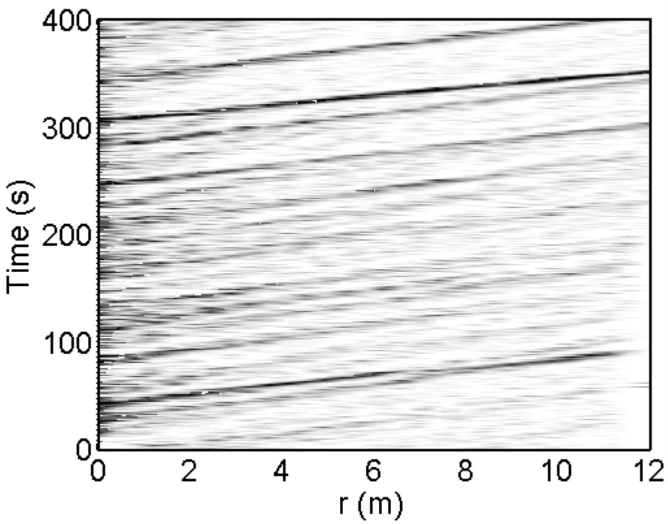
Transition from Smooth to Stop-and-Go Flow

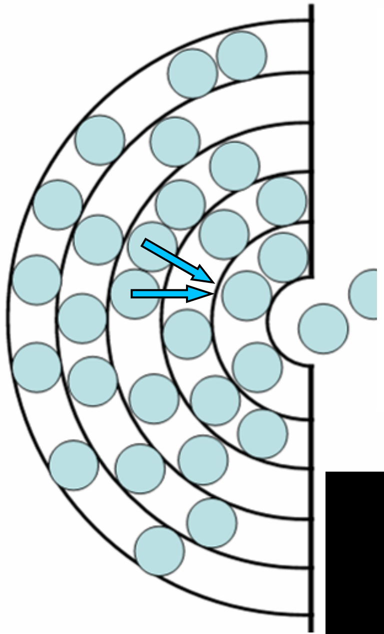


Mechanism is very different from vehicle traffic!

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

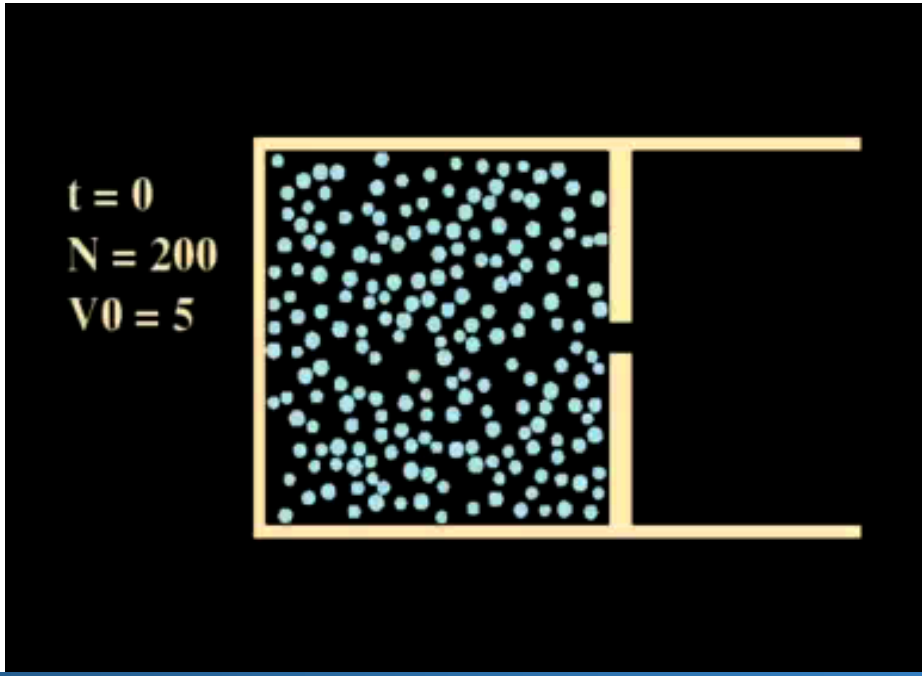
Competition for a scarce resource, here: space.



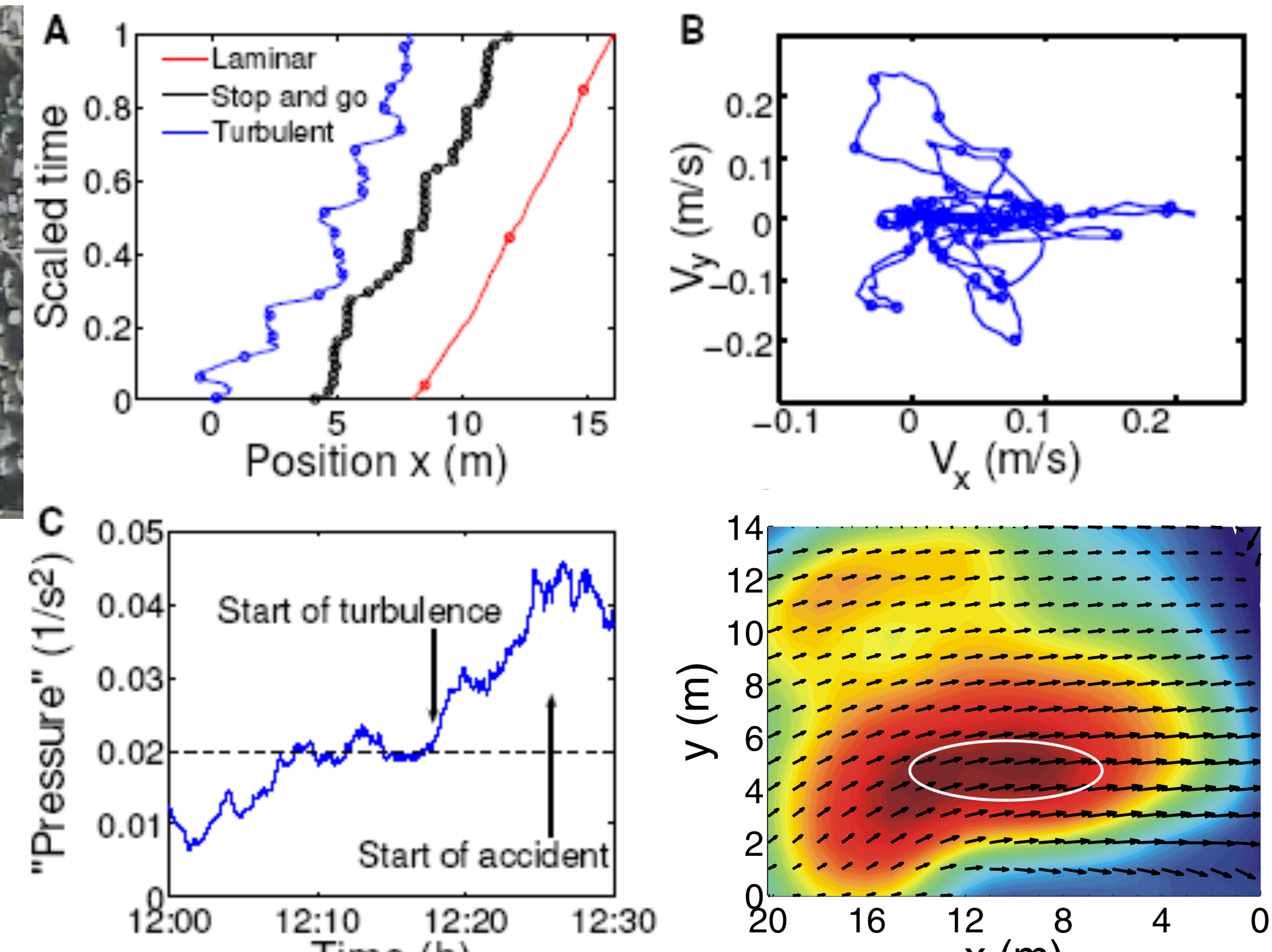


At high densities, several people may compete for the same gap and block each other. This constitutes a conflict and causes an alternation between downstream pedestrian and upstream gap propagation.

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



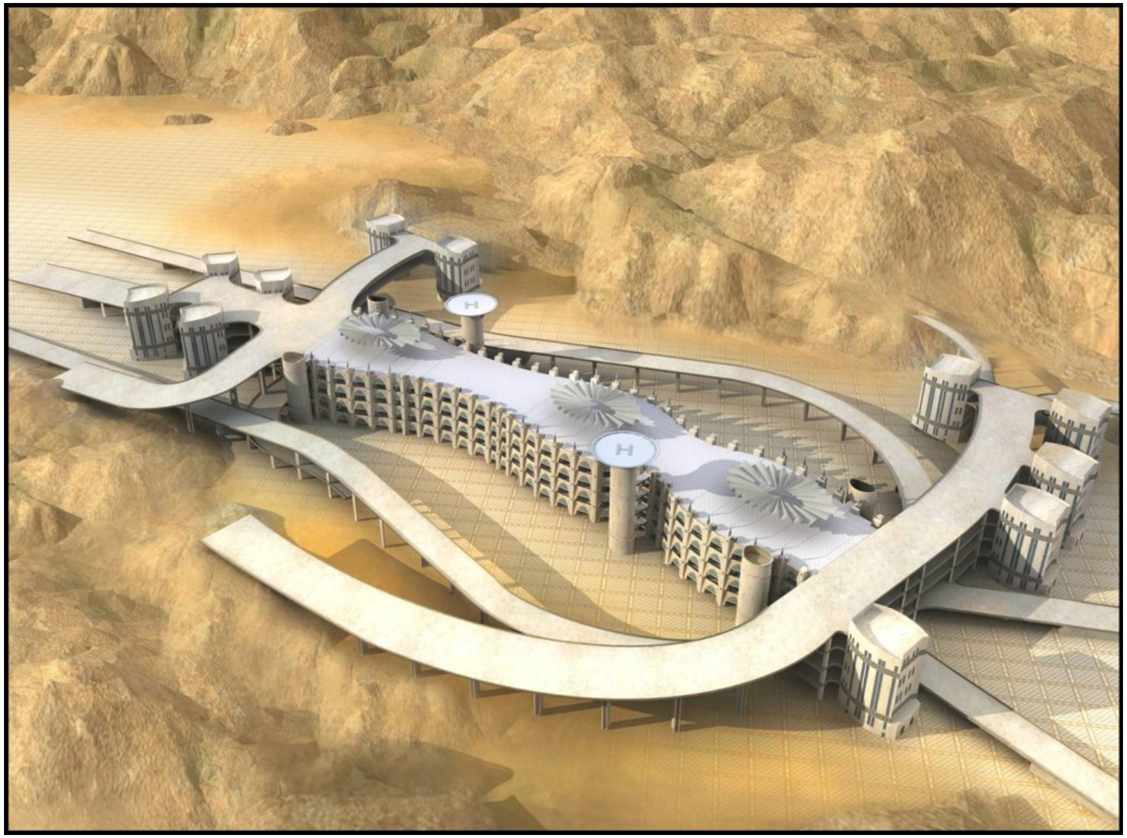
The density times the variation in speeds constitutes the hazard! Pressure fluctuations cause turbulent motion and potentially the falling and trampling of people.

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

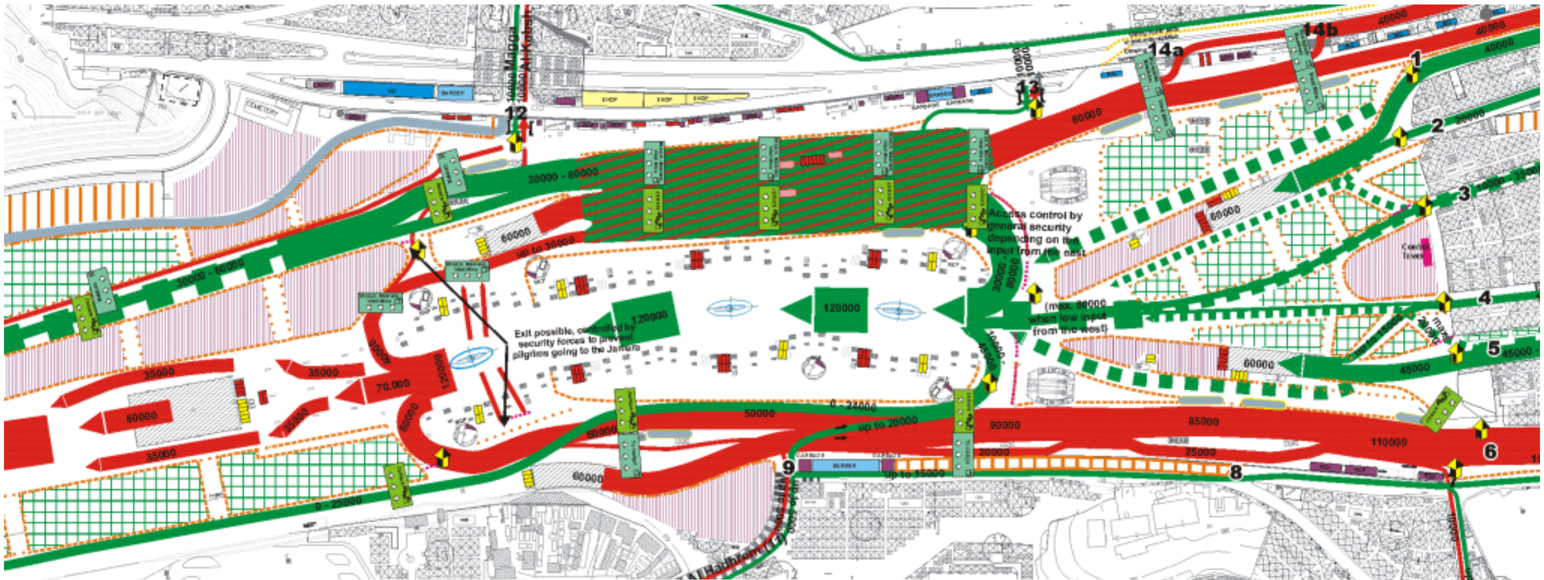
The New Jamarat Bridge and Its Advantages

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.

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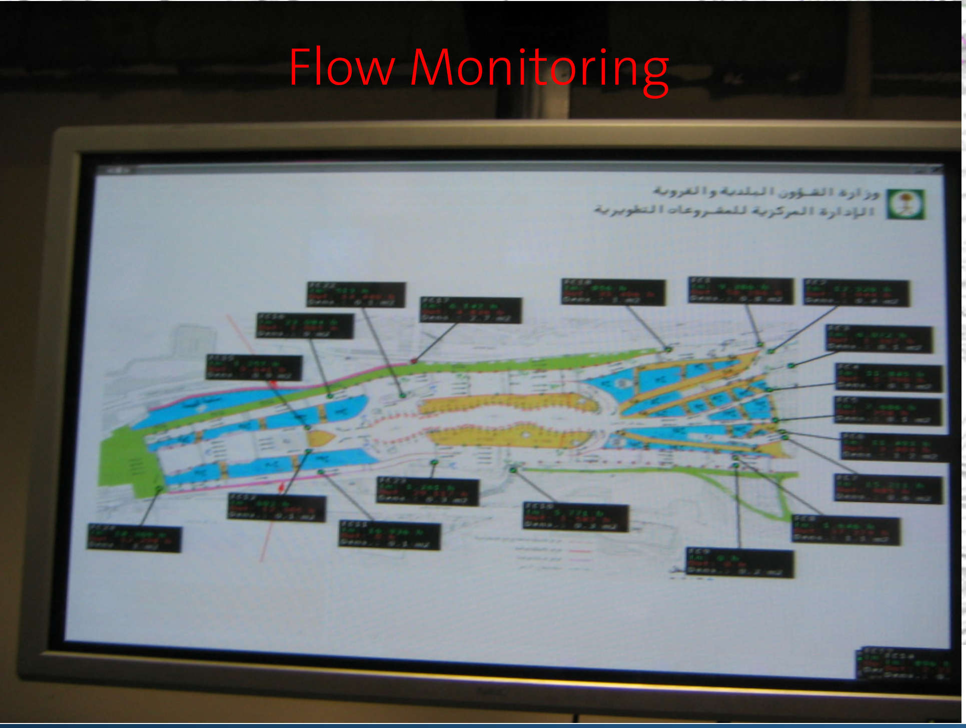
Scheduling, Flow Monitoring and Adaptive Rerouting

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

Some possibilities for adaptive rerouting

Flow Monitoring



Scheduling