ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Crowd Dynamics and Evacuation

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Dense Crowds and Crowd Disasters

Recent Stampedes

South Africa – Soccer Stadium, 2001

43 deaths. The disaster happened when fans outside the stadium pushed to enter in order to see the game. Most of the deaths occured when fans surged forward, pushing their way through the fence around the stadium or climbed over gates.

The gates leading to the stadium were closed after it was filled to capacity, but thousands of excluded fans shoved through the fence, breaking it in four places.

(APTN)

(APTN)

Recent Stampedes

Moscow, Russia – Rock Festival, 2003

Two female suicide bombers caused the death of 15 persons at a rock festival in Moscow. The blasts happened away from the main crowd as the bombers were stopped at the concert entrance.

Ignorance of Side or Emergency Exits

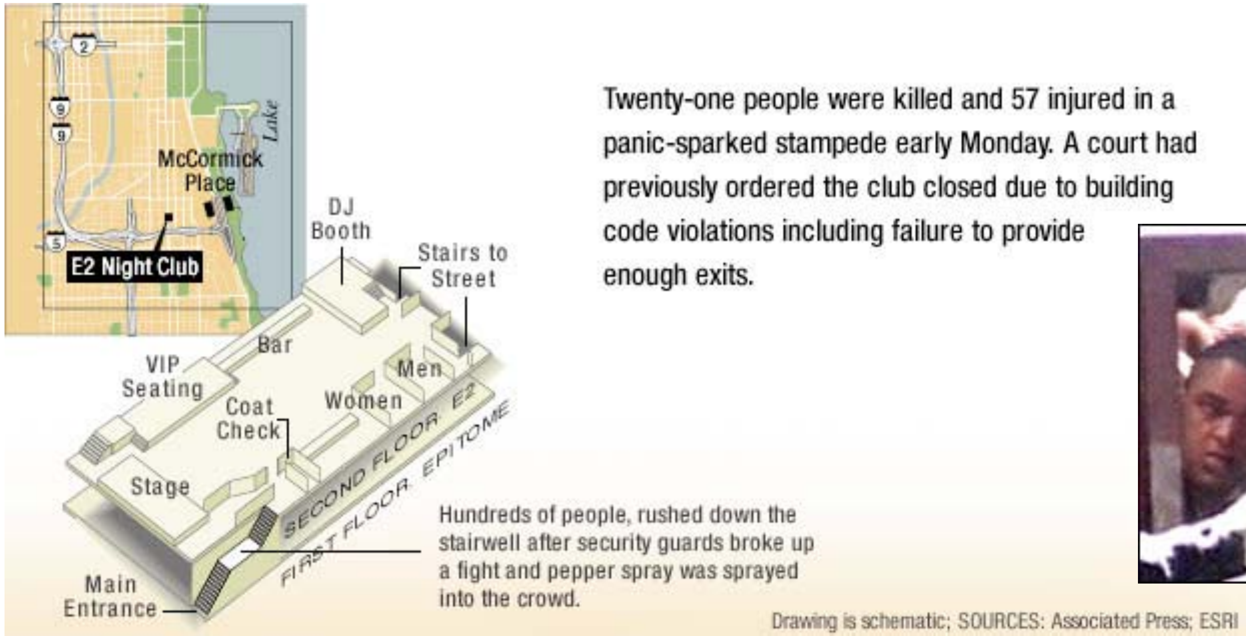
Rhode Island, USA – Fire at a Nightclub, 2003

The nightclub had been engulfed in flame within three minutes and, in the panic, people had neglected to use the fire exits, creating a bottleneck at the main entrance where some suffocated. People tried to go out the same way they came in. They did not use the other three fire exits. Some visitors thought that the fire was part of the show and therefore delayed their evacuation.

Recent Stampedes

Chicago, USA – Nightclub stampede, 2003

Two women began fighting and security guards tried to break up the fight with pepper spray, which was misinterpreted as a poisonous gas attack by terrorists. The burning mist created a stampede towards the steep and narrow staircase. Security guards blocked the exit at the end of the staircase in order to get control over the crowd. The result was that people where piling up at the end of the staircase and 21 persons died.

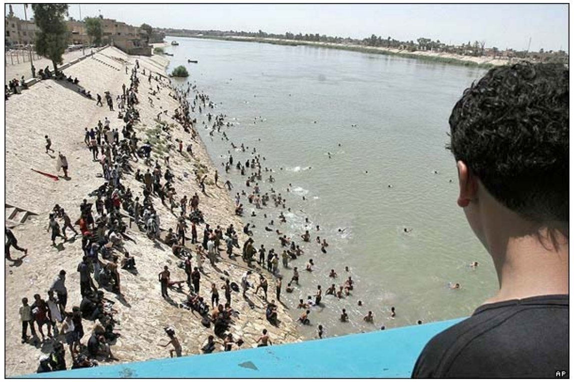


Recent Stampedes

Iraq - al A'imma Bridge in Baghdad, 2005

About thousand deaths. "Phantom panic" after rumors of an imminent suicide bomber. Most people died by drowning after jumping into the Tigris river in desperation to escape the crowded bridge. Others where trampled to death.






Model Validation and Calibration

A huge collection of video material of pedestrian crowds, and specialized software has made it possible to create an environment for evaluating and calibrating pedestrian models.

Videos

$$\vec{f}_{\alpha\beta}(t) = A \frac{\vec{d}}{\|\vec{d}\|} \exp(-\|\vec{d}\| / B)$$

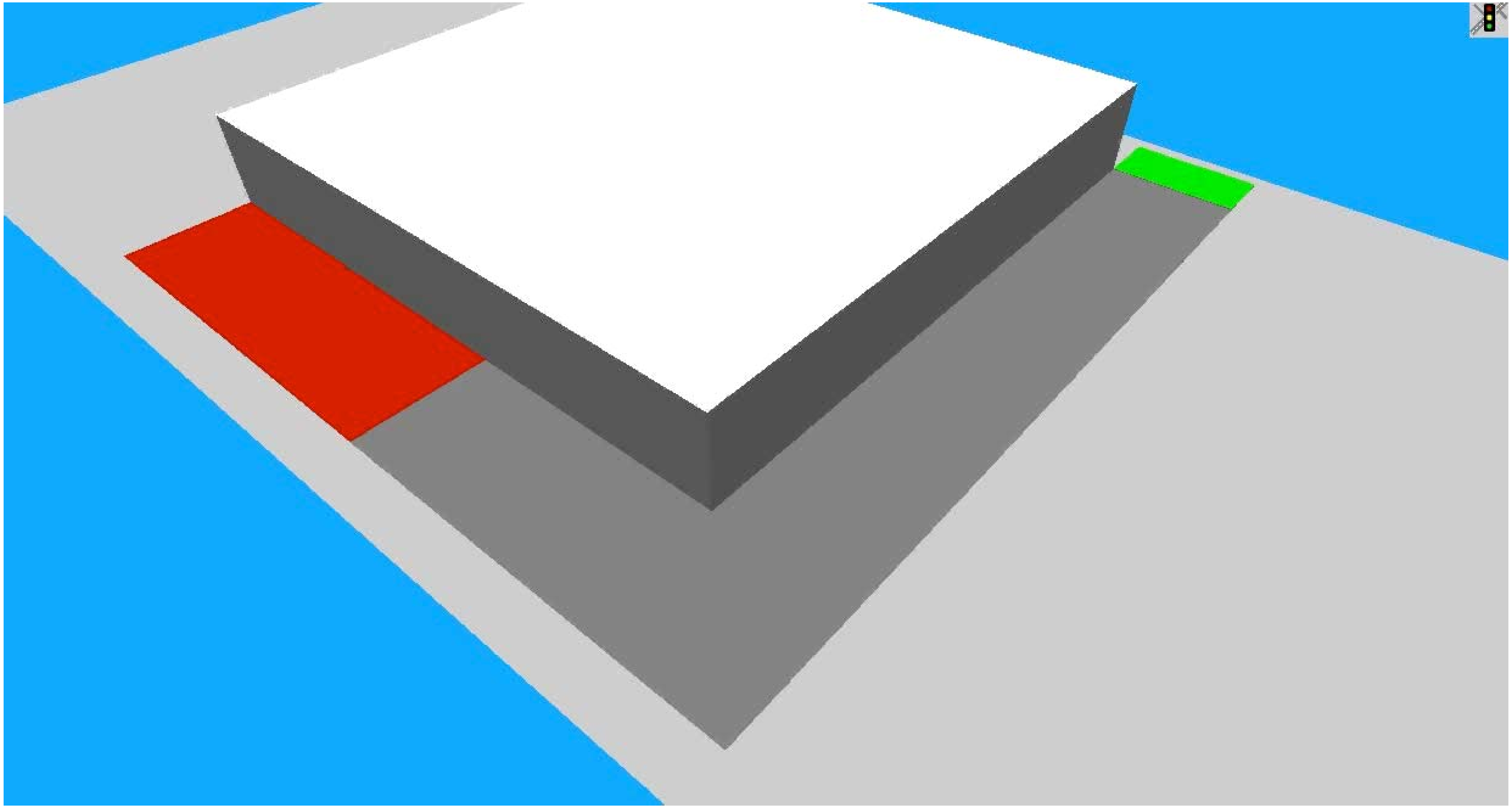
Model

Brutus cluster at ETH

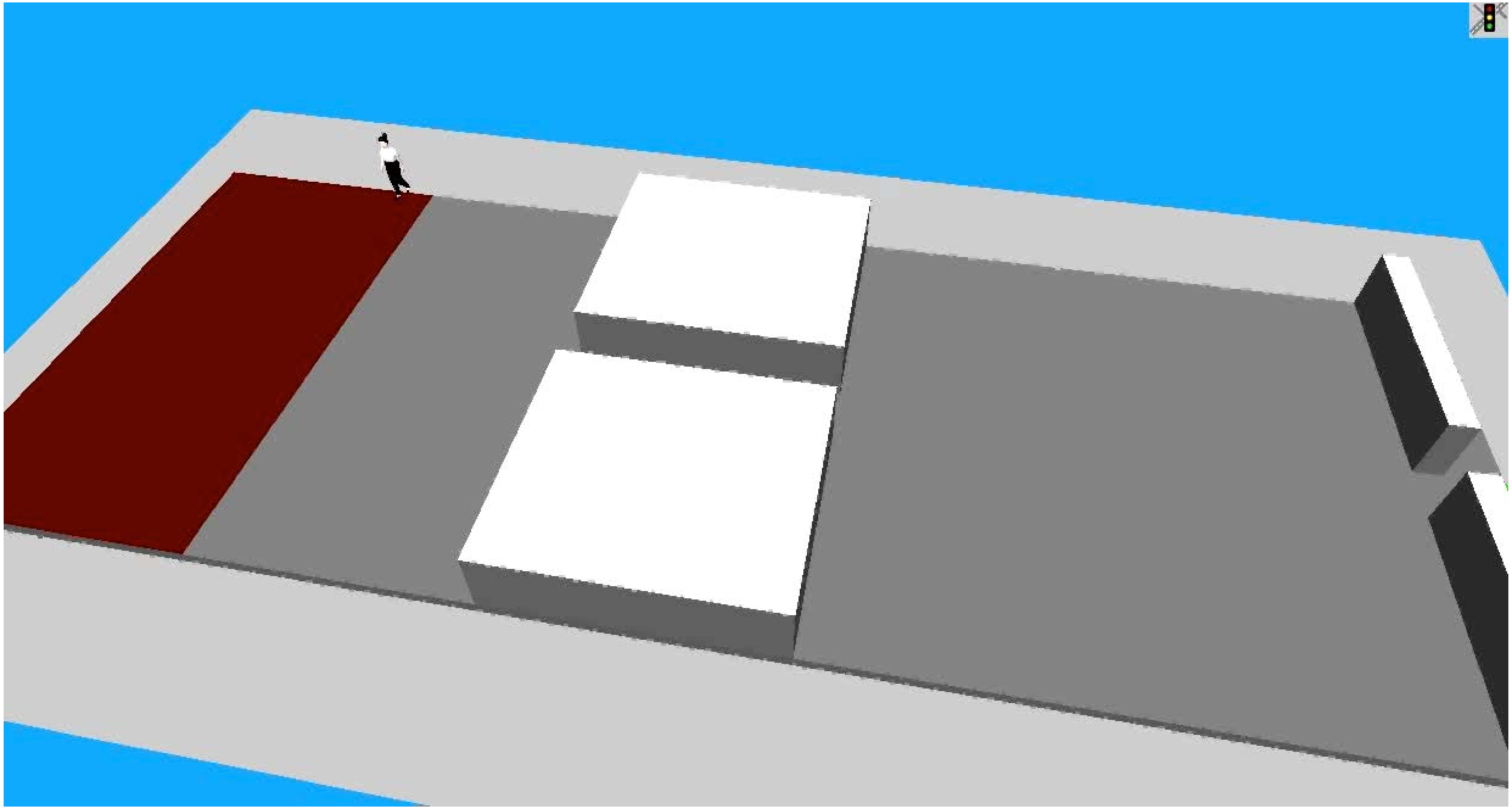
Model	N	Angular dependence	A_s	B_s	τ	Speed percentile	ΔT
Circular	17	λ =0.02	0.04	1.28	0.59	48	-
Elliptical I	9	λ =0.22	0.85	0.38	0.64	53	0.87
Elliptical II	9	λ =0.25	0.42	0.48	0.61	51	1.04
Circular	4	$\lambda = 1$	0.03	2.30	0.57	43	-
Elliptical I	1	$\lambda = 1$	0.52	0.37	0.56	42	0.53
Elliptical II	13	$\lambda = 1$	0.39	0.31	0.56	43	1.88
Circular	10	Half circle	0.79	0.37	0.61	52	-
Elliptical I	19	Half circle	0.24	0.63	0.61	53	1.54
Elliptical II	10	Half circle	0.39	0.54	0.61	53	0.47
Circular	∞	λ =0.14	0.03	2.03	0.62	52	-
Elliptical I	∞	λ =0.11	0.23	0.45	0.61	43	2.26
Elliptical II	∞	λ =0.09	0.05	1.47	0.63	54	1.17
Circular	∞	$\lambda = 1$	0.70	0.26	0.61	42	-
Elliptical I	∞	$\lambda = 1$	0.03	0.96	0.57	42	1.00
Elliptical II	∞	$\lambda = 1$	0.55	0.32	0.56	43	0.91
Circular	∞	Half circle	0.11	1.05	0.62	53	-
Elliptical I	∞	Half circle	0.60	0.40	0.60	53	1.62
Elliptical II	∞	Half circle	2.27	0.18	0.53	43	0.20

Evaluation and calibration results

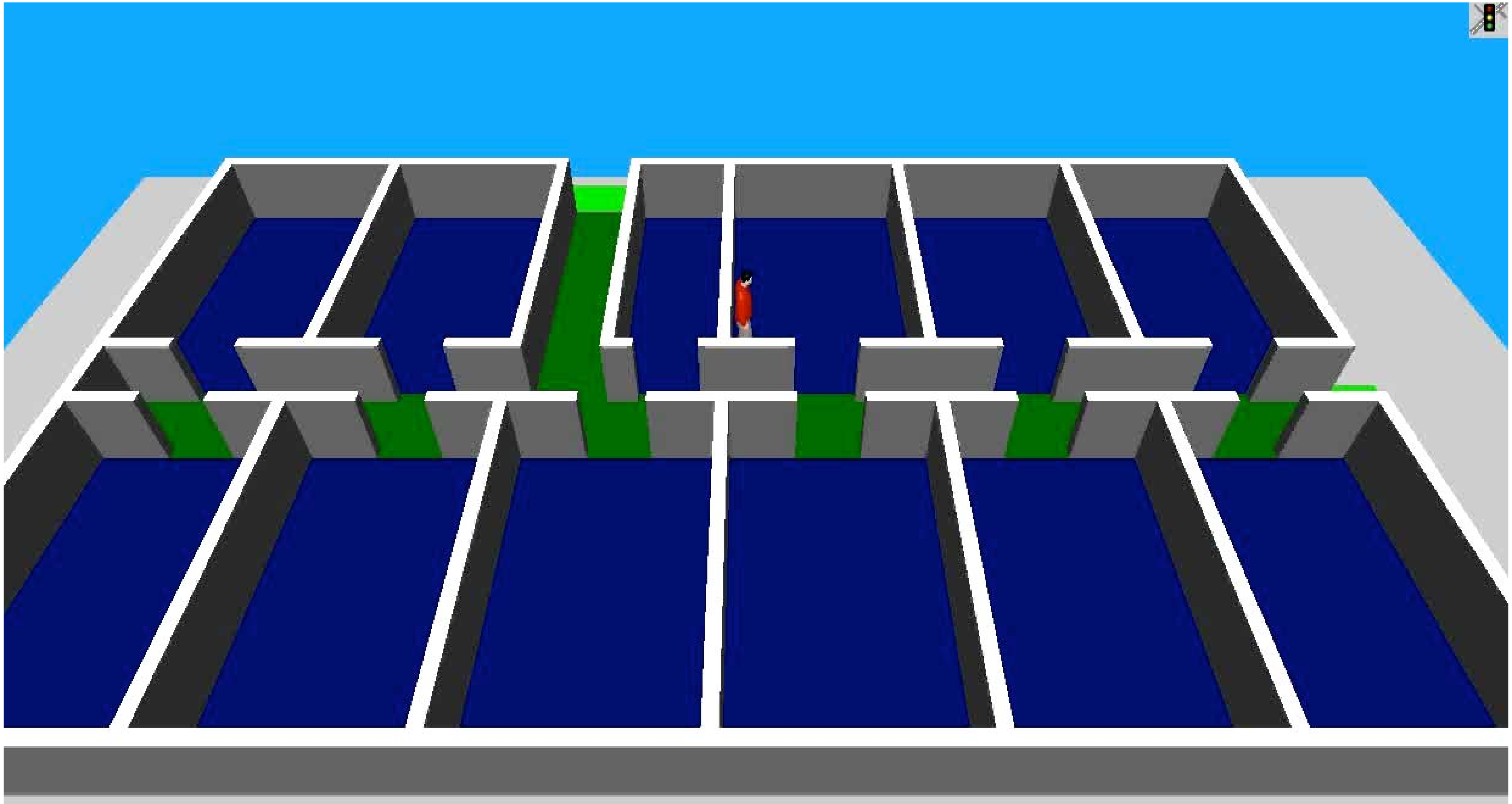
Social Force Model - Corners



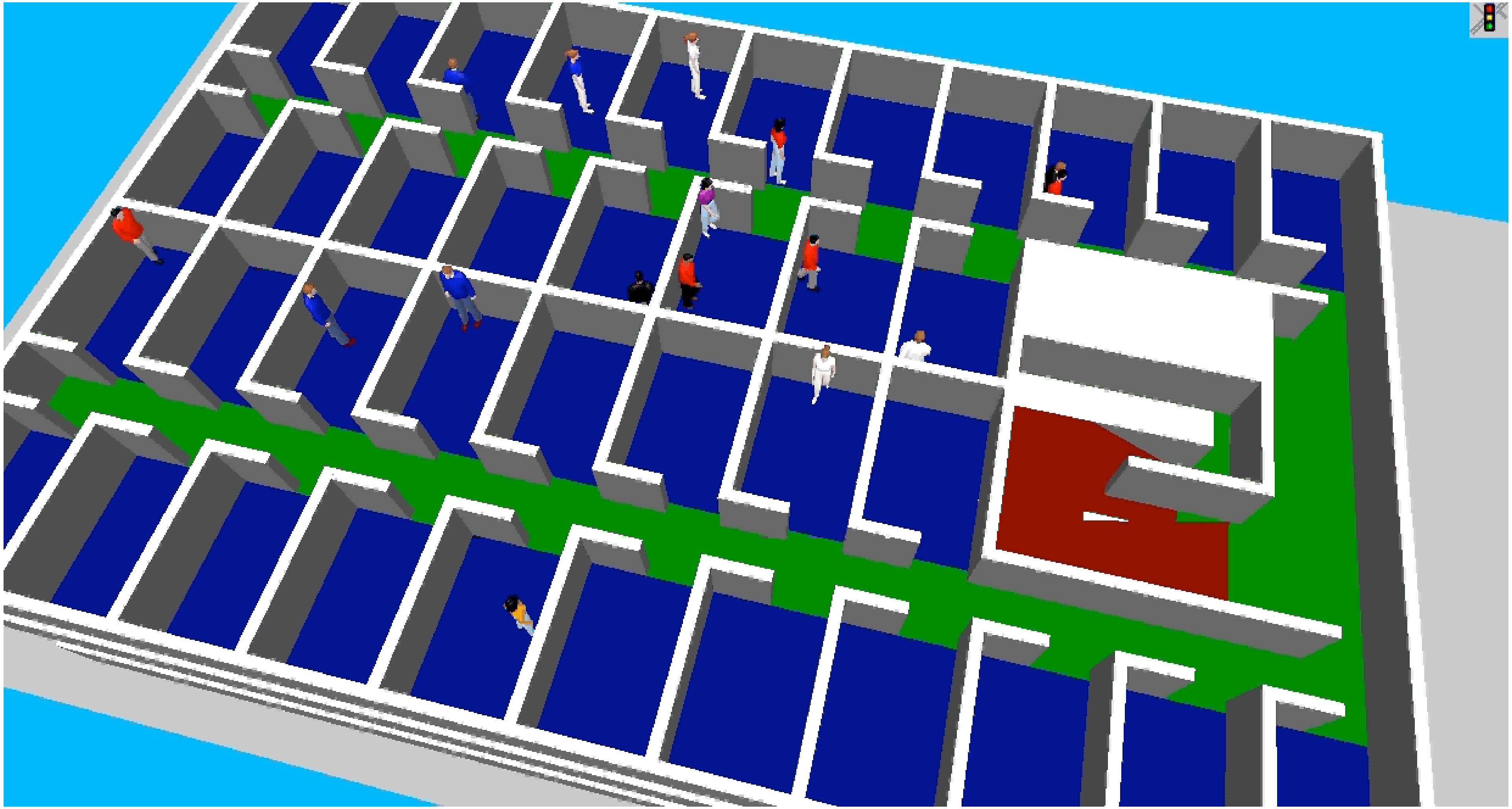
Social Force Model - Bottlenecks



Social Force Model - Complex Environments

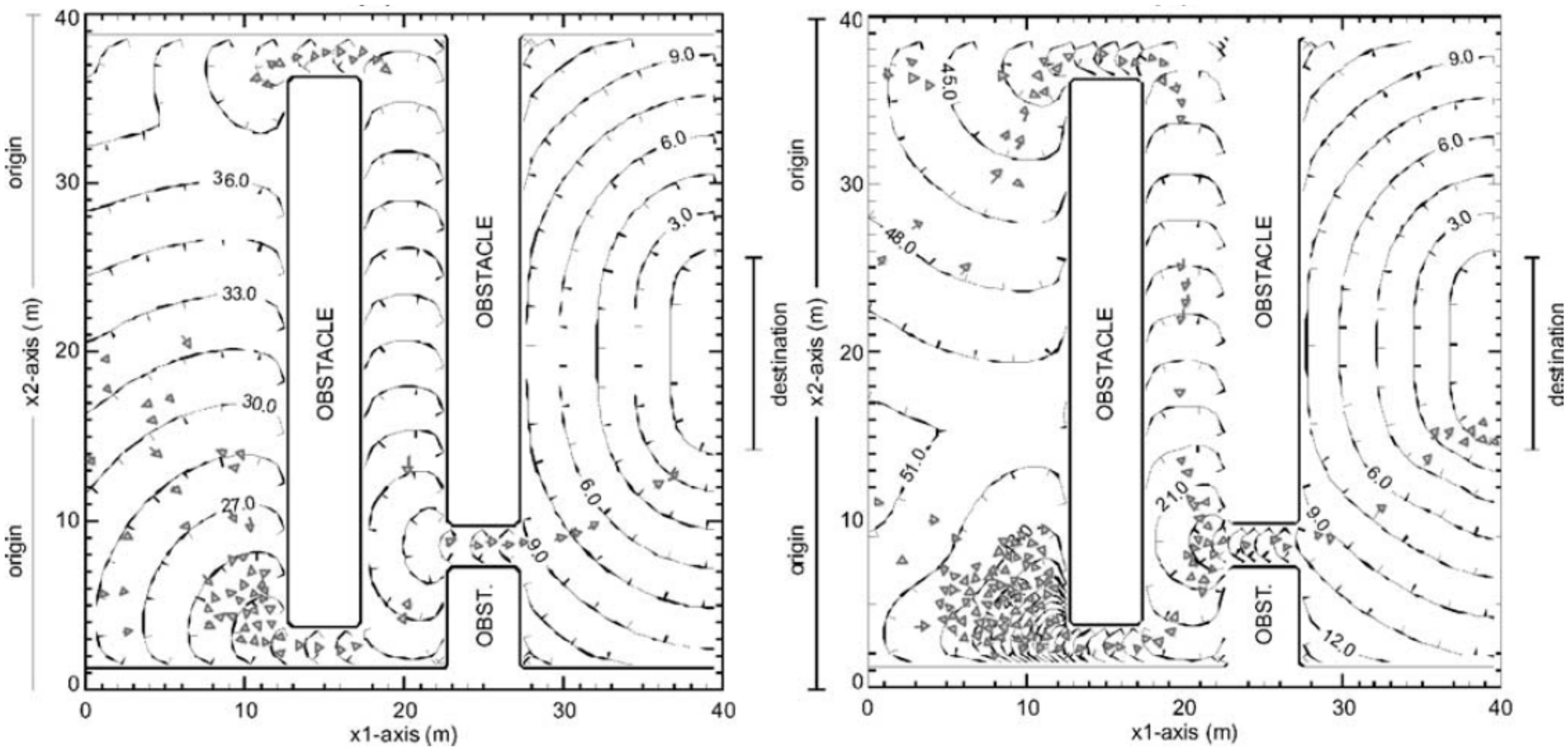


Rimea Scenarios - Evacuation of a Hotel



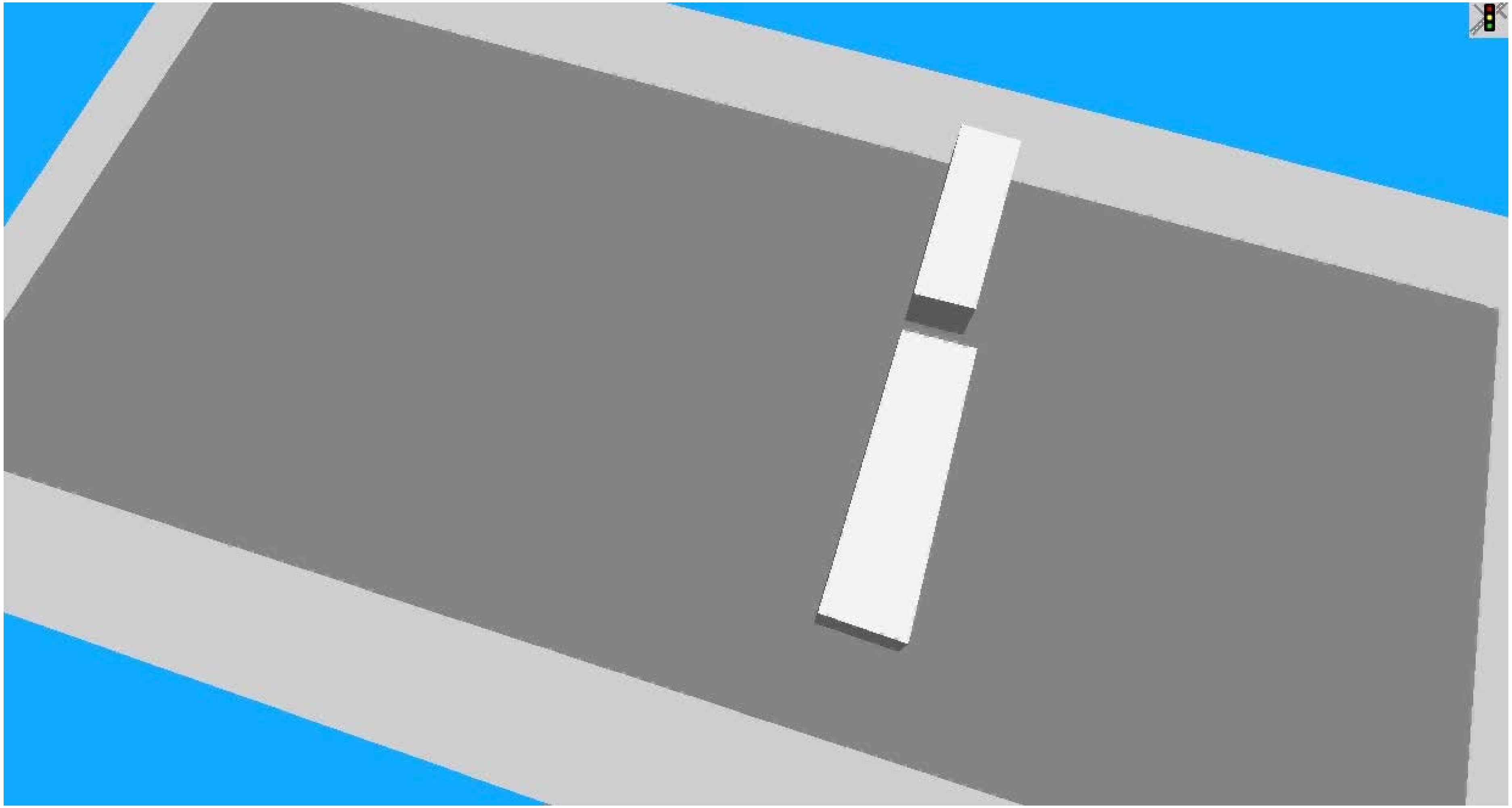
Utility Maximization / Shortest Paths

Expected minimum perceived disutility

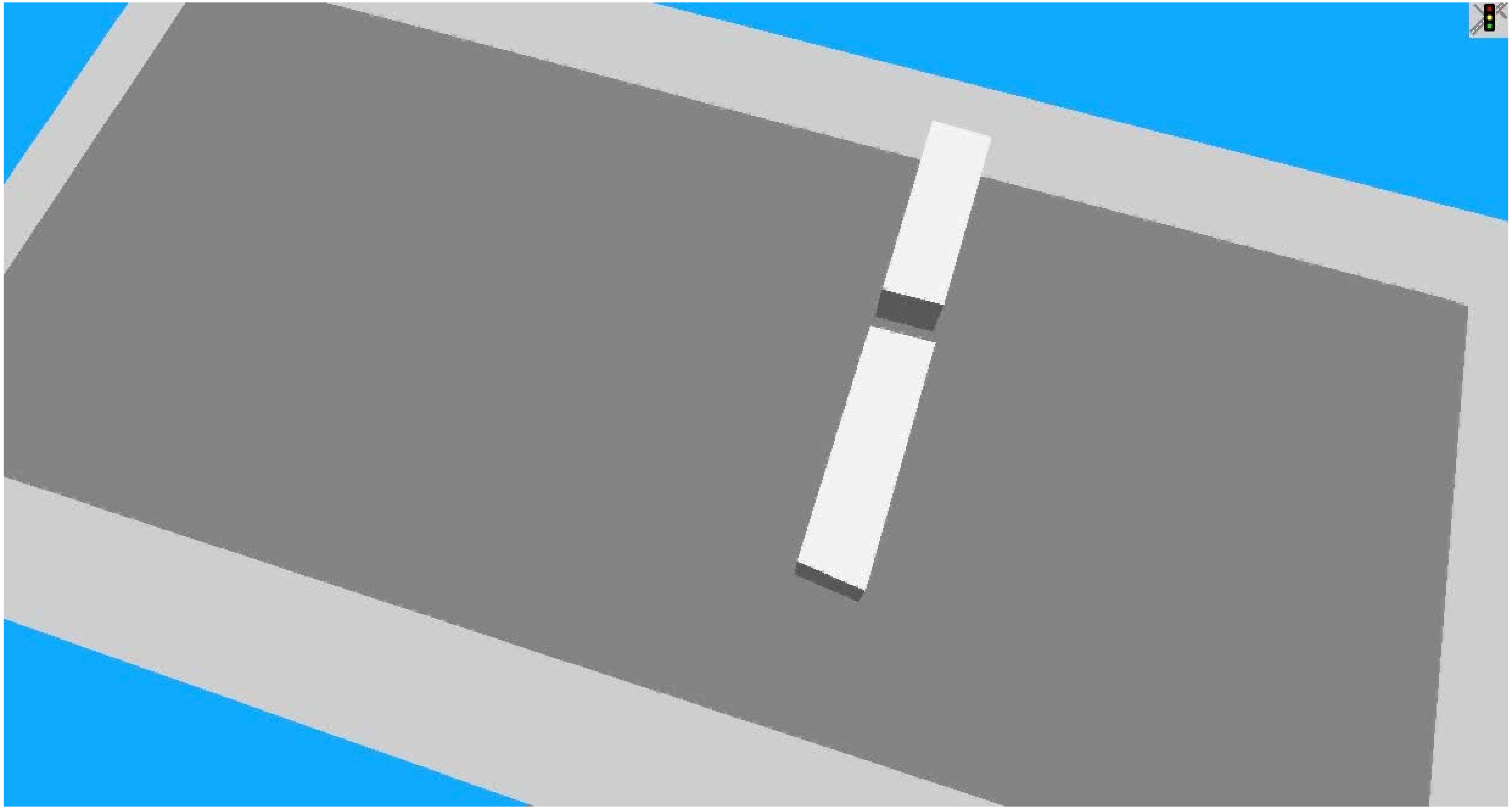


Hoogendoorn & Bovy (2004)

Social Force Model - Route Choice I



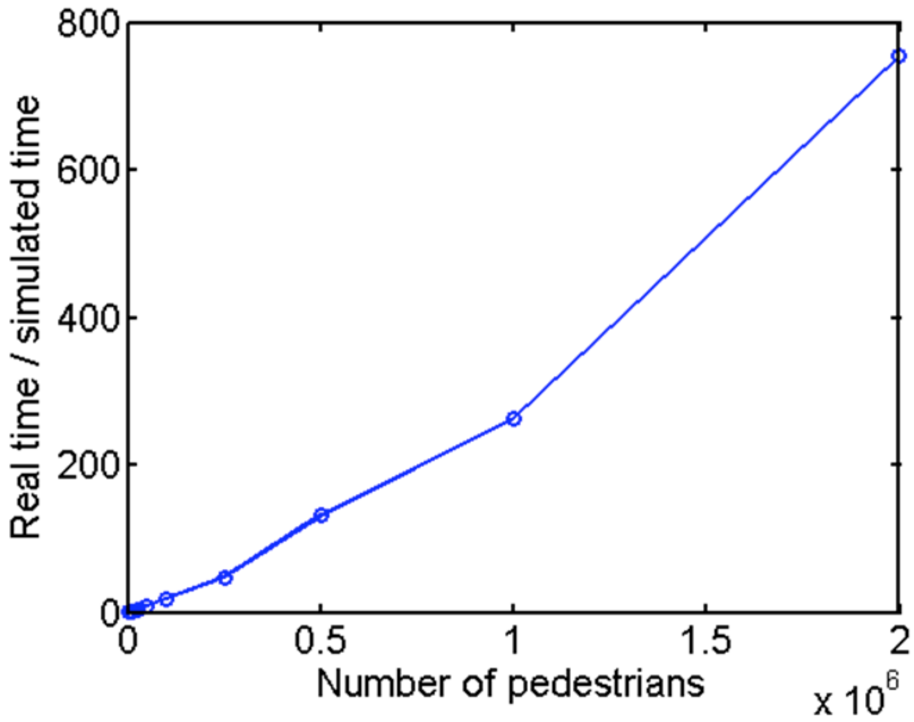
Social Force Model - Route Choice II



Speed

- The computational speed of the original social-force model is $O(n^2)$ for the number of pedestrians *n*.

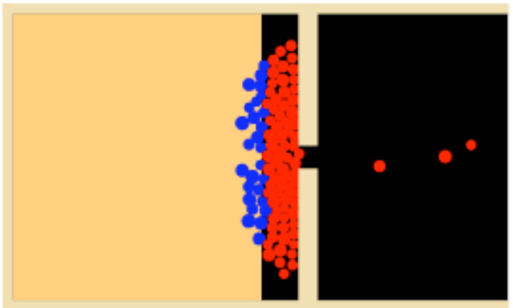
- The social-force model implementation in VISSIM however, is scaling $O(n)$, i.e. linearly in the number of pedestrians, which makes it suitable for large-scale simulations.



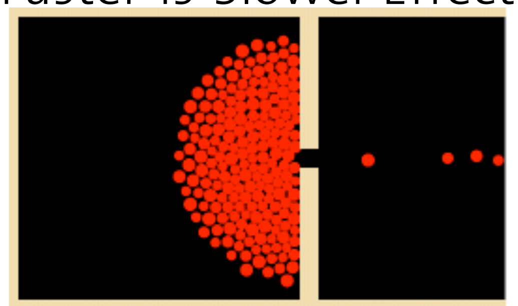
Social Force Model – Putting It All Together

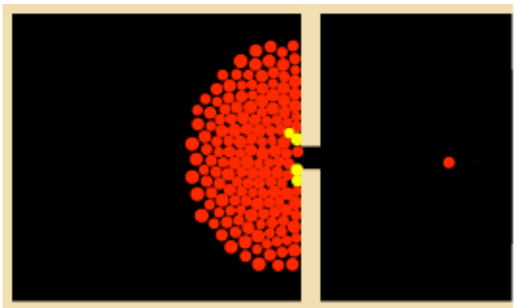
Clogging at Bottlenecks and "Faster-is-Slower Effect"

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

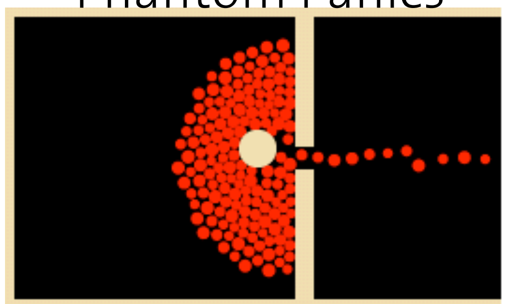


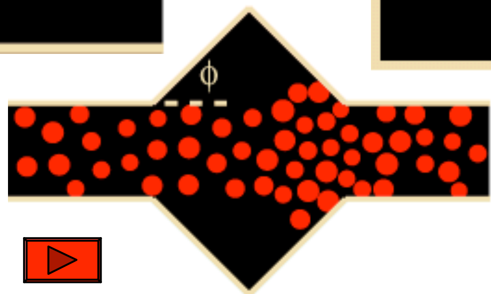
Faster-is-Slower Effect





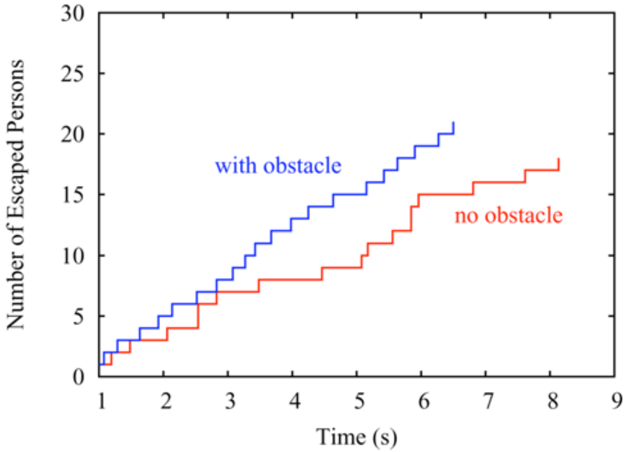
Phantom Panics

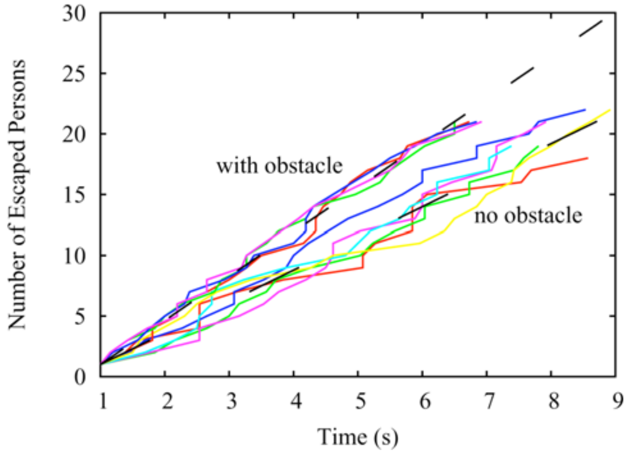




Application to the
Simulation of
Evacuation Scenarios

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).

Multiple Column Designs?

Clogging Occurs Only Below Some Critical Exit Width

W. J. Yu et al - Jamming at exits

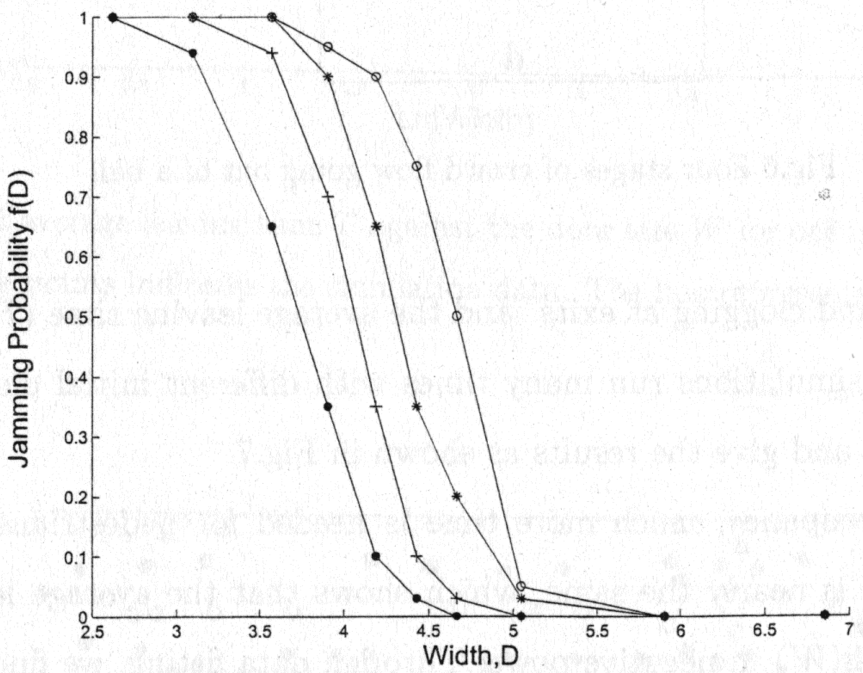


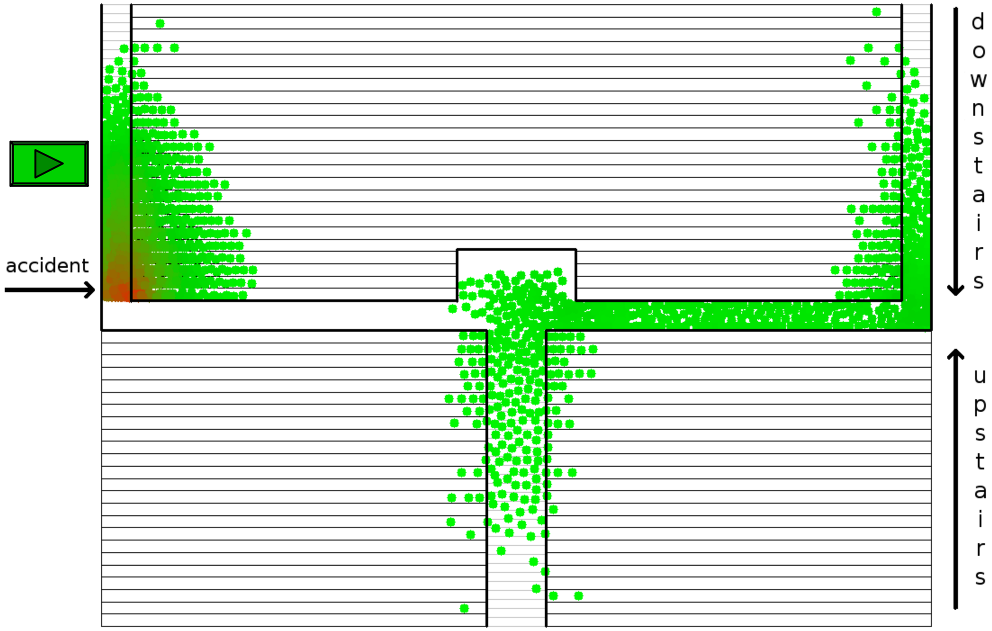
Fig.5 Jamming probability f(D) for occupancies of 0.1(.), 0.2(+), 0.4(*), 0.8(o), while the opening varies from 2.5D to 7D. The size of room is $18m \times 16m$

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

Safety Assessment of Architectural Designs

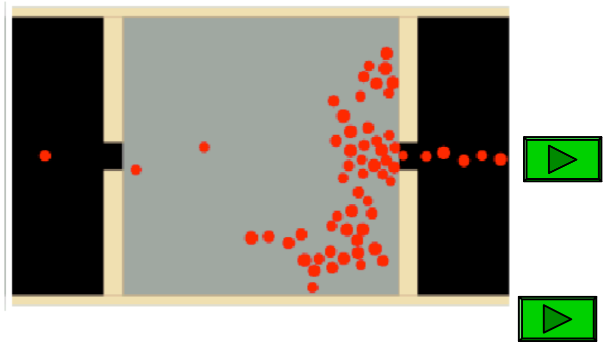
Conventional

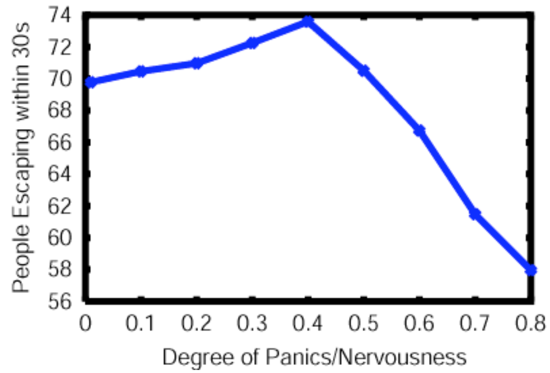


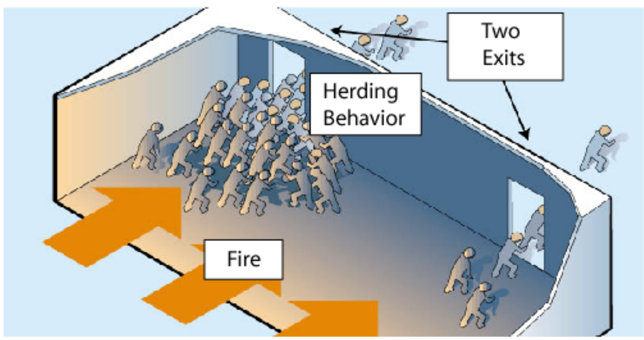
Improved

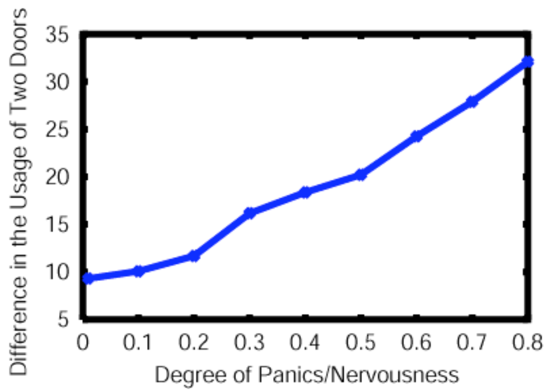
Herding Behavior in Situations of Bad Orientation

Mixture of individualistic behavior and herding:







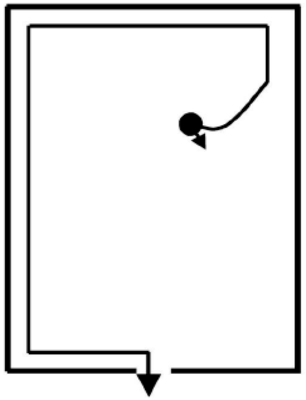


Inefficient Usage of Doors due to Herding Effect

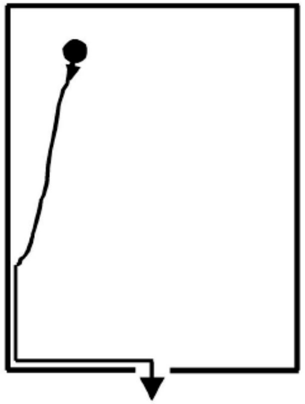
D. H., I. Farkas, and T. Viscek, *Nature* **407**, 487 (2000).

Escape with Reduced Visibility and Orientation

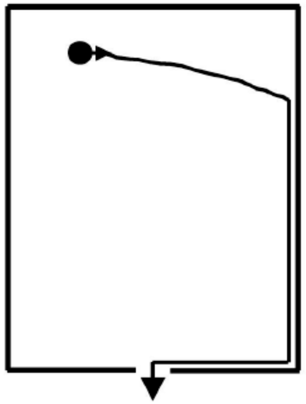
People tend to move along the wall, tend to ignore exits on the other side (tunnel experiment).



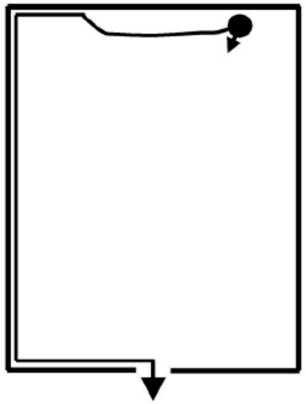
$t_e = 39$ sec



$t_e = 25$ sec

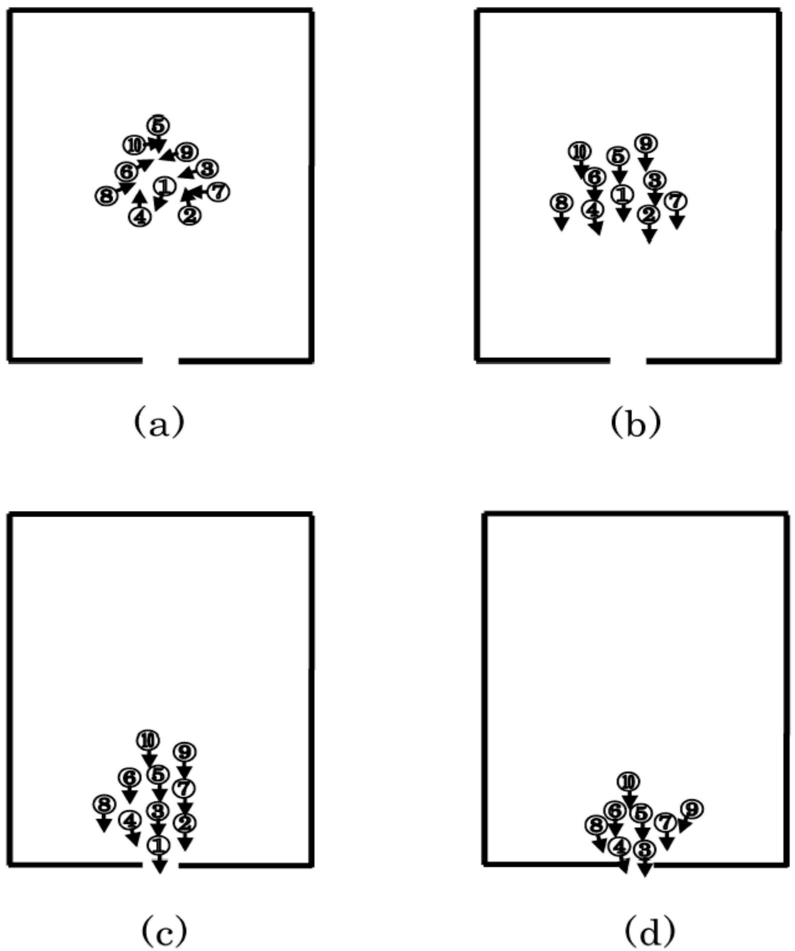


$t_e = 23$ sec

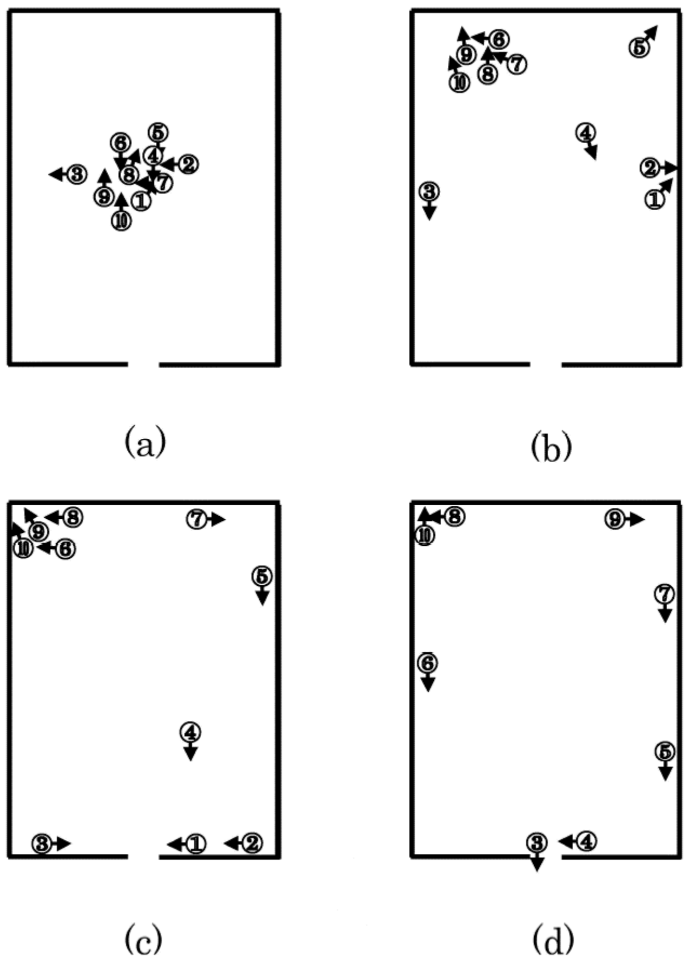


$t_e = 38$ sec

Behavior with and without Visibility



With visibility



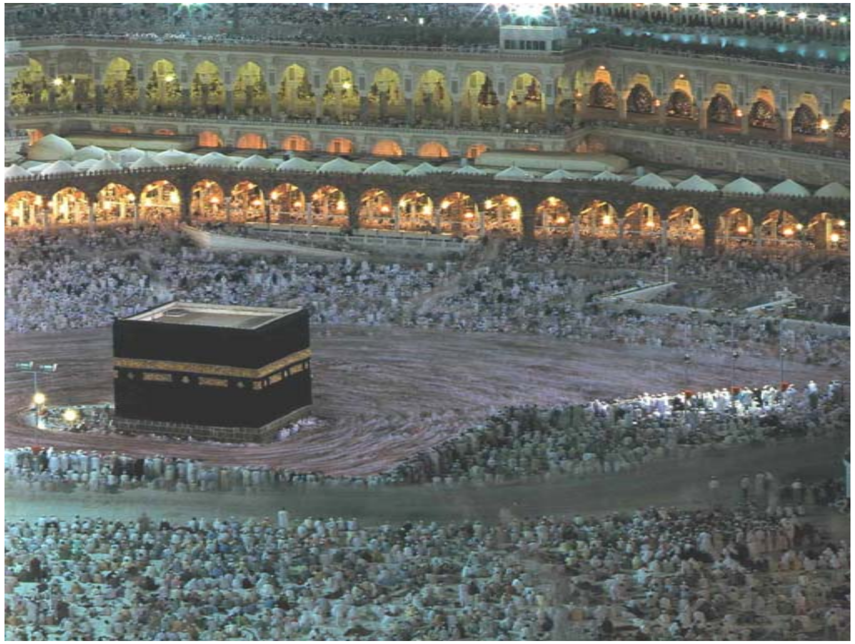
Smoky enviroment without visibility

Influencing Crowd Evacuation by Lighting Conditions

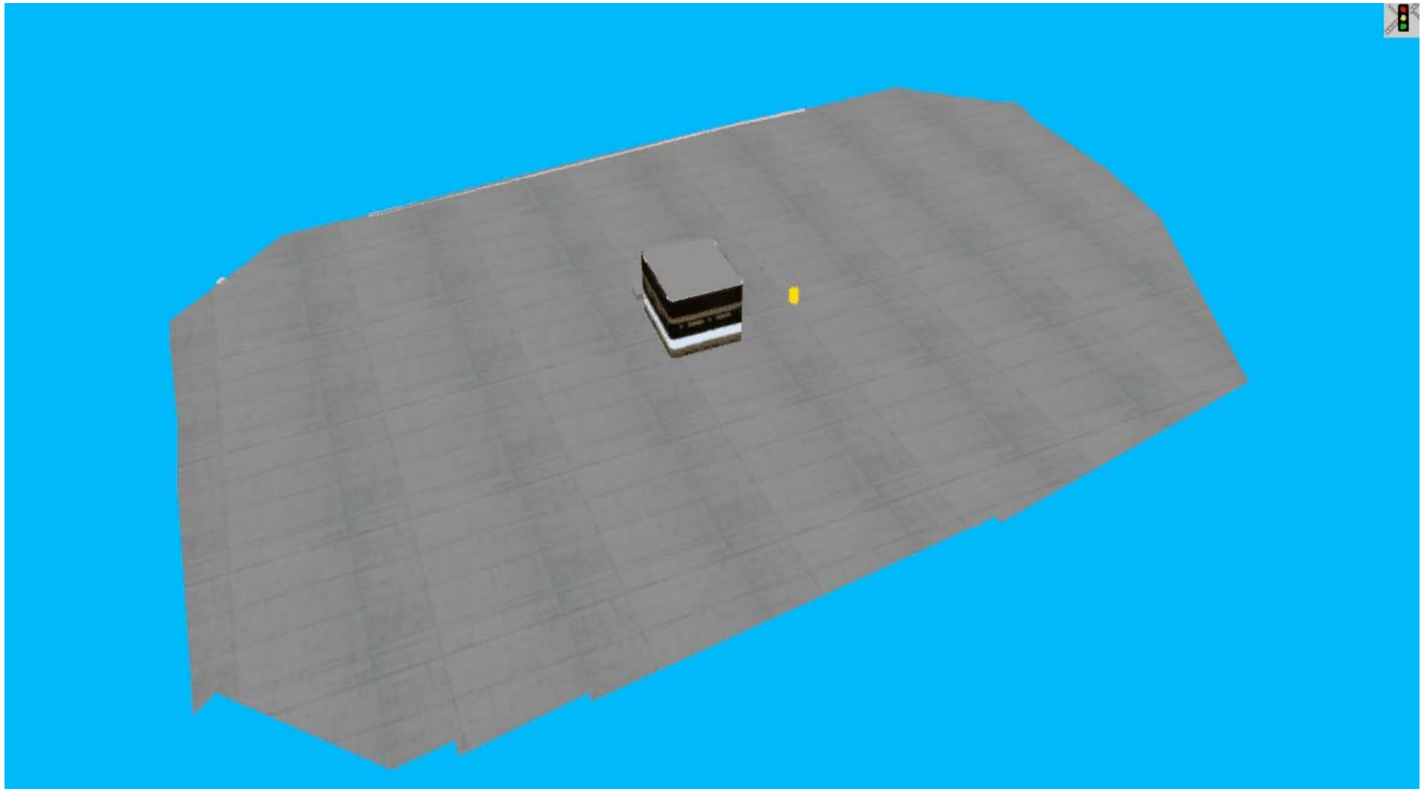
Y-Tunnel Experiment

Annual Pilgrimage in Makkah

Orderly behavior is supported by social norms and imitation.



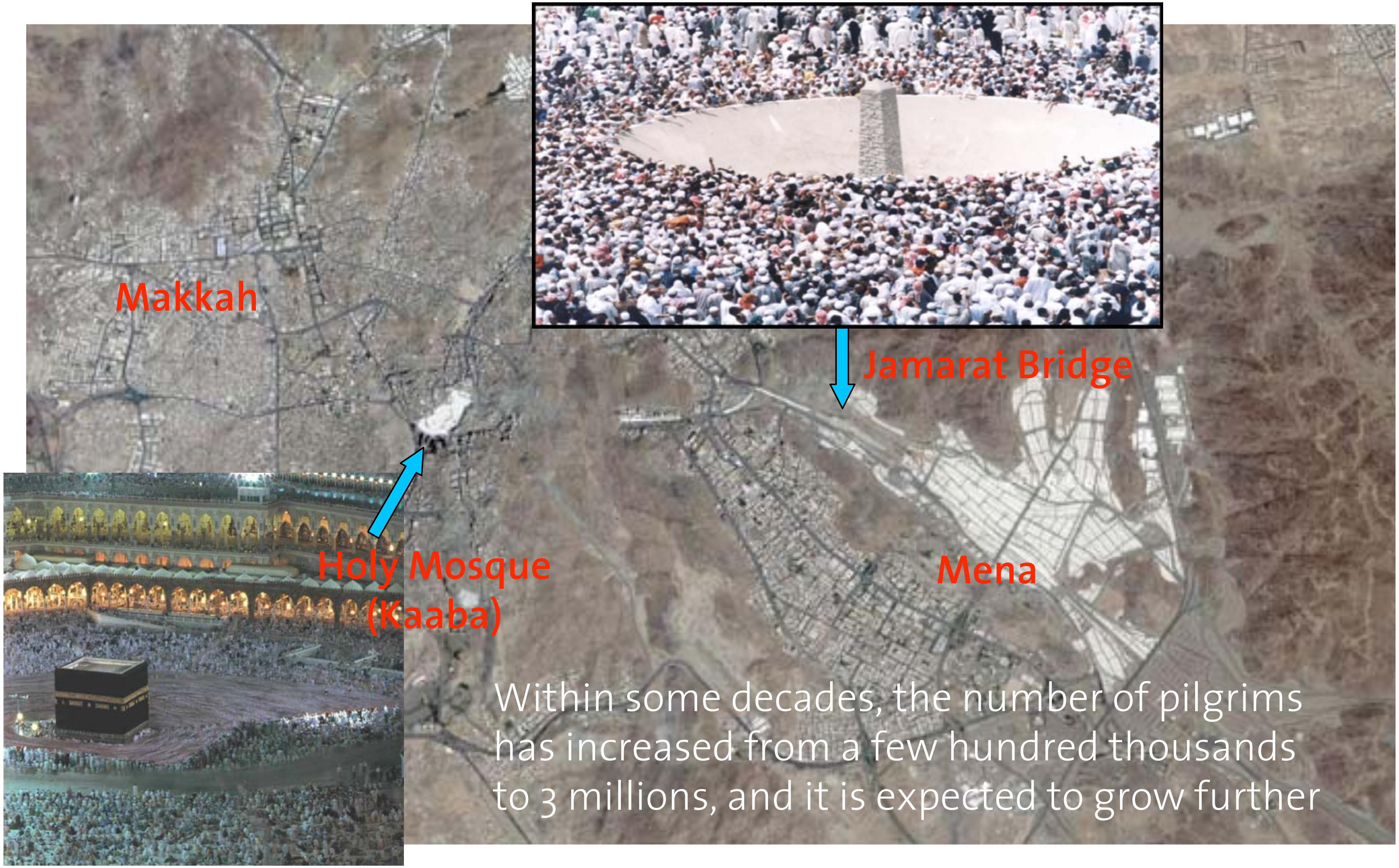
Simulation of the Tawaf



43,000 pilgrims, Holy Mosque, Mecca

The social-force model implementation in VISSIM supports parallelization (OpenMP), which makes it suitable for running large simulations

Supporting Believers Who Want to Perform their Religious Duties




Ka'bah
Al-Hajun
Al-Jamarat
Mina
Muzdalifah
Namirah
Arafah
Mount of Mercy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Al-Hajun
Al-Jamarat
Mina
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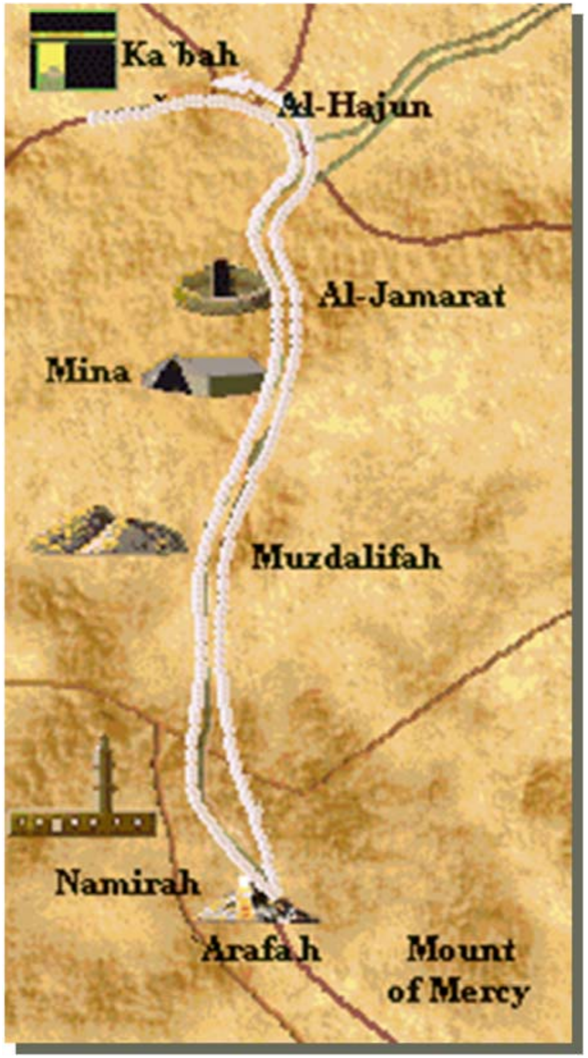
Namirah
Arafah
Mount of Mercy

Mount Arafat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Arafah
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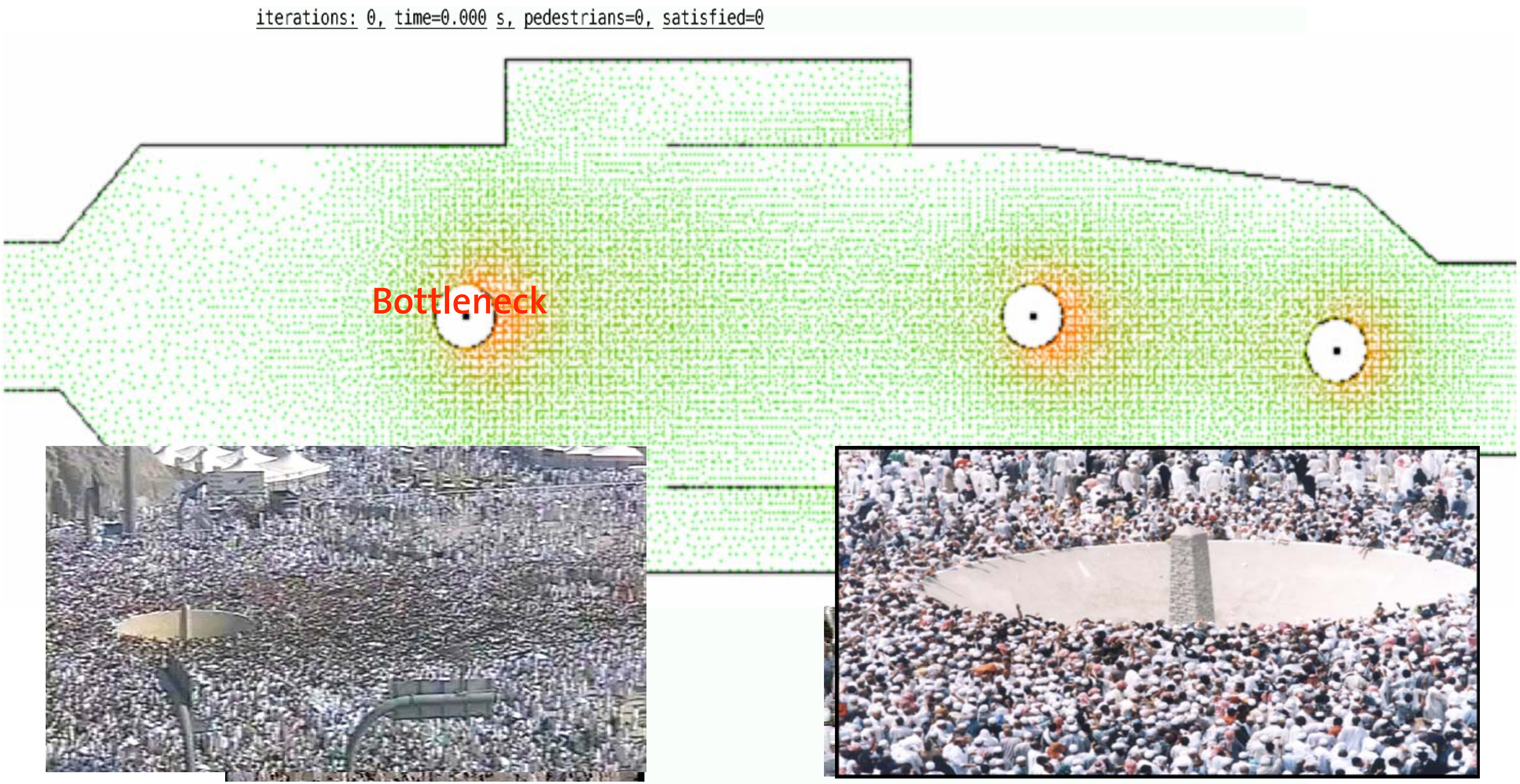
Tent City and Location of Jamarat Bridge

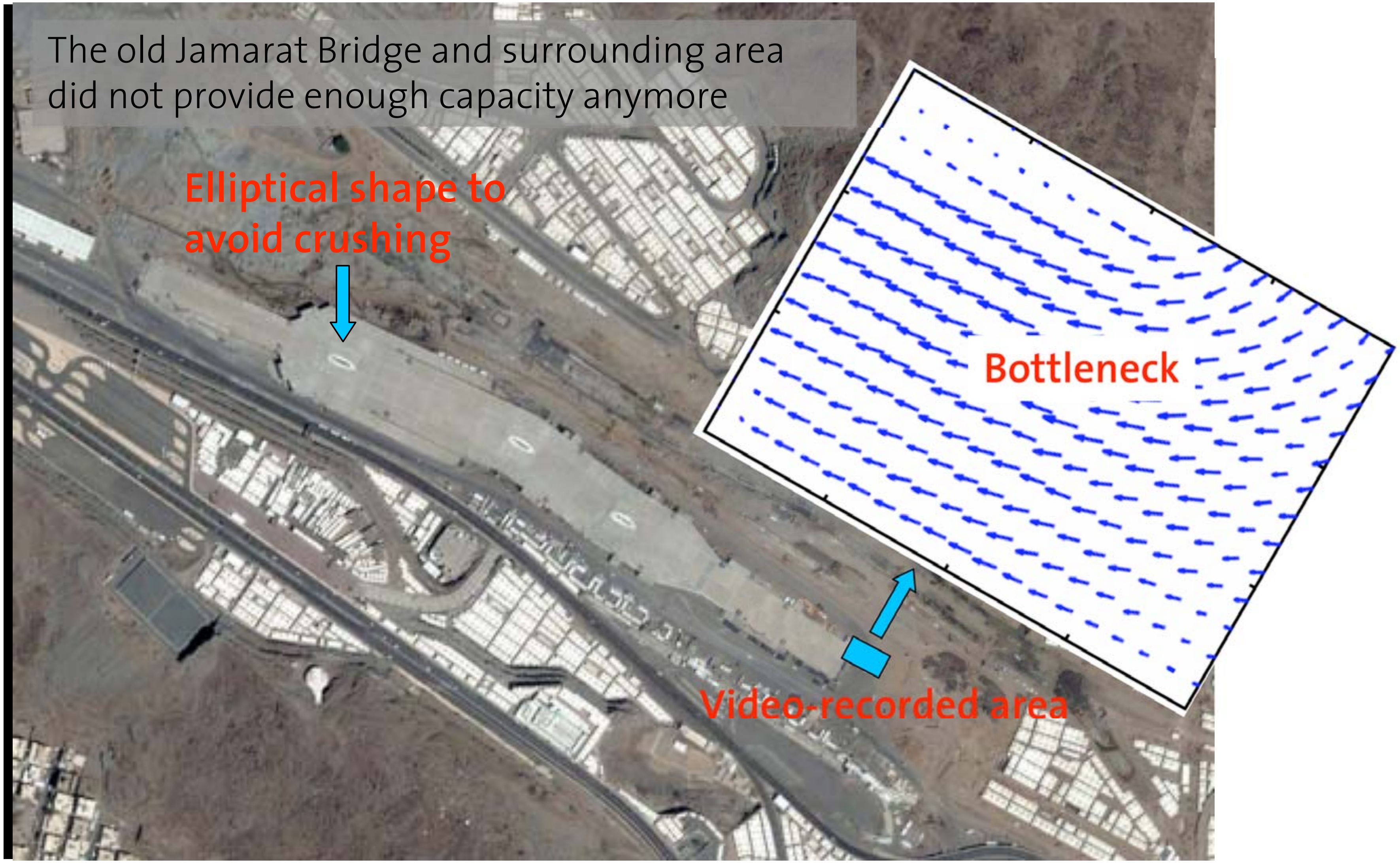
The Jamarat Bridge (as of January 2006)

The Jamarat Bridge (as of January 2006)

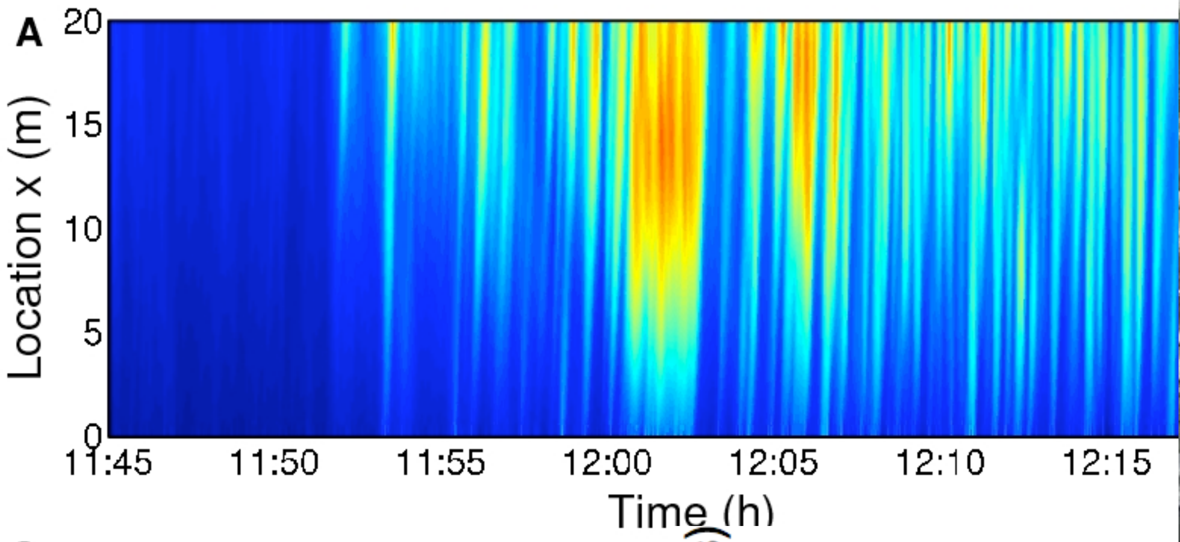
Stoning-the-Devil Ritual on the Jamarat Bridge

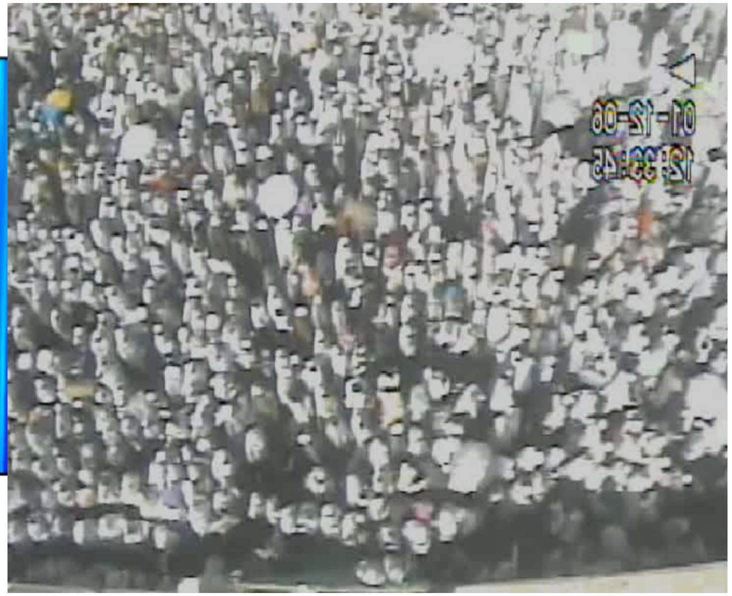


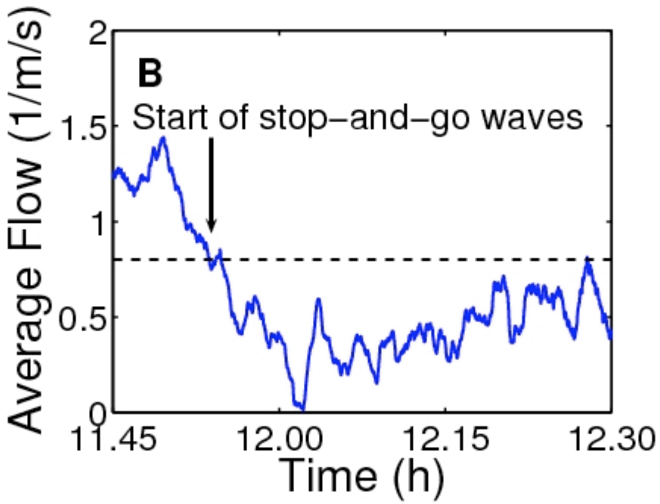
The Jamarat Bridge (as of January 2006)

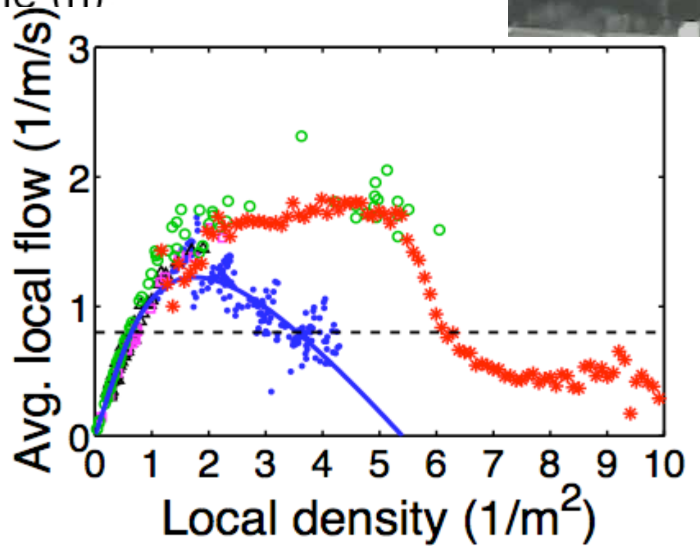


Transition from Smooth to Stop-and-Go Flow



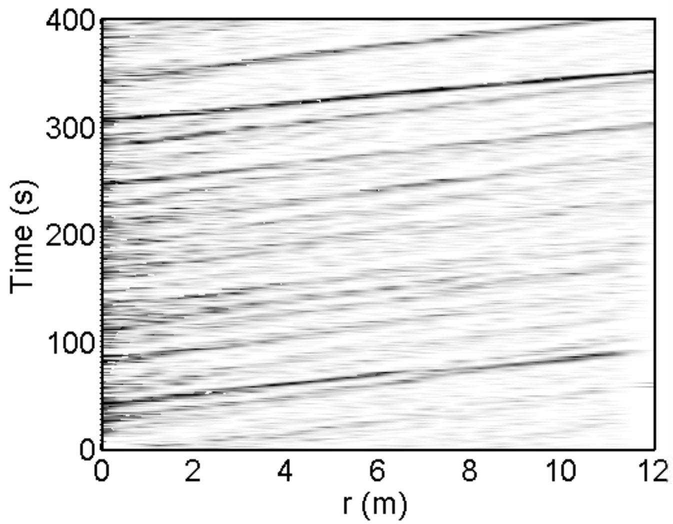


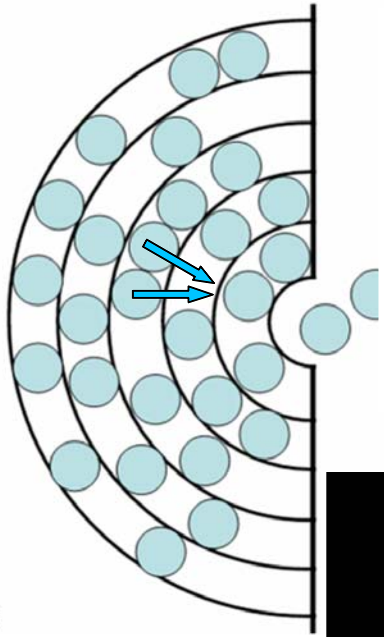




Modeling the Transition from Smooth to Stop-and-Go Flow

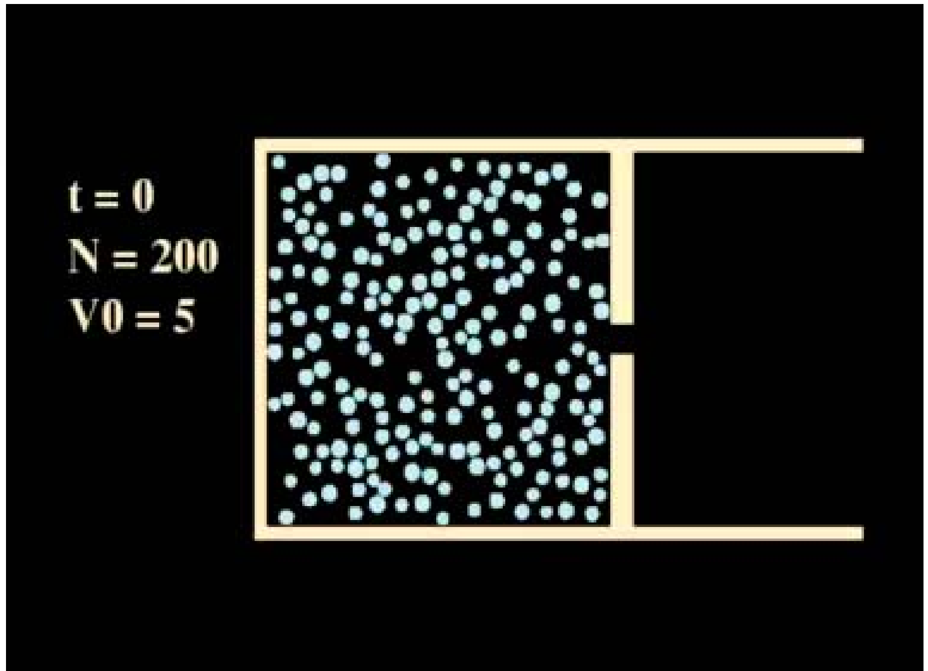
Competition for a scarce resource, here: space.



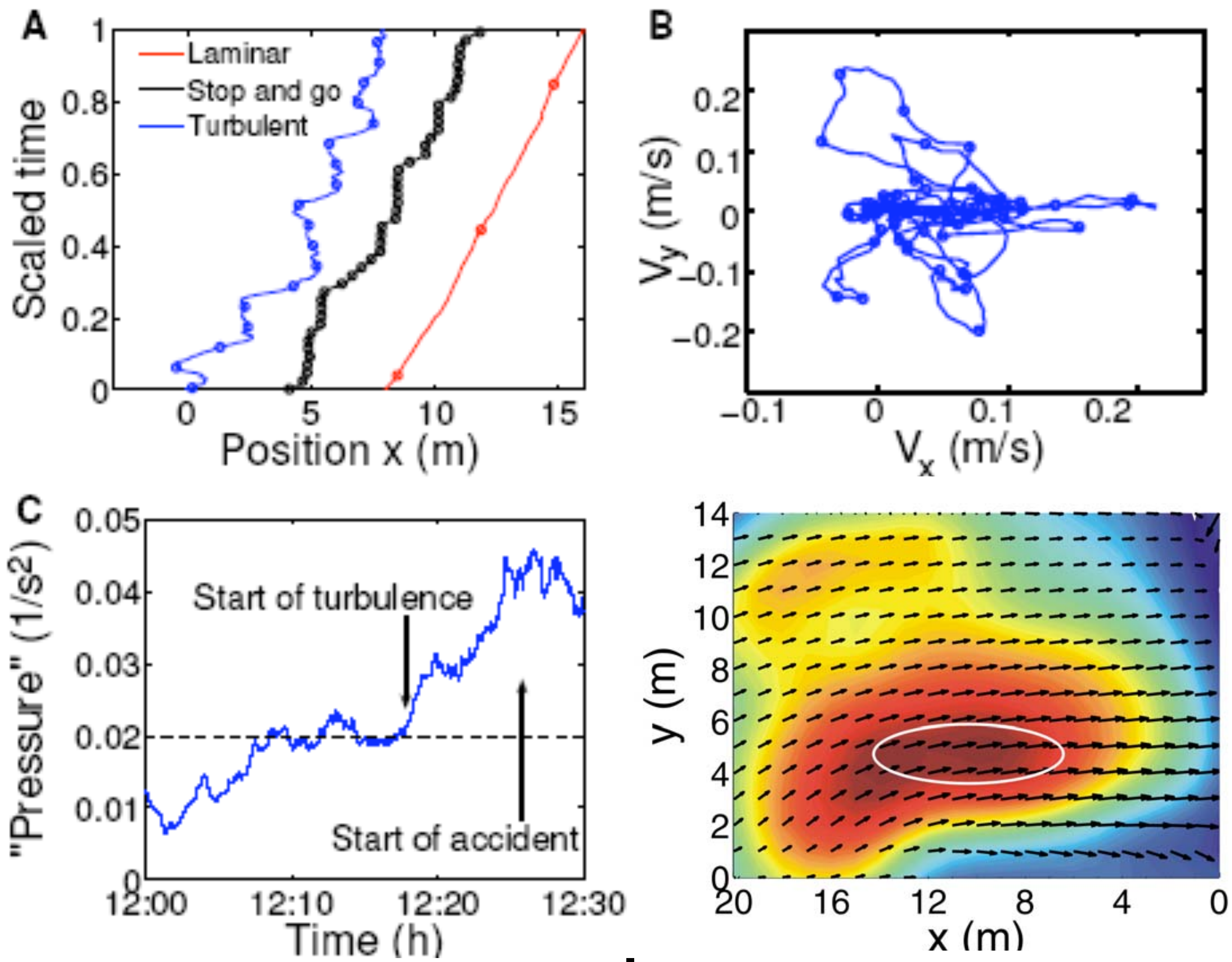


At high densities, several people may compete for the same gap and block each other. This constitutes a conflict and causes an alternation between downstream pedestrian and upstream gap propagation.

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.



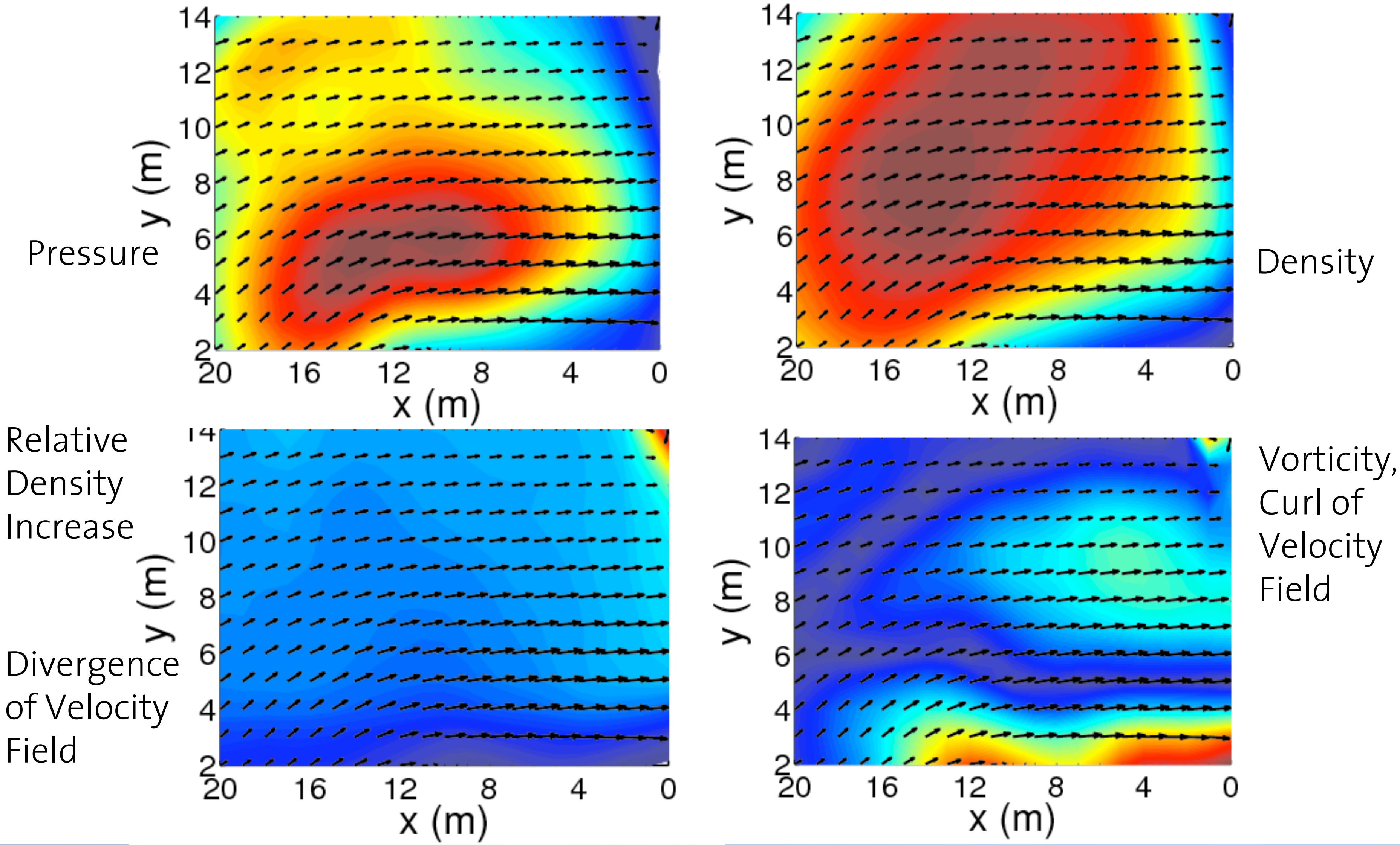
Transition from Stop-and-Go Flow to "Crowd Turbulence"



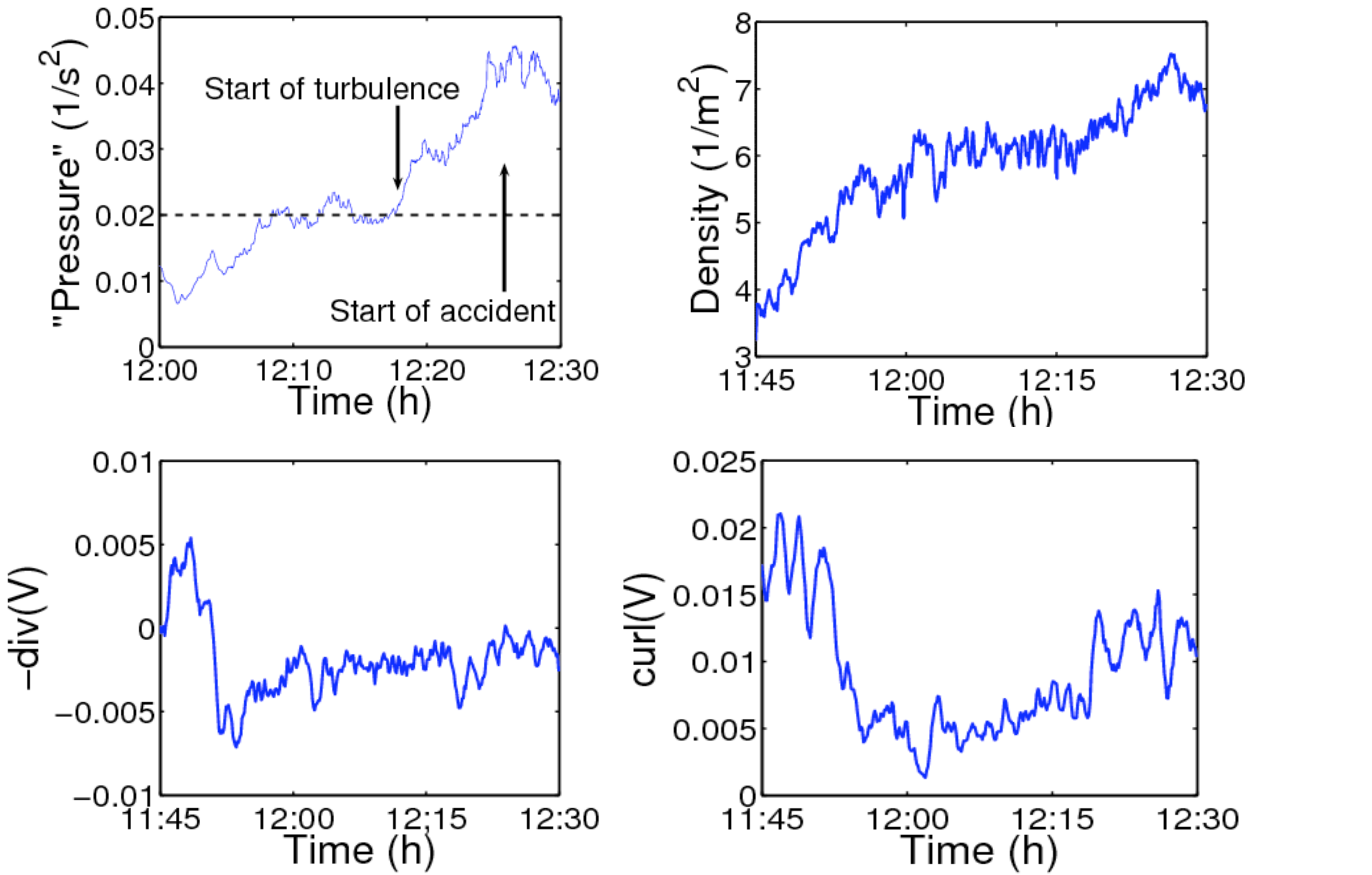
The density times the variation in speeds constitutes the hazard! Pressure fluctuations cause turbulent motion and potentially the falling and trampling of people.

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

Appropriate Measures of Criticality in the Crowd?

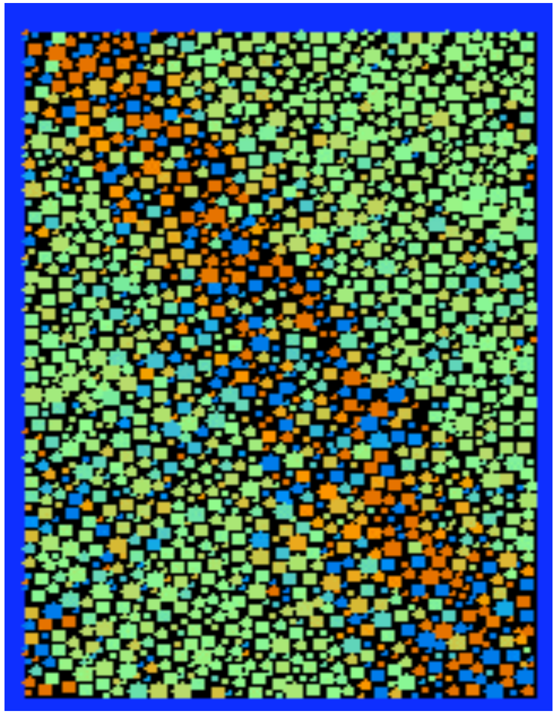


Appropriate Measures of Criticality in the Crowd?

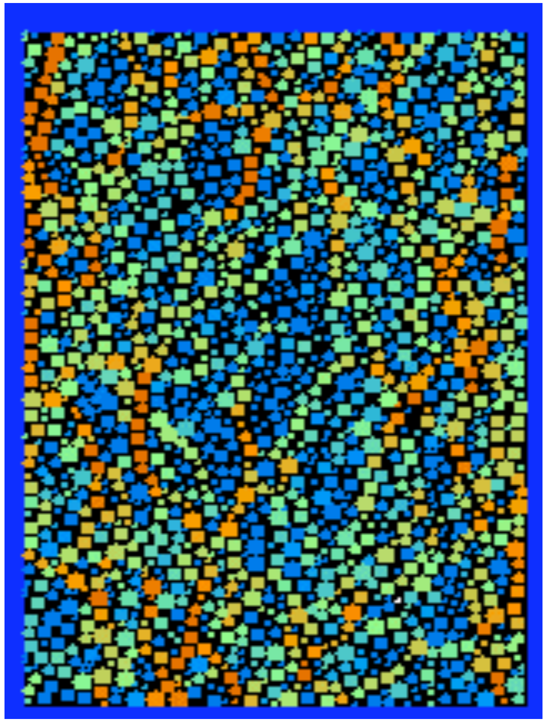


Force Lines in Granular Materials

The pressure is not just a function of the density: Force lines develop in very dense crowds, which can lead to extreme local forces and strong variations of pressure in space. Sudden stress release can lead to earthquake-like eruptions.

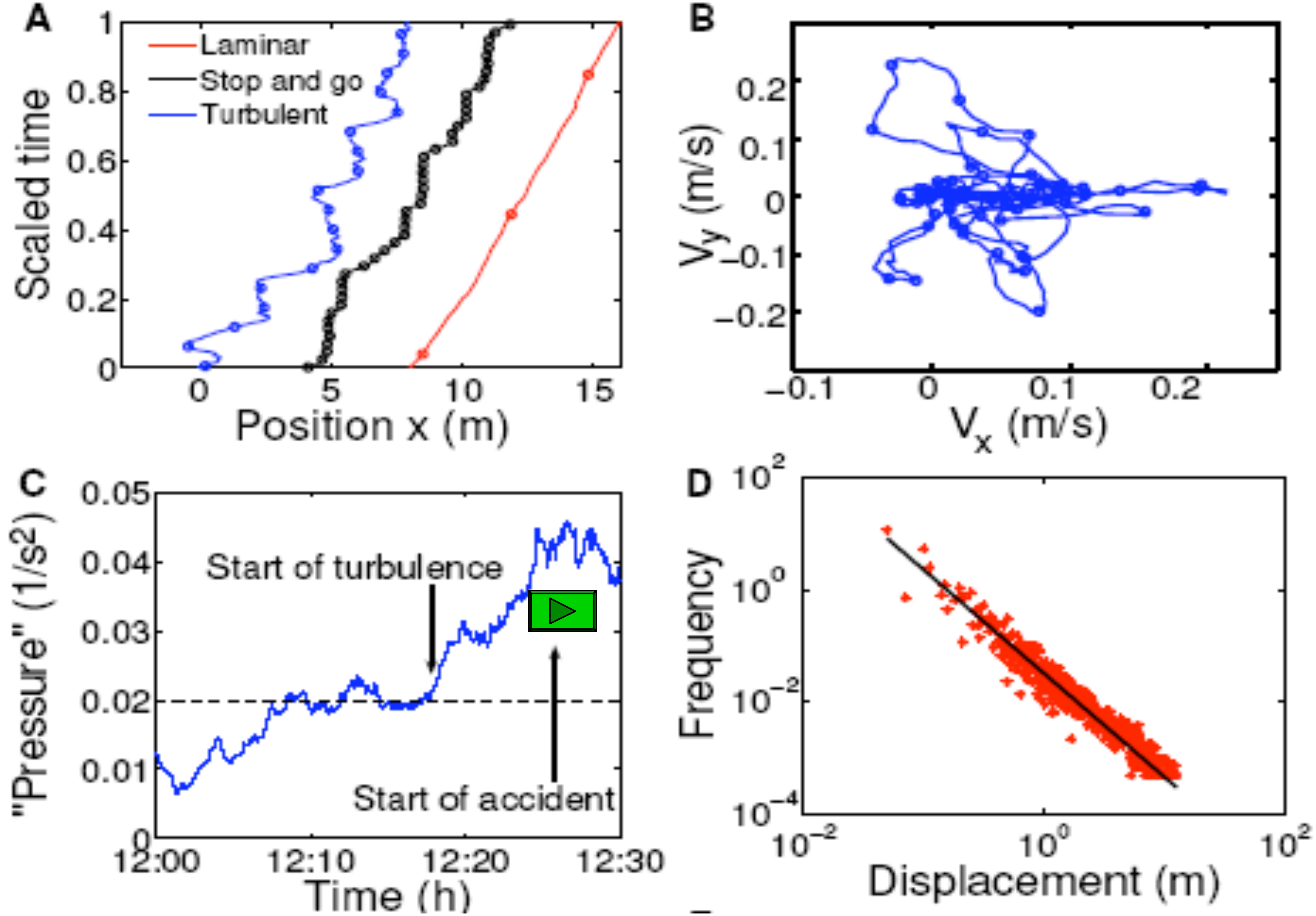


Reaction to shear forces

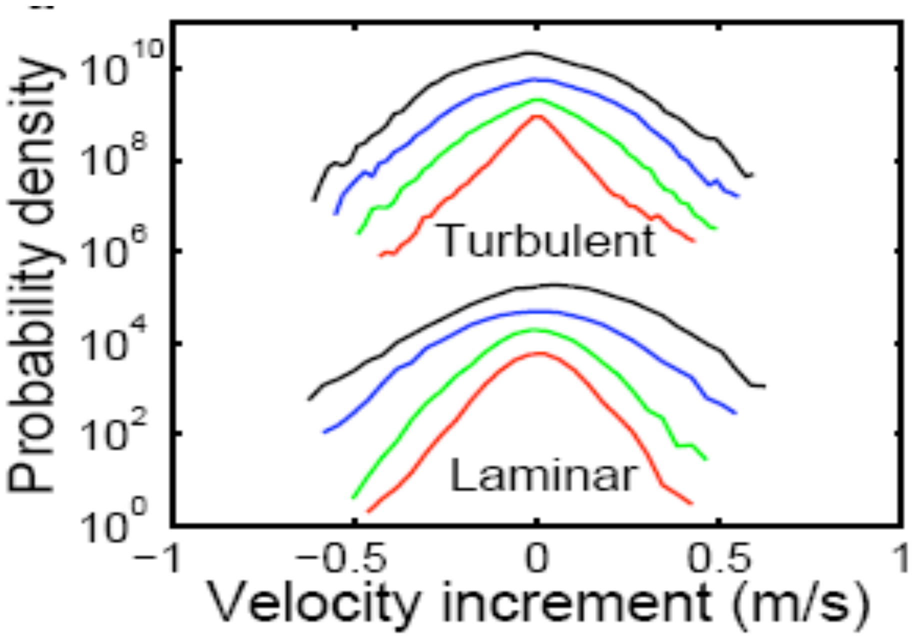


Simulation videos by Hans Herrmann, Stefan Luding, and their team members.

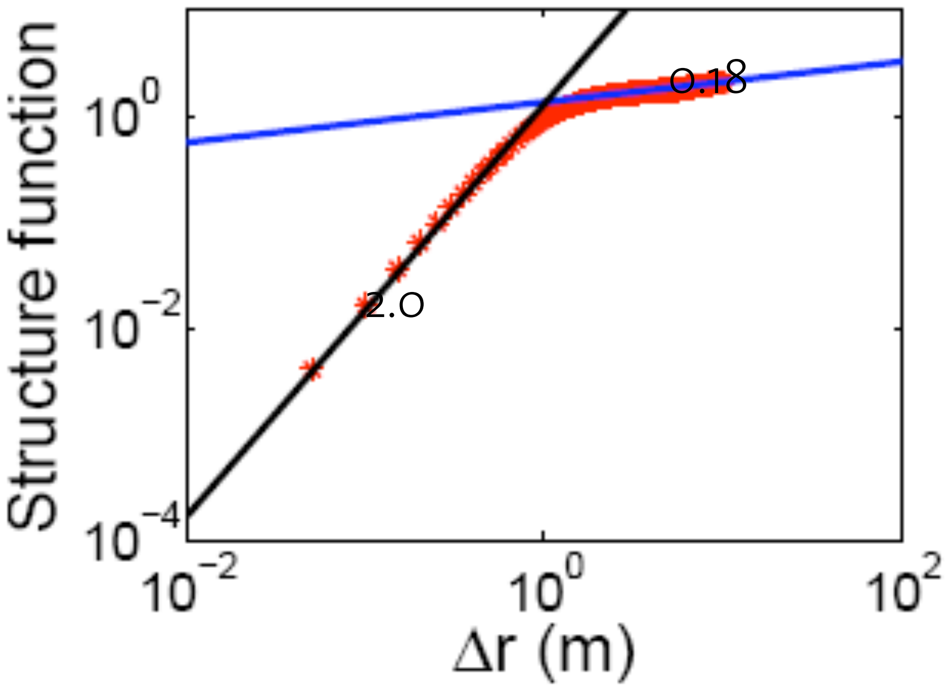
Transition to "Crowd Turbulence"



Characteristics of Turbulence



$$S(\triangle\vec{r}) = \langle \|\vec{v}(\vec{r}+\triangle\vec{r},t) - \vec{v}(\vec{r})\|^2 \rangle_{\vec{r},t}$$



Extended Social Force Model

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

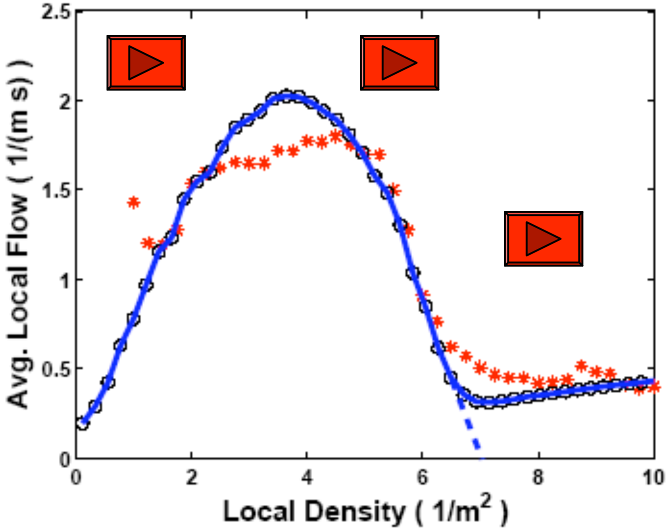
$$\vec{f}_i(t) = m_i \frac{1}{\tau}(v_i^0 \vec{e}_i - \vec{v}_i) + \sum_{j(\neq i)} \vec{f}_{ij}(t)$$

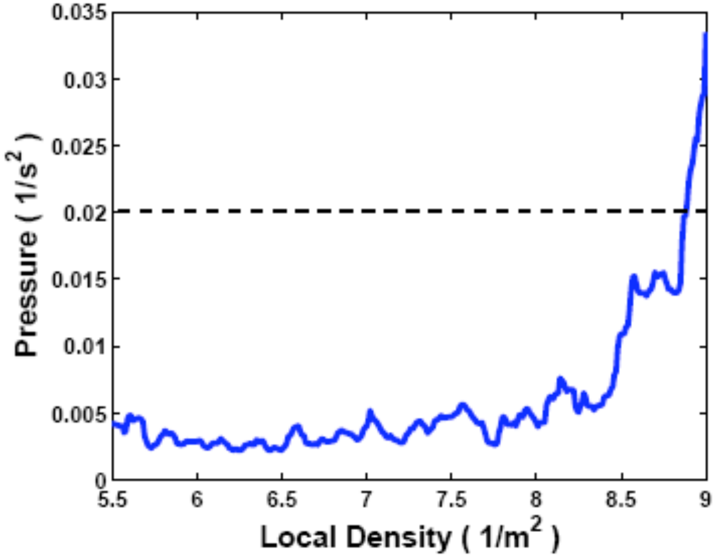
$$\vec{f}_{ij} = F\Theta(\varphi_{ij}) \exp[-d_{ij}/D_0 + \boxed{(D_1/d_{ij})^k}]\vec{e}_{ij}$$

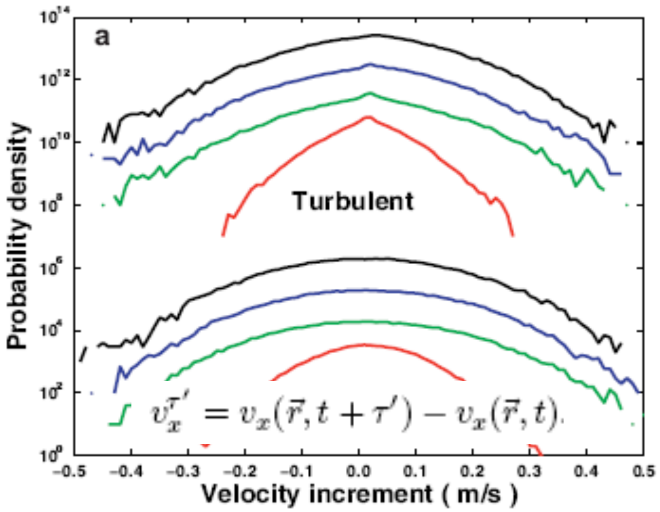
$$\Theta(\varphi) = \left(\lambda + (1-\lambda)\frac{1+\cos(\varphi)}{2}\right)$$

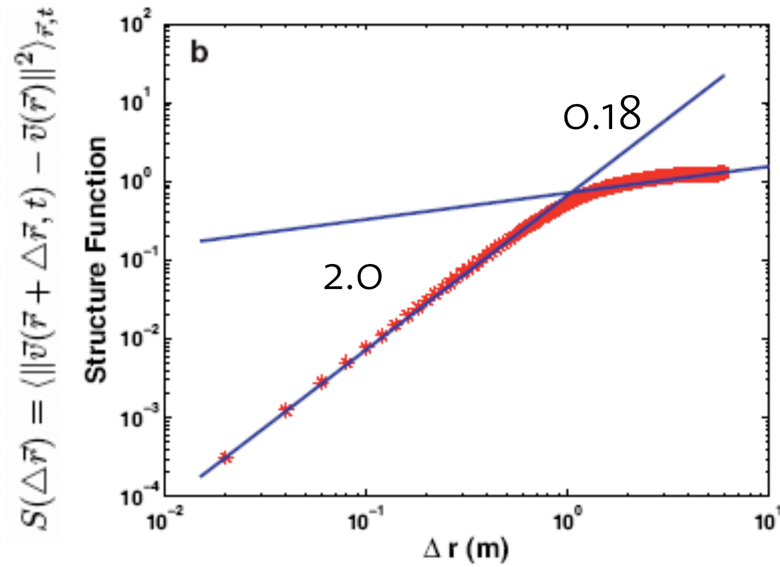
$$p = \rho_i \mathrm{Var}(\vec{v}_i) \qquad \rho_i = \sum_j \frac{1}{\pi R^2} exp(-\|\vec{r_j}(t) - \vec{r_i}(t)\|^2/R^2)$$

Simulation Results (W. Yu & A. Johansson)







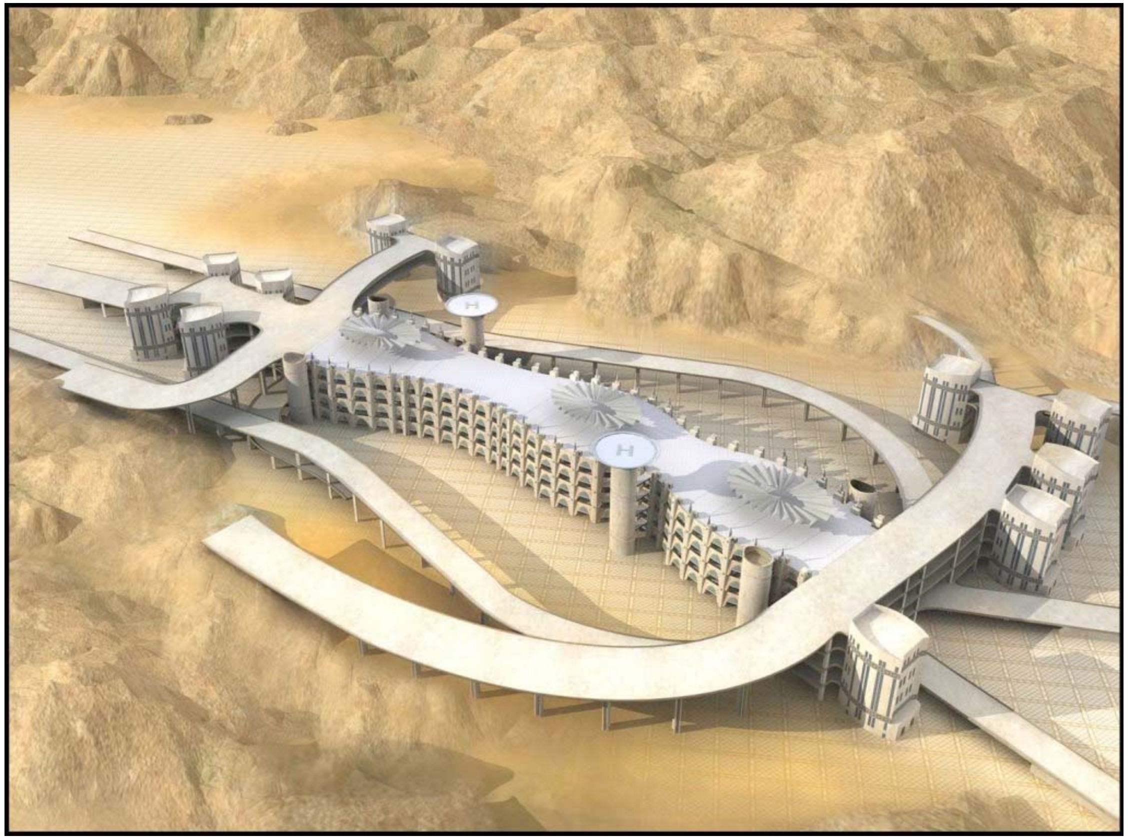


http://www.trafficforum.org/turbulence_sim

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.