Real-Time Modeling of Millions of Pedestrians

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Outline

- Motivation
- Pedestrian Motion: Empirical/Experimental Data
- Modeling Options
- PedFlow
- Large-Scale, Real-Time Computing
- Examples
- Coupling CFD-CCD / Biomed
- Conclusions and Outlook
- References

Motivation

Why Pedestrian Flow Simulation ?

- Situations With Many Individuals:
  - **Airports/Train/Bus Stations/Ports**
  - Sport/Music/Cinema/Theater
  - Museums/Conferences/Conventions
  - **Pilgrimage Centers**
  - Demonstrations

Why Pedestrian Flow Simulation ?

- Simulations of Interest For:
  - Comfort/Event Experience
  - Traffic Management
  - Evacuation
  - Avoidance of Injury/Death
  - **Spread of Disease**

Large Gatherings…

Number of Pilgrims /Yr

• Hindu Mela, India	O(10-70M)
• Ayyappan Saranam, India	O(20M)
• Our Lady of Guadalupe, Mexico	O(13M)
• Amritsar (Sikh)	O(10M)
• Tirupati, India	O(10M)
• Arba'een, Karbala, Iraq	O(8M)
• Our Lady of Aparecida, Brazil	O(8M)
• Lourdes, France	O(7M)
• Hajj, Makkah	O(2M)

Visitors to Religious Sites/Yr

- Notre Dame, Paris: O(13M)
- Makkah & Medina: O(10M)
- St. Peters, Rome: O(7M)
- Western Wall, Jerusalem: O(3M)
- Bethlehem, Palestine: O(2M)

Airports (2014)

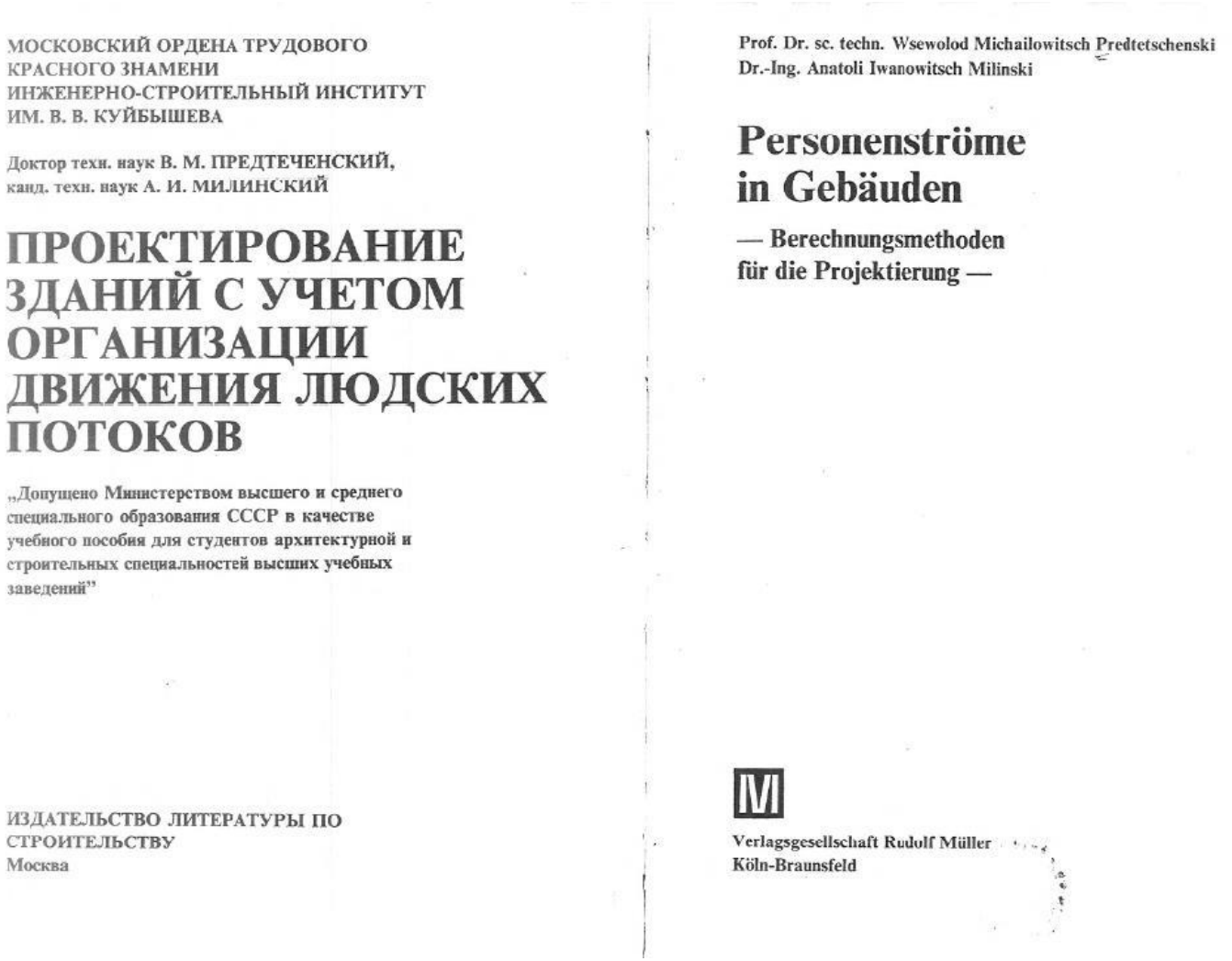
- Atlanta: O(96M) [0.25M/Day !]
- Beijing: O(86M)
- Heathrow: O(74M)
- Tokyo: O(73M)
- Los Angeles: O(71M)
- Dubai: O(70M)
- Chicago: O(70M)

Train Stations (2014)

- Shinjuku, Tokyo: O(1,260M) [>3M/Day !]
- Shibuja, Tokyo: O(1,090M)
- Ikebukuro, Tokyo: O(910M)
- Umeda, Osaka: O(820M)
- Yokohama, Kanagawa: O(760M)
- Gare du Nord, Paris: O(120M)

Pedestrian Motion: Empirical Data

Predtetschenski & Milinski



МОСКОВСКИЙ ОРДЕНА ТРУДОВОГО
КРАСНОГО ЗНАМЕНИ
ИНЖЕНЕРНО-СТРОИТЕЛЬНЫЙ ИНСТИТУТ
ИМ. В. В. КУЙБЫШЕВА

Доктор техн. наук В. М. ПРЕДТЕЧЕНСКИЙ,
канд. техн. наук А. И. МИЛИНСКИЙ

ПРОЕКТИРОВАНИЕ ЗДАНИЙ С УЧЕТОМ ОРГАНИЗАЦИИ ДВИЖЕНИЯ ЛЮДСКИХ ПОТОКОВ

„Допущено Министерством высшего и среднего специального образования СССР в качестве учебного пособия для студентов архитектурной и строительных специальностей высших учебных заведений"

ИЗДАТЕЛЬСТВО ЛИТЕРАТУРЫ ПО СТРОИТЕЛЬСТВУ
Москва

Prof. Dr. sc. techn. Wsewolod Michailowitsch Predtetschenski
Dr.-Ing. Anatoli Iwanowitsch Milinski

Personenströme in Gebäuden

— Berechnungsmethoden für die Projektierung —

Verlagsgesellschaft Rudolf Müller
Köln-Braunsfeld

Empirical Data

- Predtetschenski & Milinski
  - German Edition: 1971 !
  - Large Compilation of Empirical Data
  - Standard Reference for Pedestrian Traffic Design
- Fruin
- Many Other Smaller Reports

Empirical Data

- Current Work
  - Seyfried (Jülich)
    - Measurements and Modeling
  - Torrens (Arizona, Maryland)
    - Extensive Review of Physiological and Psychological Data/Measurements
  - Manocha et al. (UNC Chapel Hill) http://gamma.cs.unc.edu/LARGE
    - Visualization, GPS-based Tracking, Photo-Realism
  - INRIA, Others…

We Are Not Machines…

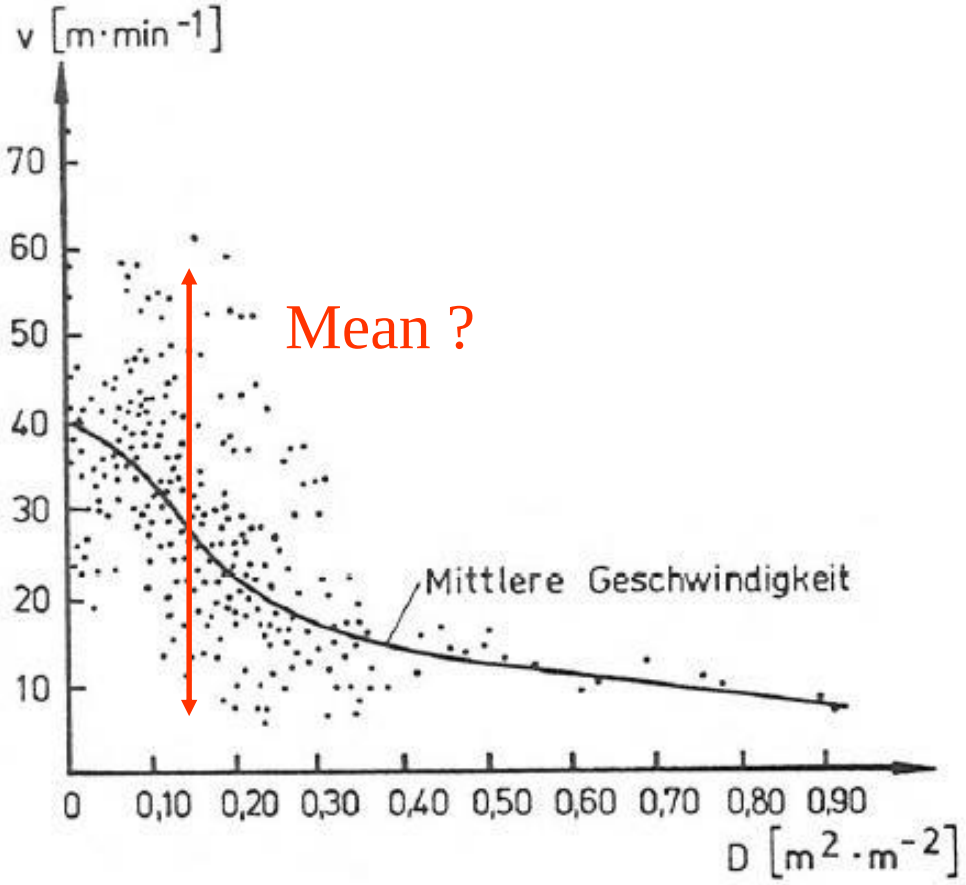


Abb. 14:
Ergebnisse praktischer Messungen der Bewegungsgeschwindigkeit von Personenströmen über Treppen aufwärts

We Are Not Machines…

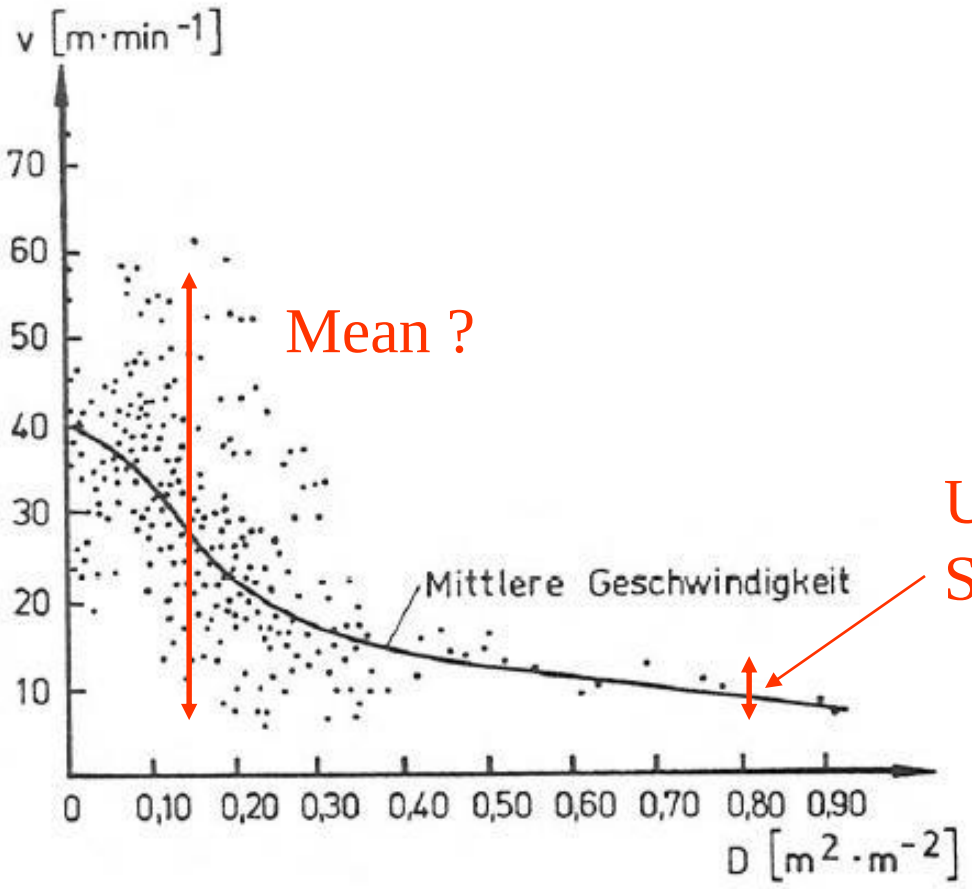


Abb. 14:
Ergebnisse praktischer Messungen der Bewegungsgeschwindigkeit von Personenströmen über Treppen aufwärts

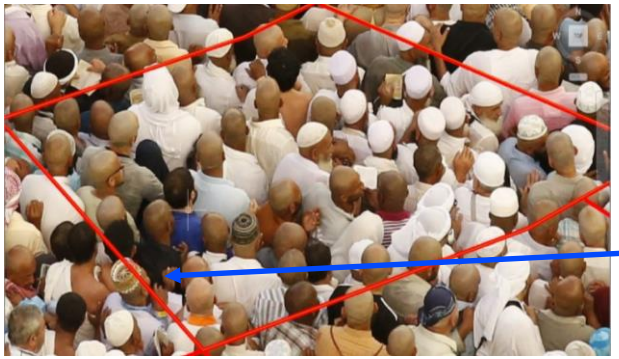
Hajj 2014 Data

- Done by Prabhu Dambalbarth and Britto Muhammad (SLR)
- Aim: Fill Data Gap for High Density Flows
- Video Data
  - Need Video to Ensure Correct IDs
- Cover Region with 10sqm Cells
- Tag Individual, Measure Velocity / Density
- Total of 350 Data Points
  - From 20,500 Individual HR Photos

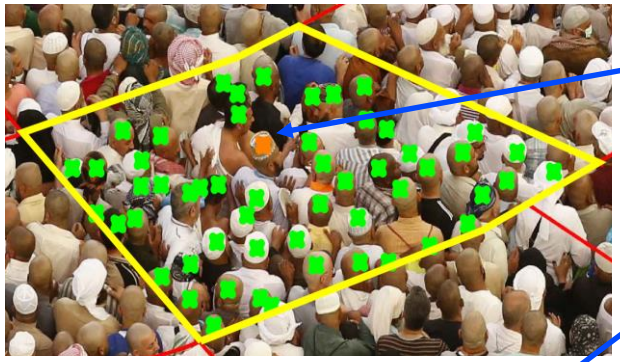
Hajj 2014

Evaluation of Images

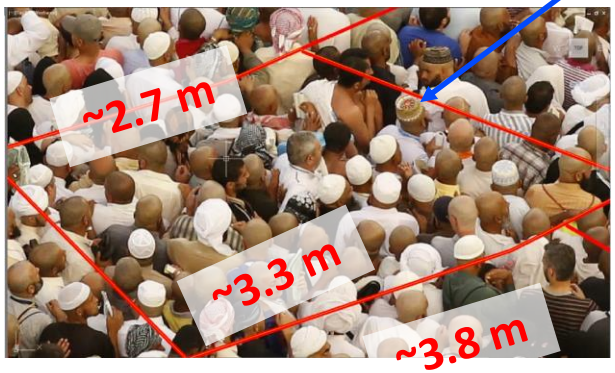
At Time
0 sec



At Time
~6.0 sec



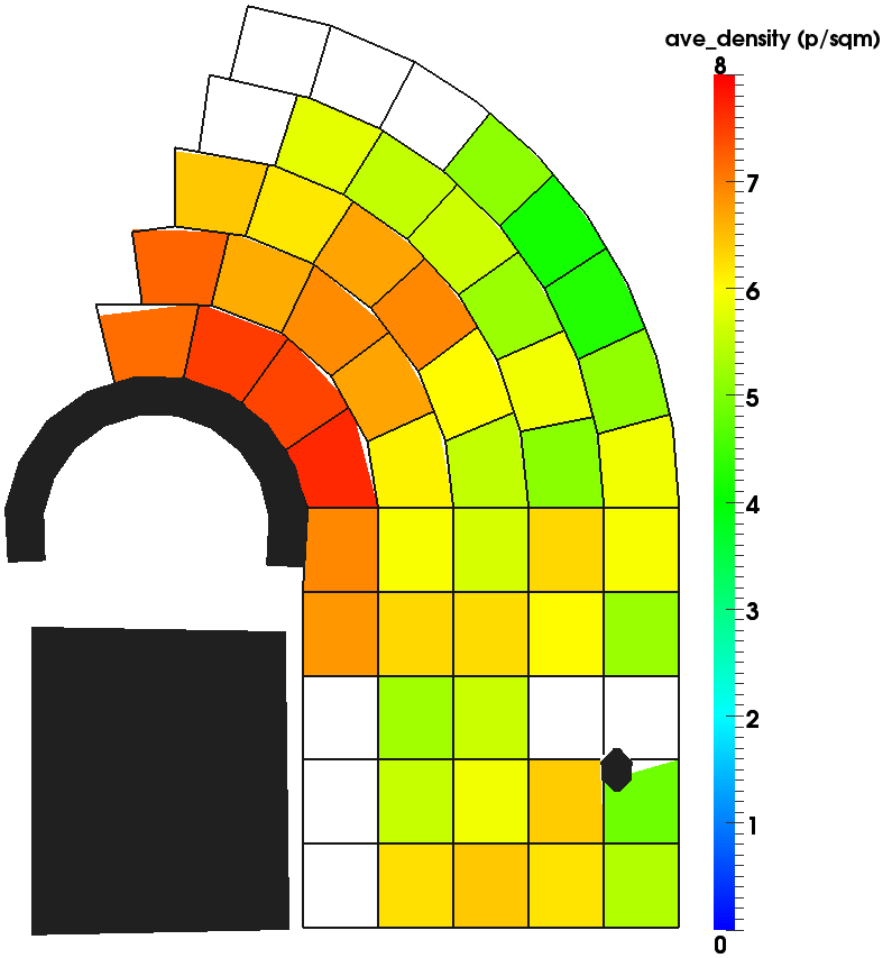
At Time
8.8 sec



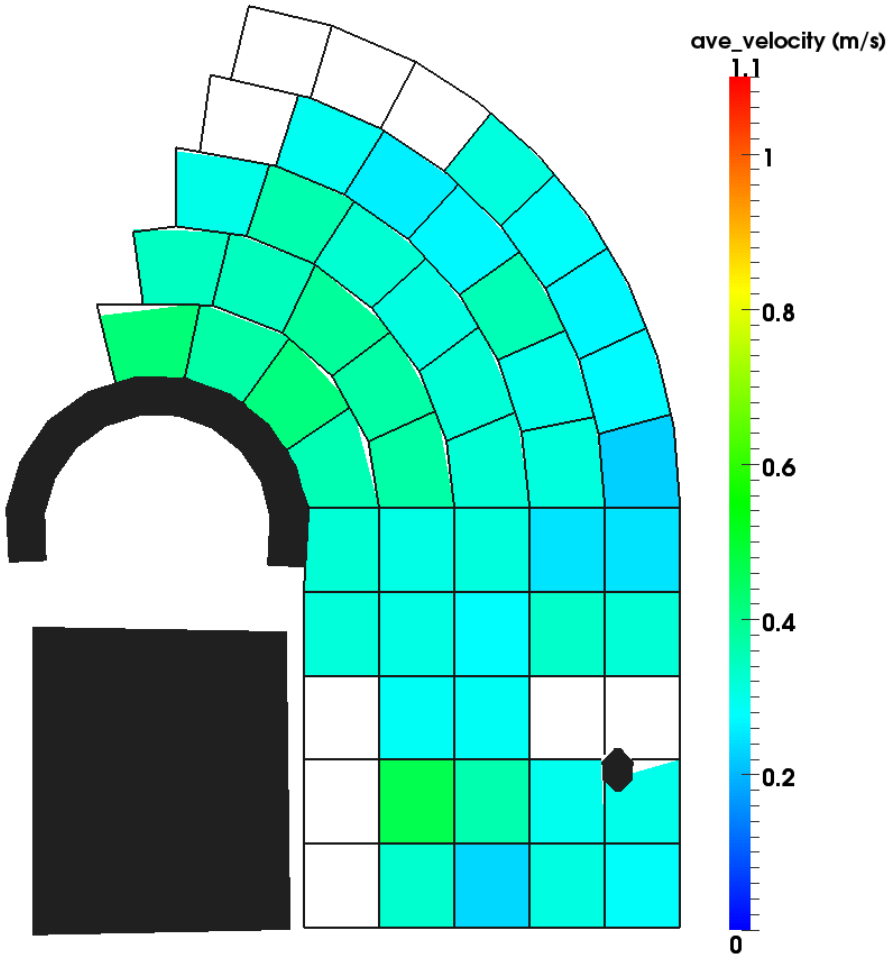
Observed Person – with a cap

Grid Name: C2

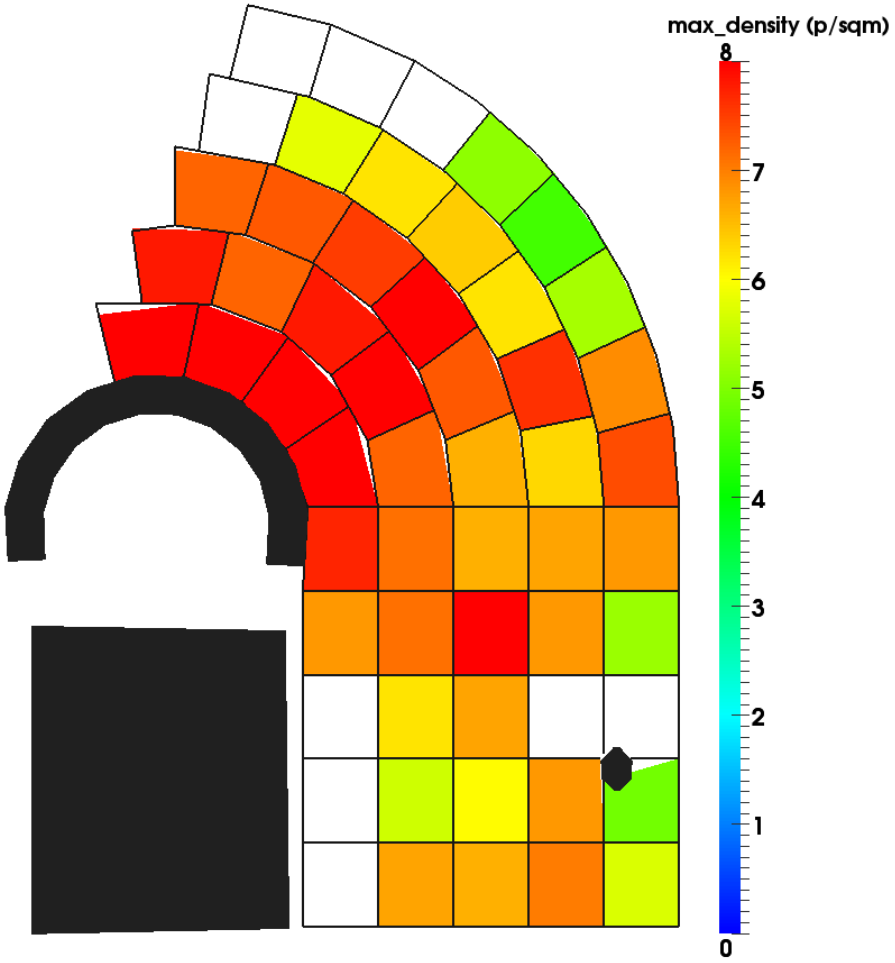
Nr. of Pilgrims	: 55 Persons
Cell area	: 10 sqm
Density	: 5.5 p/m²
Time	: 8.83 sec
Distance	: 3.3 m
Velocity	: 0.37 m/s



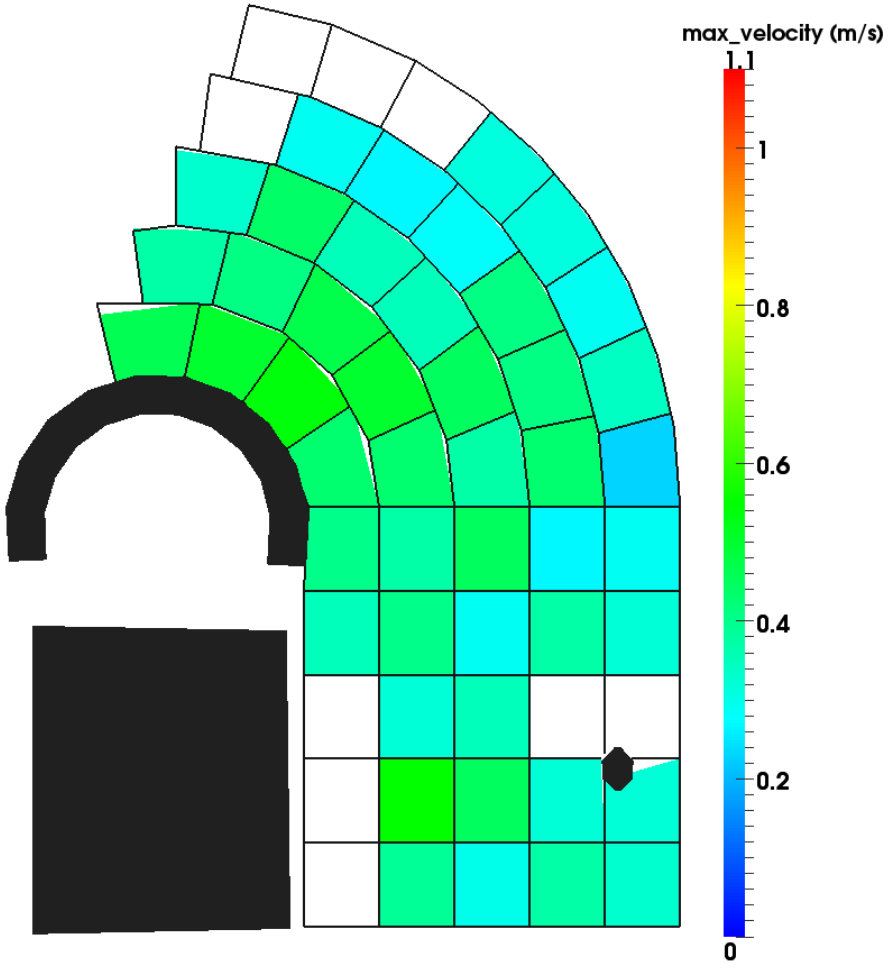
Average Density distribution
on 04.10.14 - 10th Dhu al-Hijjah



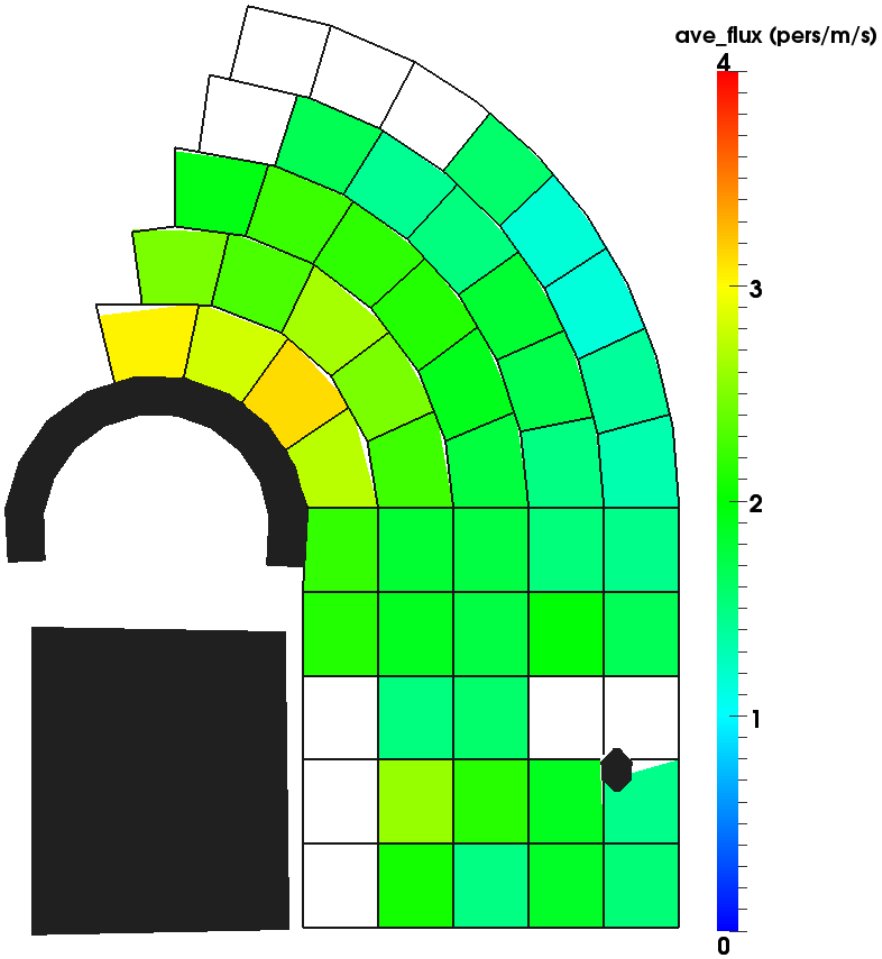
Average Velocity distribution
on 04.10.14 - 10th Dhu al-Hijjah



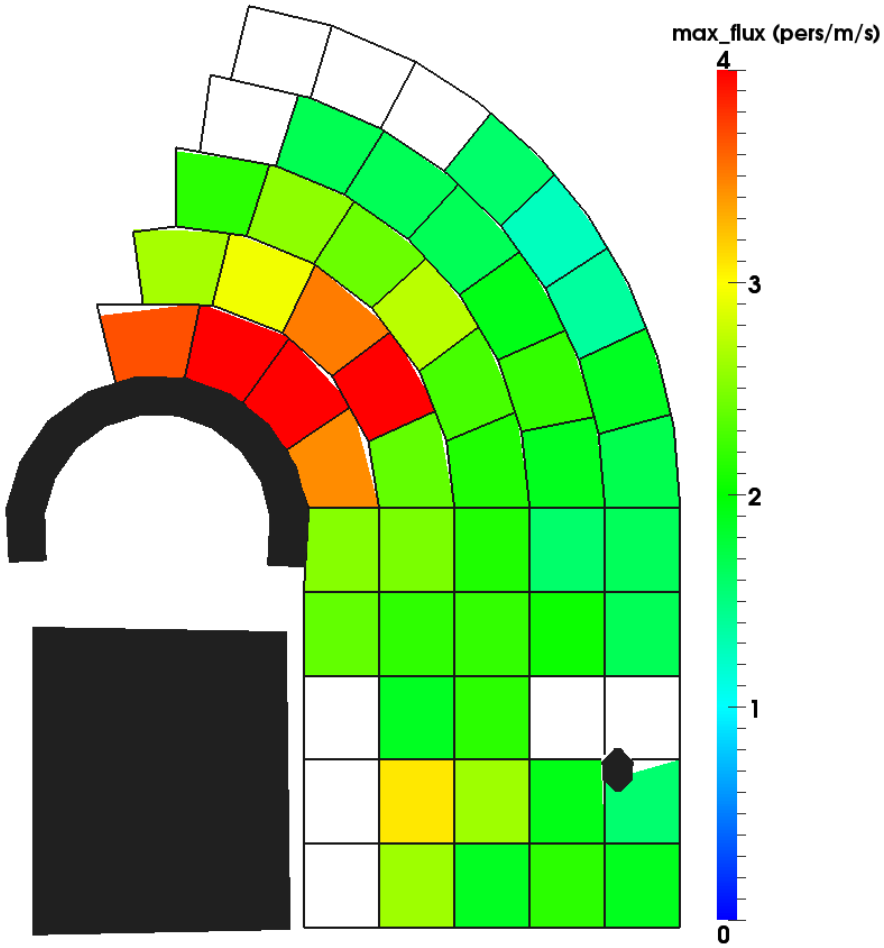
Maximum Density distribution
on 04.10.14 - 10th Dhu al-Hijjah



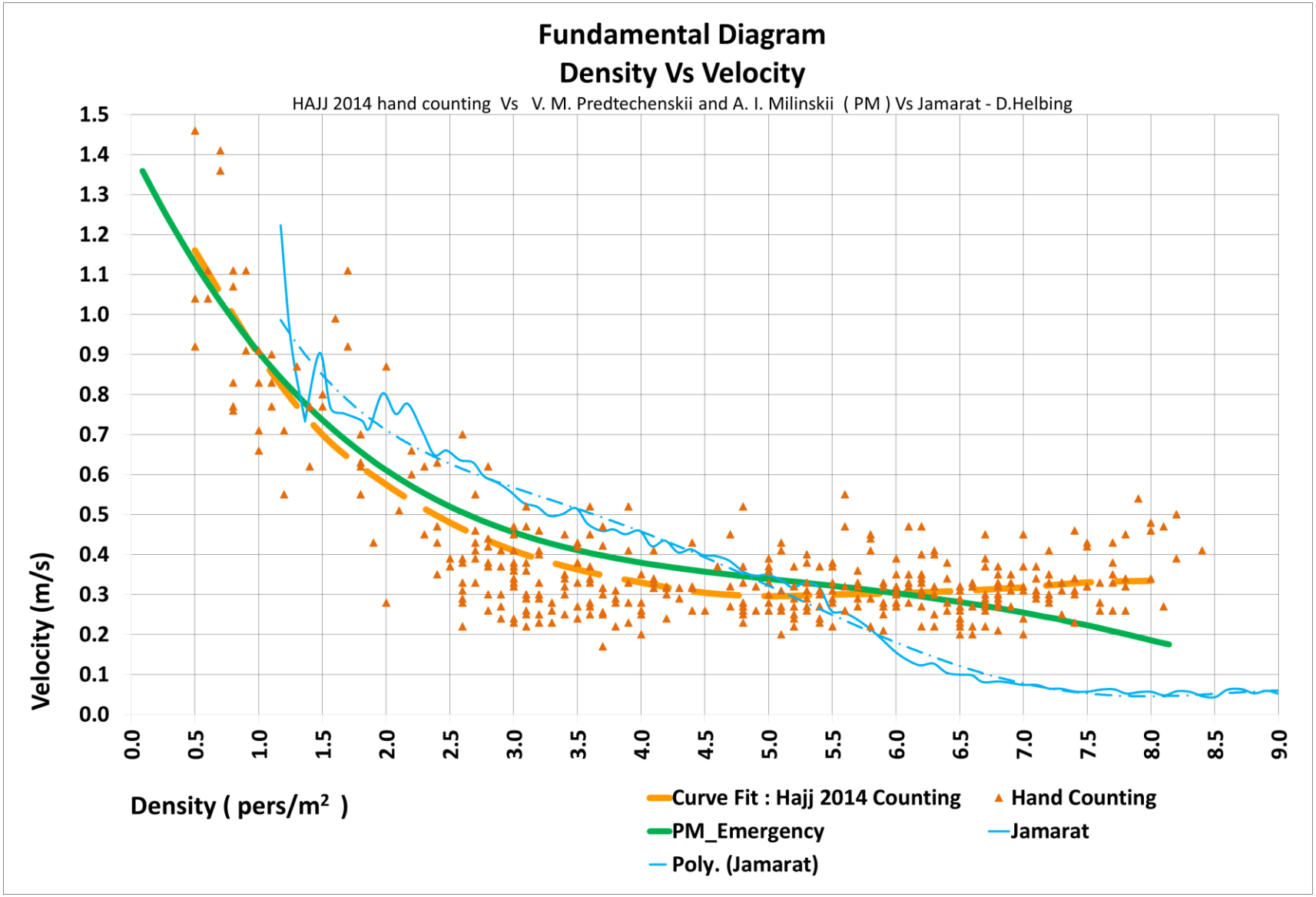
Maximum Velocity distribution
on 04.10.14 - 10th Dhu al-Hijjah

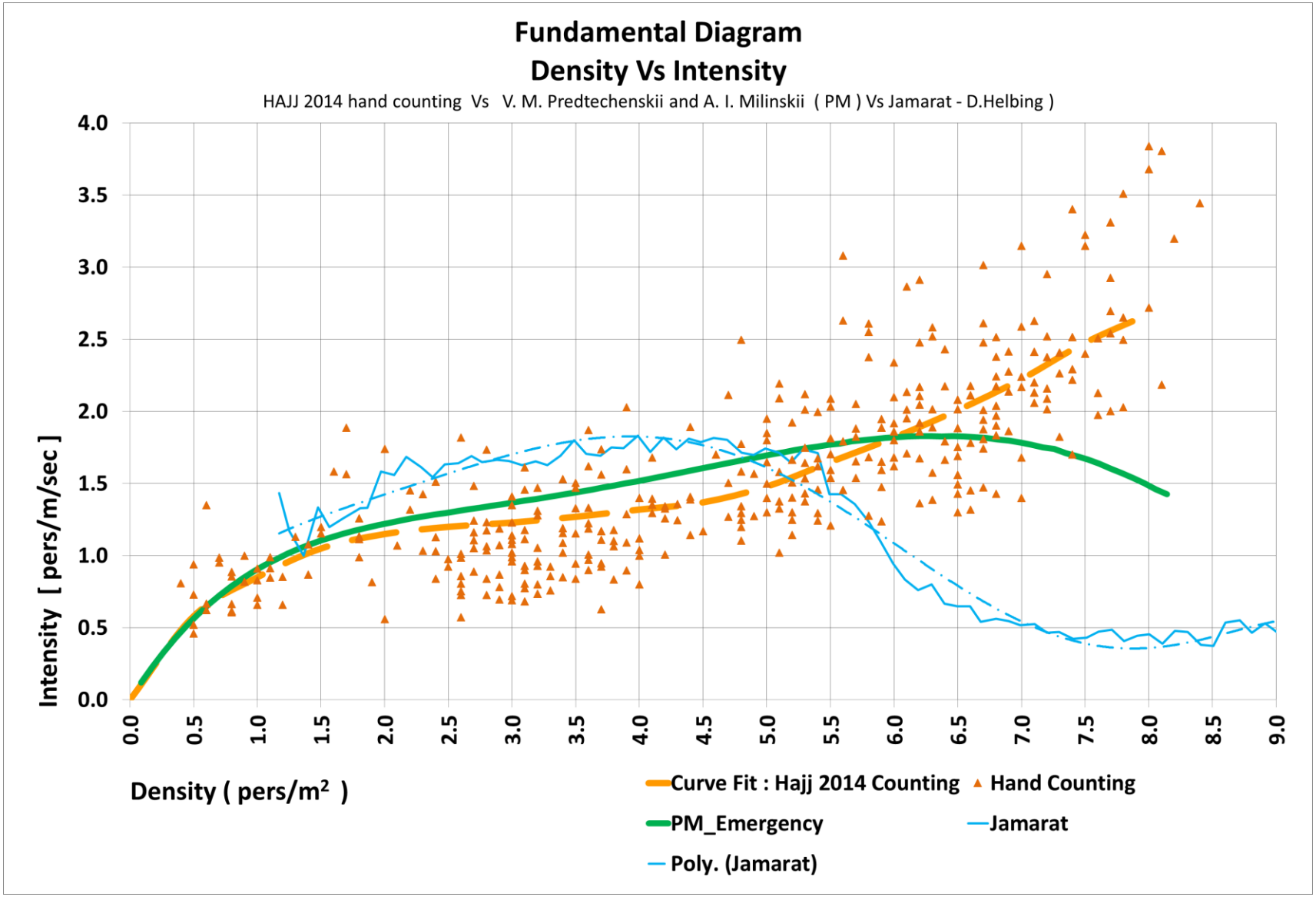


Average Flux distribution
on 04.10.14 - 10th Dhu al-Hijjah



Maximum Flux distribution
on 04.10.14 - 10th Dhu al-Hijjah


Fundamental Diagram
Density Vs Velocity
HAJJ 2014 hand counting Vs V. M. Predtechenskii and A. I. Milinskii (PM) Vs Jamarat - D.Helbing
Velocity (m/s)
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0 5.5 6.0 6.5 7.0 7.5 8.0 8.5 9.0
Density (pers/m²)
Curve Fit : Hajj 2014 Counting
Hand Counting
PM_Emergency
Jamarat
Poly. (Jamarat)


Fundamental Diagram
Density Vs Intensity
HAJJ 2014 hand counting Vs V. M. Predtechenskii and A. I. Milinskii (PM) Vs Jamarat - D.Helbing)
Intensity [pers/m/sec]
Density (pers/m²)
Curve Fit : Hajj 2014 Counting
Hand Counting
PM_Emergency
Jamarat
Poly. (Jamarat)

Other Empirical Data

- Memory Map of Planned Route / Stations
- Visual Horizon
  - 2.5 – 5.0 m
  - 120 Deg Perception
- `Personal Comfort Zone'
  - Dependent on Culture

Modeling Options

Pedestrian Flow Simulation (1)

- Discrete Space Model
  - Cellular Automata
  - Pedestrians at Nodes of (Adaptive) Grid
  - Allow Motion to One Neighbouring Cell/Place
  - Integrate in Time (Discrete/Fixed Intervals)
  - Schadschneider, Blue & Adler, … *Pedestrian and Evacuation Dynamics* (2002)
- Current Shortcomings
  - Motion Limited by Underlying Grids
  - Max Density Prescribed by Underlying Grid

Pedestrian Flow Simulation (2)

- Social Force Model
  - Treat Every Individual
  - Model Forces Influencing Motion
  - Integrate in Time
  - Helbing-Molnar-Farkas-Viczek (HMFV) *Nature* (2002)
  - Improvements by Lakoba et al. *Simulation* (2005)
- Current Shortcomings
  - Forces Symmetric [Removed in Some Models]
  - One Influences All / Too Many
  - Forces Difficult to Tune

Pedestrian Flow Simulation (3)

- Gas/Fluid Analogy
  - Viscosity, Forces as Functions of Density
  - Write `Euler/Navier-Stokes Like' Equations
  - Integrate in Time
  - Helbing *Complex Systems* (1992)
  - Others…Recent: Hughes *Ann. Rev. of Fluid Mech.*
- Current Shortcomings
  - No Proper Set of Equations in 2-D
    - Most of the Work 1-D
  - No Realistic Examples in 2-D
  - Difficult to Implement Crossing Streams

Pedestrian Flow Simulation (4)

- Agent-Based Simulations
  - High-Level: Finite State Machine
    - Physical State, Behaviour State, Property Set
    - FSM Transitions: Spatial, Property, Temporal, Stochastic
  - Low-Level: Local Collision Avoidance (LCA)
    - Reciprocal Velocity Obstacles (RVOs)
  - Integrate in Time
  - Manocha, Torrens, Others
- Current Shortcomings
  - Does Not Get Inter-Pedestrian Forces (Safety)
  - Expensive (CPU)

Discrete Models

Discrete Models

- Any Pedestrian Flow Simulation:
  - Global Movement: Strategic, Tactical
  - Local Movement: Operational
- Global Movement
  - Targets (Regions/Lines/…) ➔ Will Force
- Local Movement
  - Collision Avoidance
    - Social Force/ Contact Models
  - Local Geometry Info
    - Walls, Paths, Roughness, …

PEDESTRIAN MOTION

- Newton's Law:

$$m\,\mathbf{v},t = \mathbf{f}$$

$$\mathbf{x},t = \mathbf{v}$$

- m: Mass
- **v**: Velocity
- **x**: Position
- **f**: Sum of All Forces
- Modeling Effort: **f**

PEDFLOW

PEDESTRIAN FORCES

- Internal Forces
  - Will Force (Get There (in Time))
  - Pedestrian Collision Avoidance Forces: Intermediate Range
  - Pedestrian Collision Avoidance Forces : Near Range
  - Wall/Obstacle (Collision) Avoidance Forces

- External Forces
  - Contact: Other Pedestrians
  - Contact: Walls/Obstacles

PEDESTRIAN FORCES: Will Force

- Given:

  $\mathbf{v}_d$: Desired Velocity
  $\mathbf{v}$: Current Velocity

  $$\mathbf{f}_{will} = g_w (\mathbf{v}_d - \mathbf{v})$$

- Modeling Effort: g_w
  - Fitness
  - Desire to Reach a Goal
  - Climate
  - Signals
  - Noise, …

PEDESTRIAN FORCES: Will Force

- Suppose Only Will Force, From Rest:

$$m\,\mathbf{v}_{,t} = g_w\,(\,\mathbf{v}_d - \mathbf{v}\,)$$

- ➔

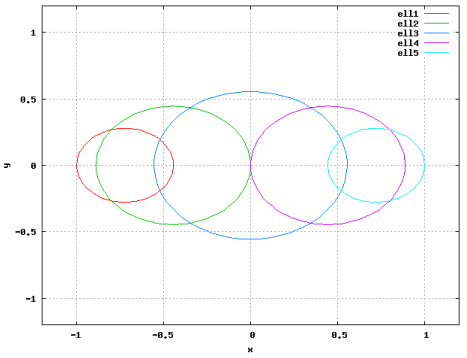
$$\mathbf{v} = \mathbf{v}_d\,(\,1 - e^{-\alpha t}\,) \quad ; \quad \alpha = g_w / m = 1 / t_r$$

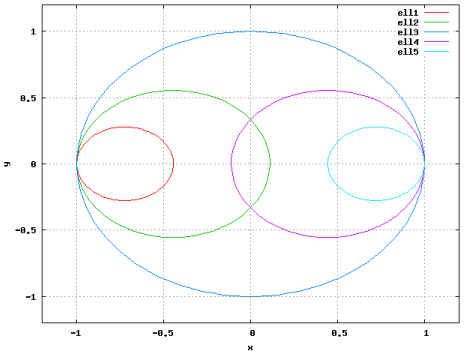
$$\mathbf{v}_{,t}(t=0) = \mathbf{v}_d \quad ; \quad \alpha = \mathbf{v}_d / t_r$$

- ➔ Can Define g_w Via Relaxation Time t_r
- Typical Values: $\mathbf{v}_d = 1.35$m/sec ; $t_r = O(0.5$sec$)$

Ellipticity

- Ellipticity:
  - Required to Achieve Higher Densities
  - Done With 5 Circles [Faster Contact]
  - e=0.0 ➔ Circle; e=1.0 ➔ Ellipse
  - Elliptical:
    - $x_{1,5}$ =1/1.8 [-/+ 1.3 + 0.5 sin(t) ; 0.5 cos(t)
    - $X_{2,4}$=1/1.8 [-/+ 0.8 + 0.8 sin(t) ; 0.8 cos(t)
    - X_3 =1/1.8 [1.0 sin(t) ; 1.0 cos(t)
  - Circular
    - $x_{1,5}$ =1/1.8 [-/+ 1.3 + 0.5 sin(t) ; 0.5 cos(t)
    - $X_{2,4}$=1/1.8 [-/+ 0.8 + 1.0 sin(t) ; 1.0 cos(t)
    - X_3 =1/1.8 [1.8 sin(t) ; 1.8 cos(t)





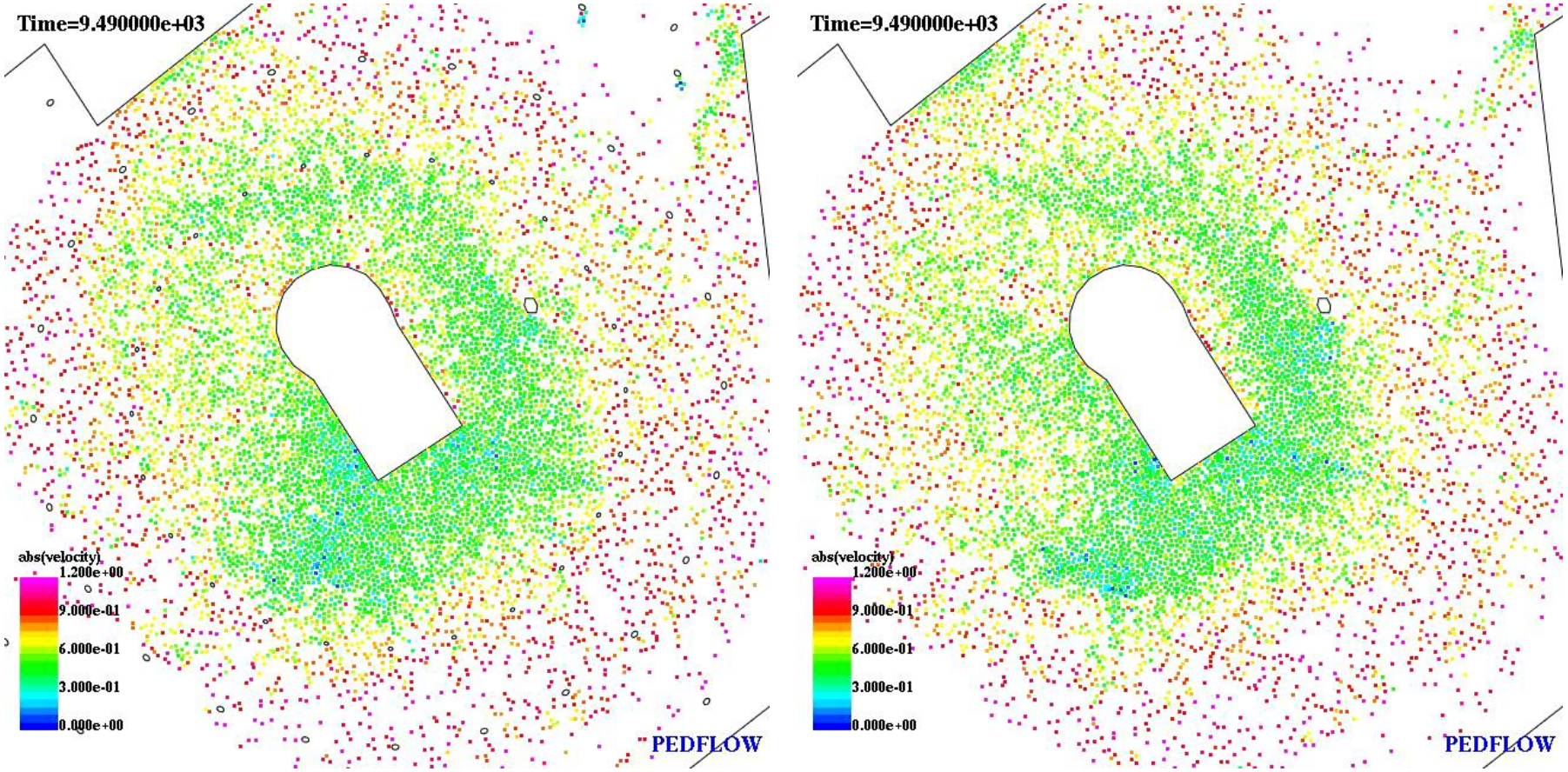
Hajj-Related Studies

Temporary Mataf

Temporary Mataf

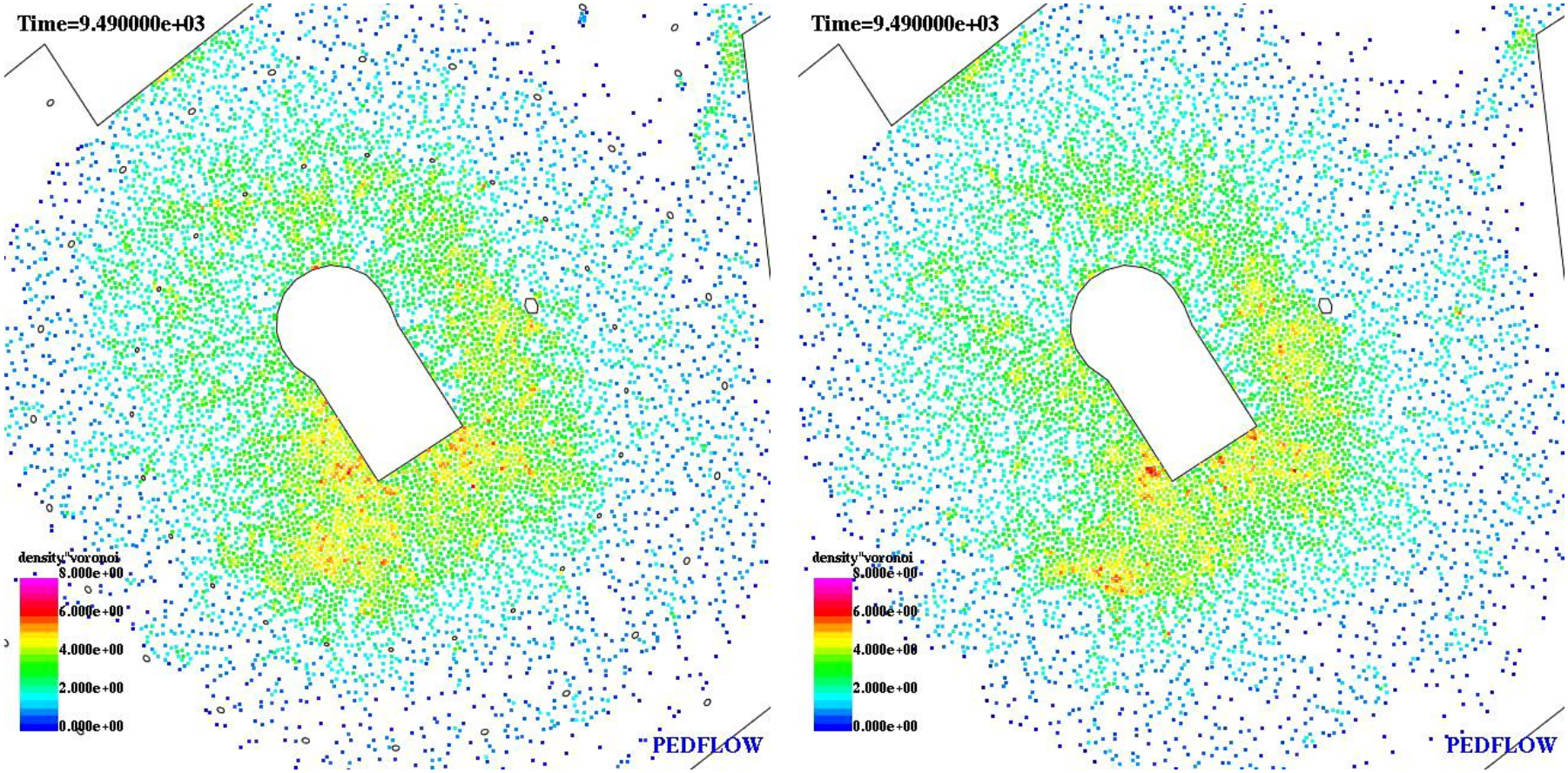
Time : Laylat al-Qadr - 25th July 2014 - TAWAF

Sahn Level; Flux=5.0p/sec



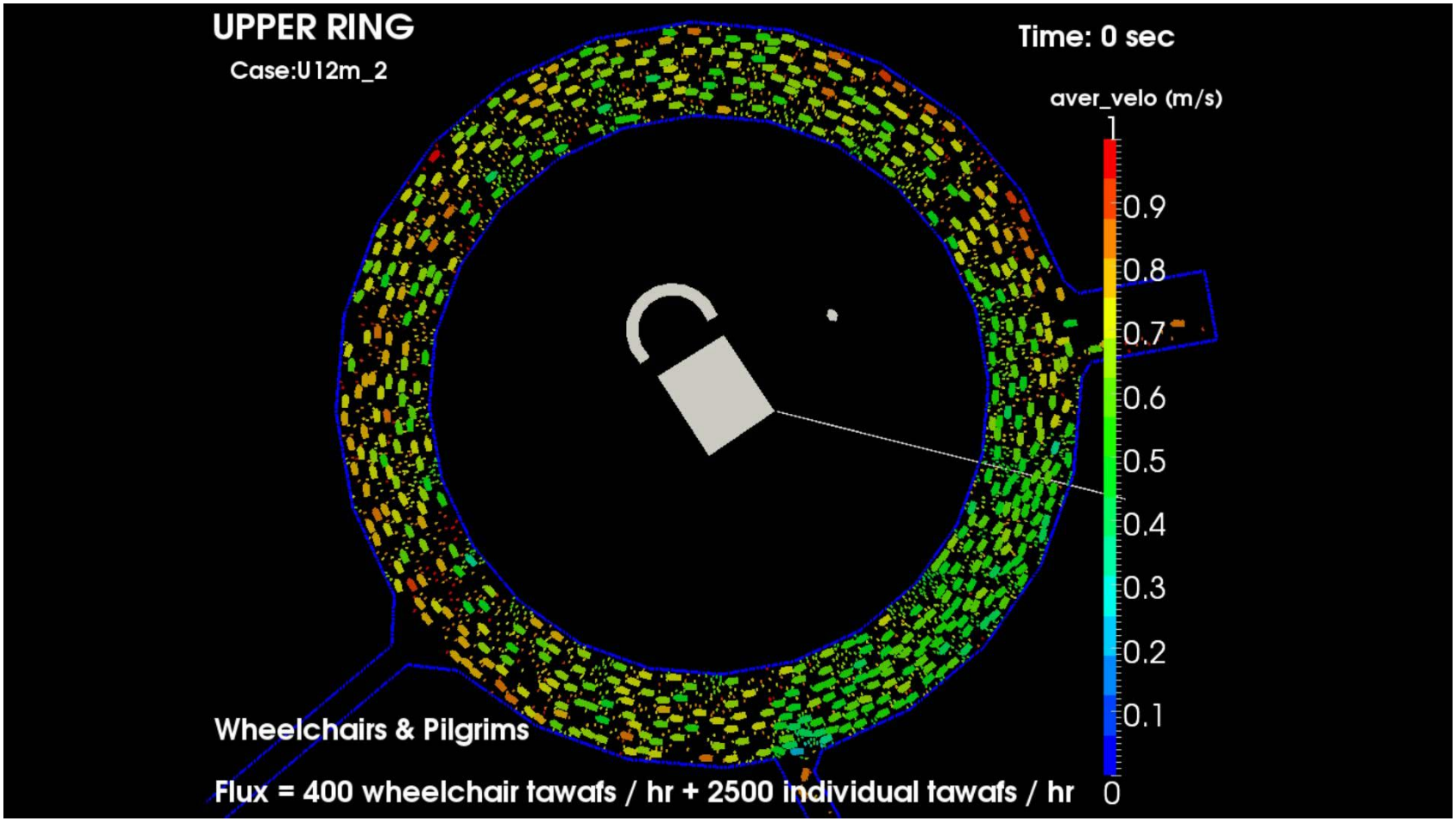
Velocity: Left: With Columns, Right: No Columns

Sahn Level; Flux=5.0p/sec



Density: Left: With Columns, Right: No Columns

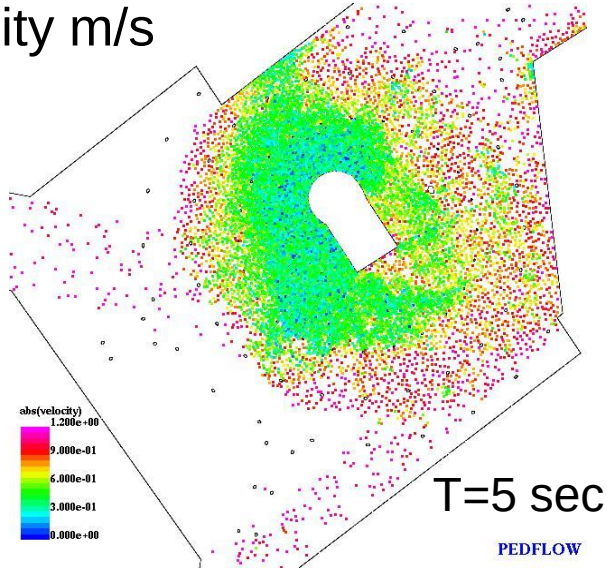
Temporary Mataf 06/13

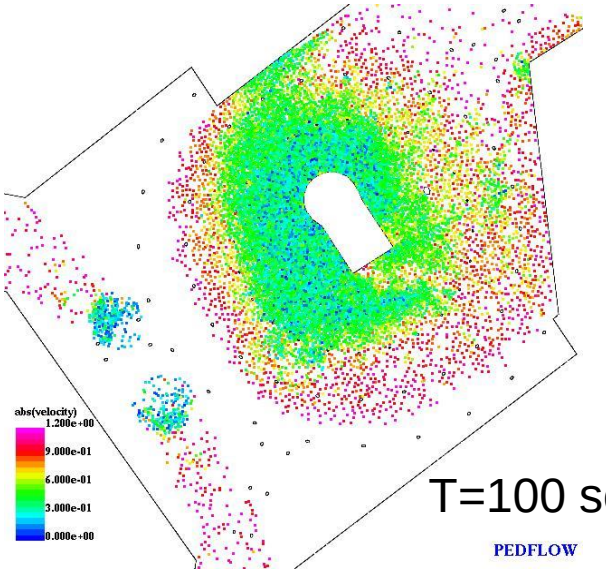


Detailed Simulation of Sahn Area

- Compute Normal Tawaf With Influx 5.0 p/sec
- Define Prayer Rows Emanating from Kaaba
- Restart from Steady State, Resetting Time=0
- Time: [0: 1.75] min
  - Additional People Stream in to Pray (8.0 p/sec)
  - People in Tawaf Continue as As Before
- Time: [1.75: 9.08] min
  - Rows Form From Outside (some from Kaaba [Film])
  - People Try to Find a Prayer Location
- Time: [9.08:12.42] min
  - Close Ranks and Move Forward If Free
- Time: [12.42:17.42] min: Prayer Time
- Time: [17.42:25.75] min:
  - People That Came in to Pray: Exit from Entry
  - People in Tawaf: Continue Ritual

Velocity m/s


abs(velocity)
1.200e+00
9.000e-01
6.000e-01
3.000e-01
0.000e+00
T=5 sec
PEDFLOW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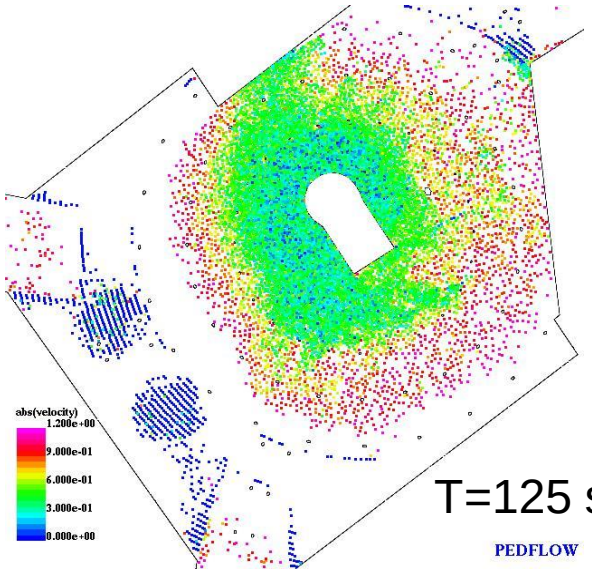
1.200e+00
9.000e-01
6.000e-01
3.000e-01
0.000e+00
T=100 sec
PEDFLOW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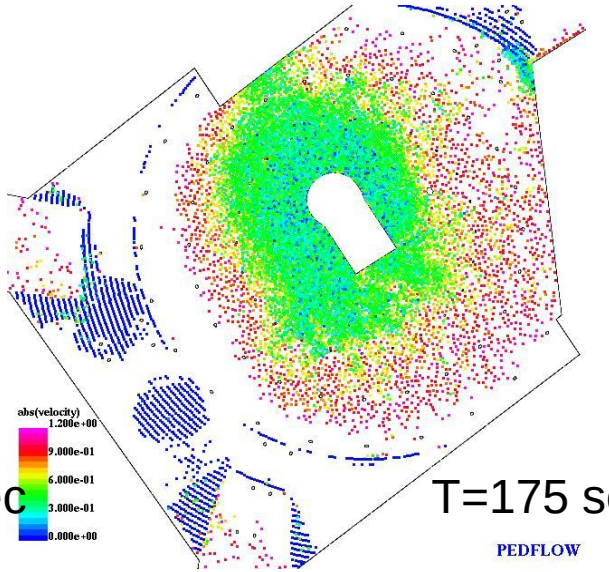
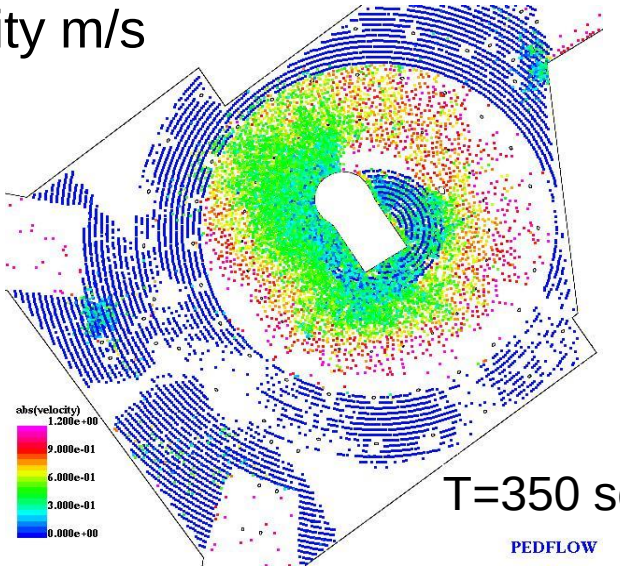
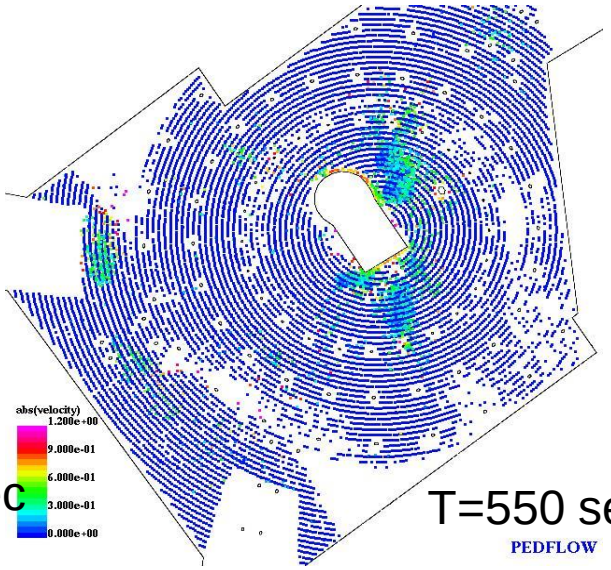
1.200e+00
9.000e-01
6.000e-01
3.000e-01
0.000e+00
T=125 sec
PEDFLOW


abs(velocity)
1.200e+00
9.000e-01
6.000e-01
3.000e-01
0.000e+00
T=175 sec
PEDFLOW

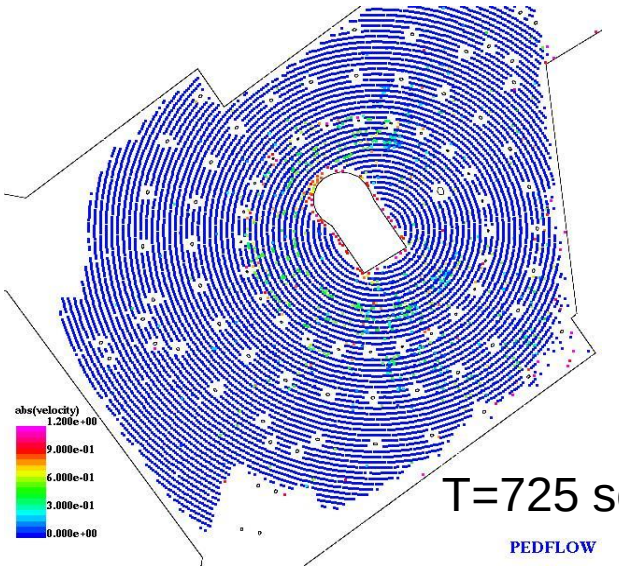
Velocity m/s



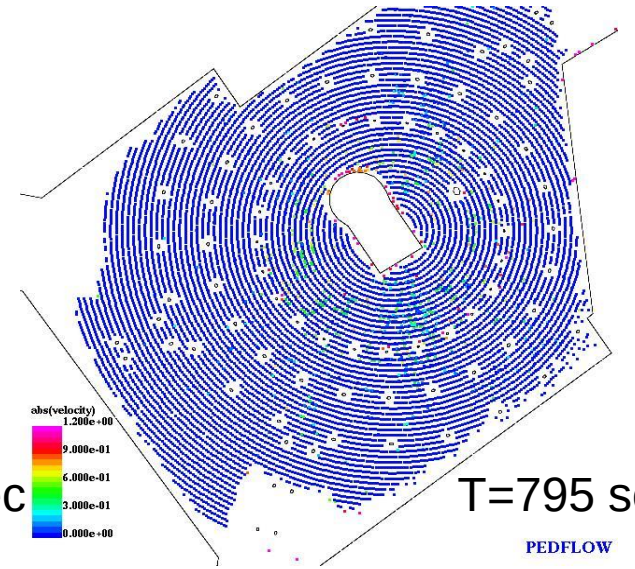
T=350 sec



T=550 sec

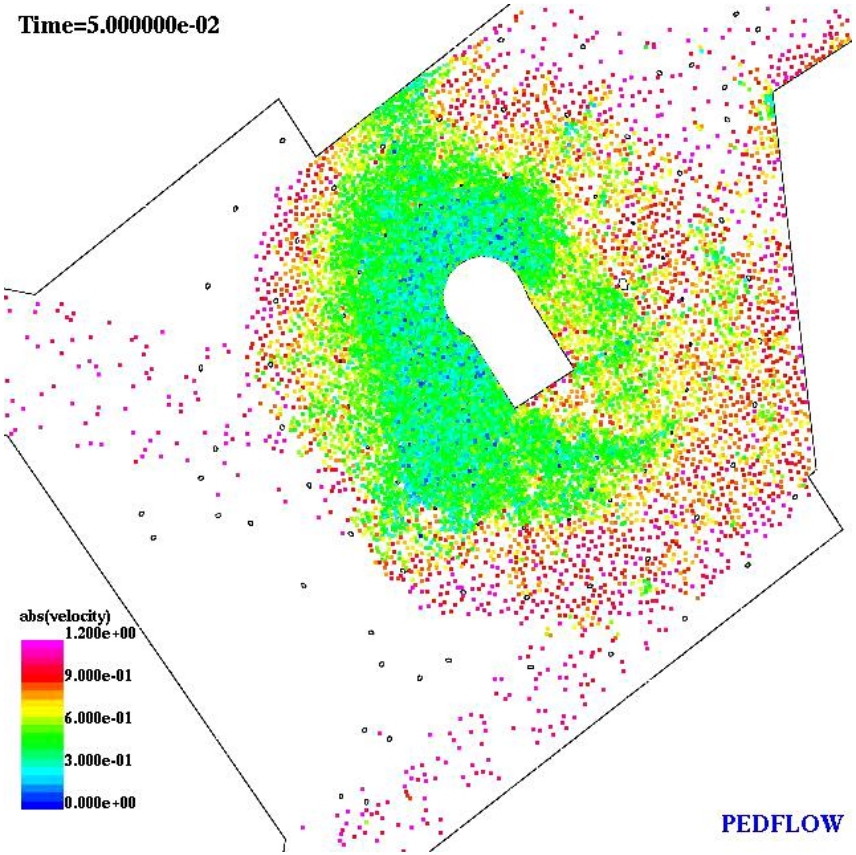


T=725 sec

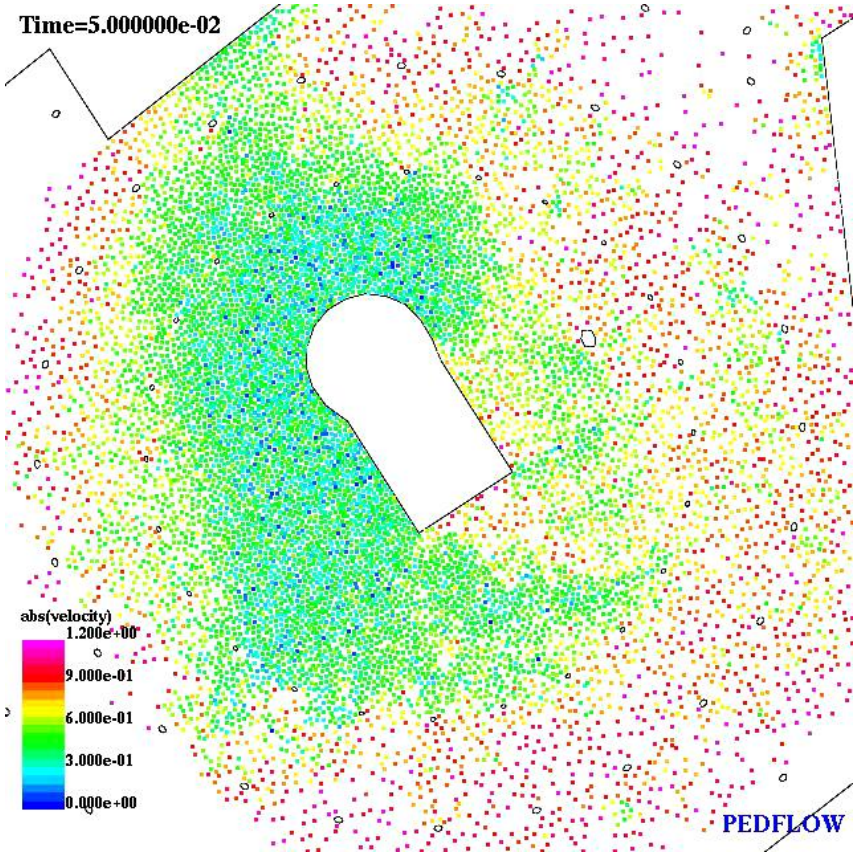


T=795 sec

Prayer Simulation: Sahn Level



Velocity: With Columns



Zoom

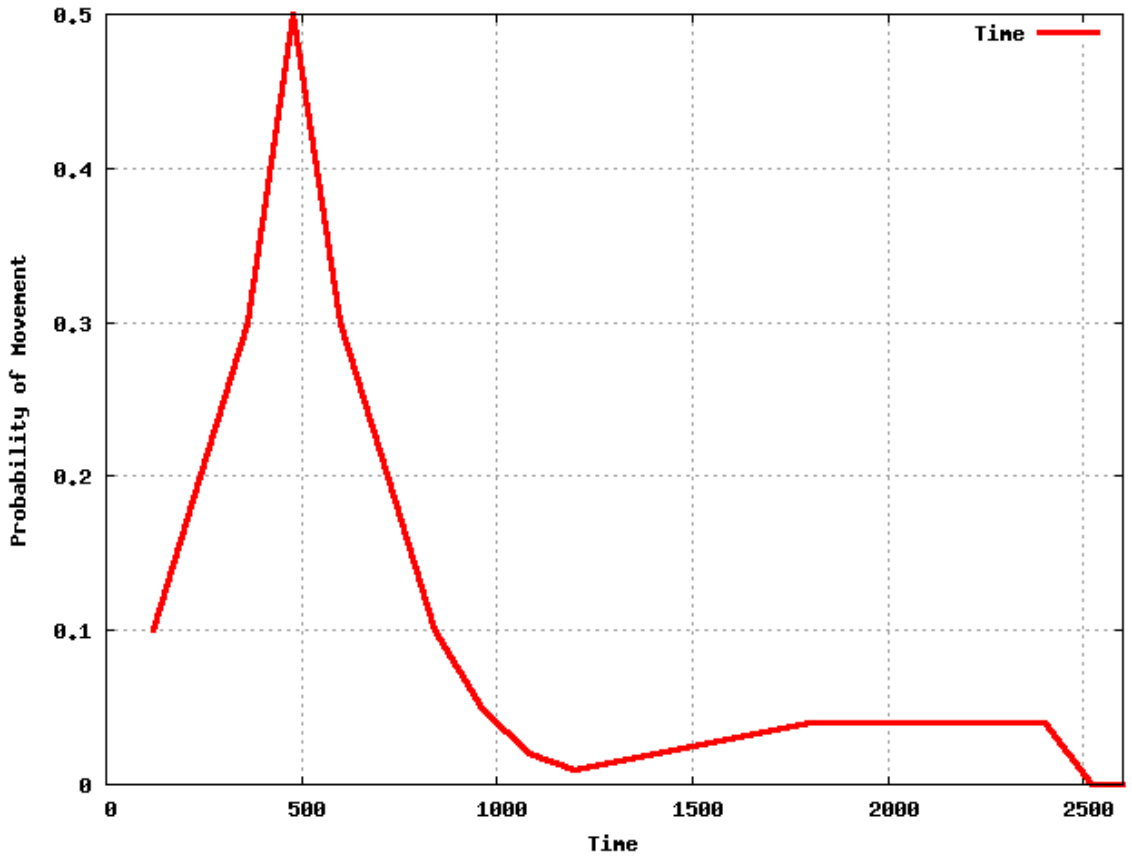
Evacuation of BCN

Barcelona: Area Considered (1)

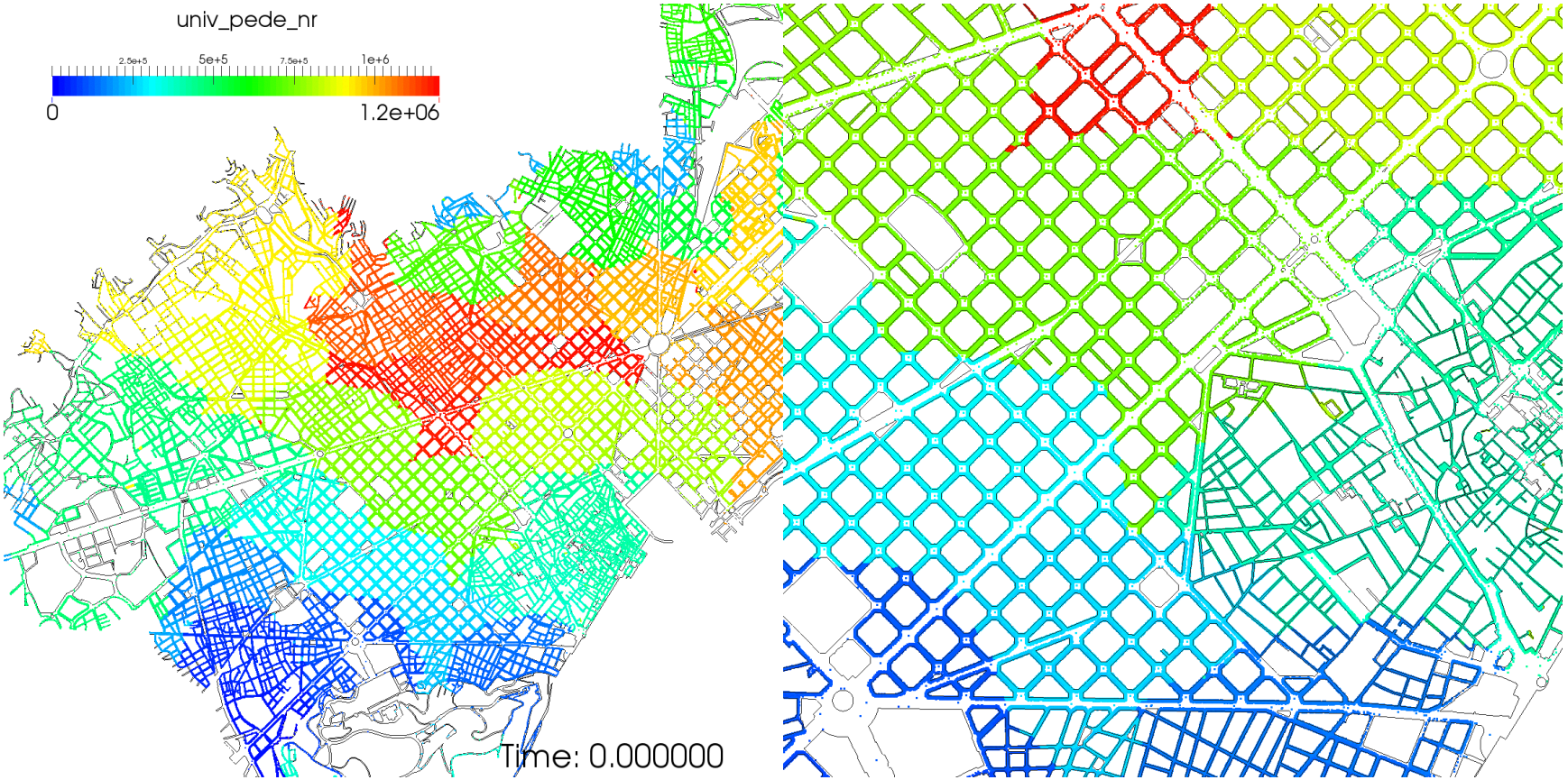
Barcelona: Area Considered (2)

Raction Time / Evacuation Delay

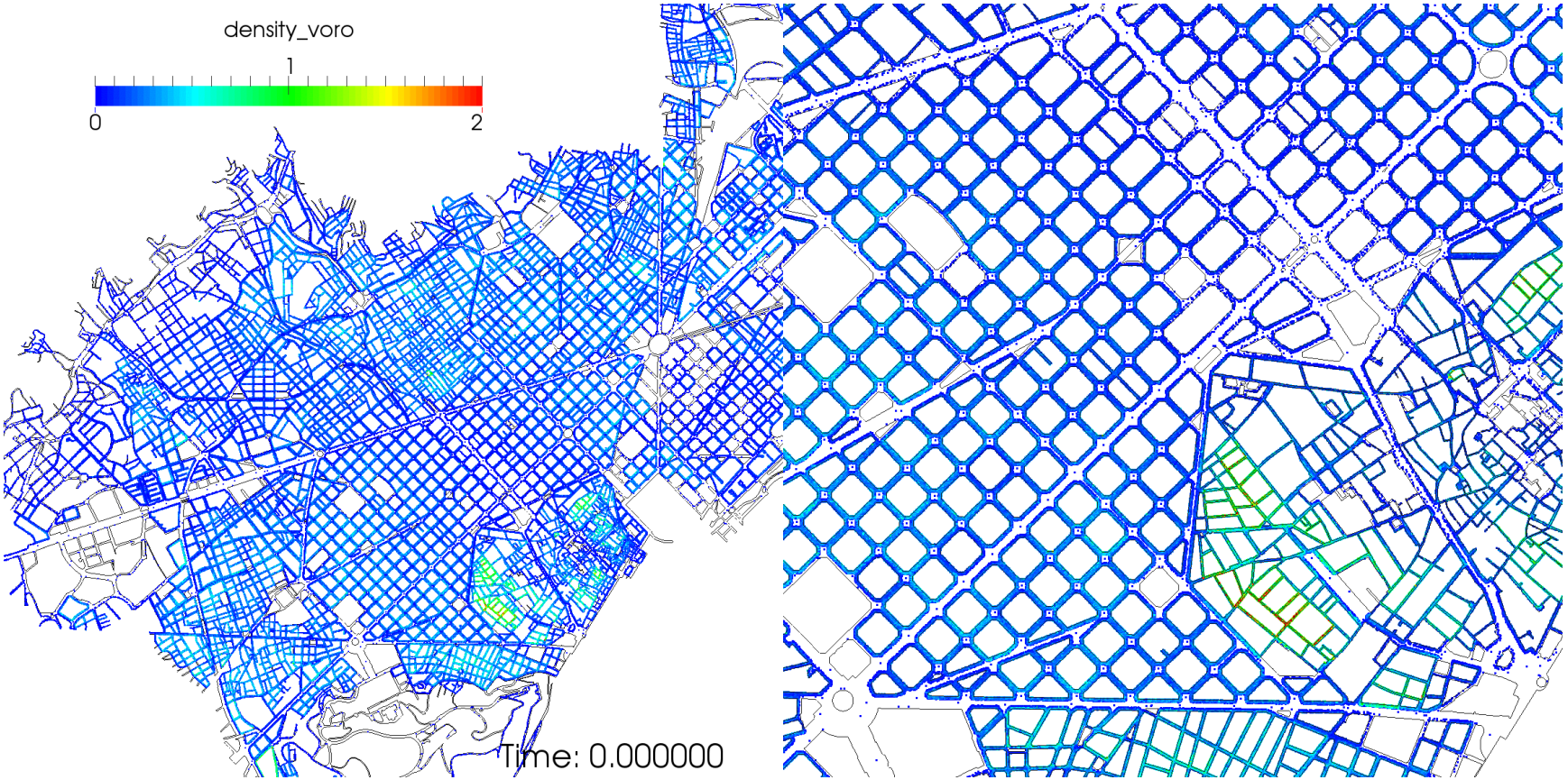
- Some Empirical Data; Used Here: Lord Data



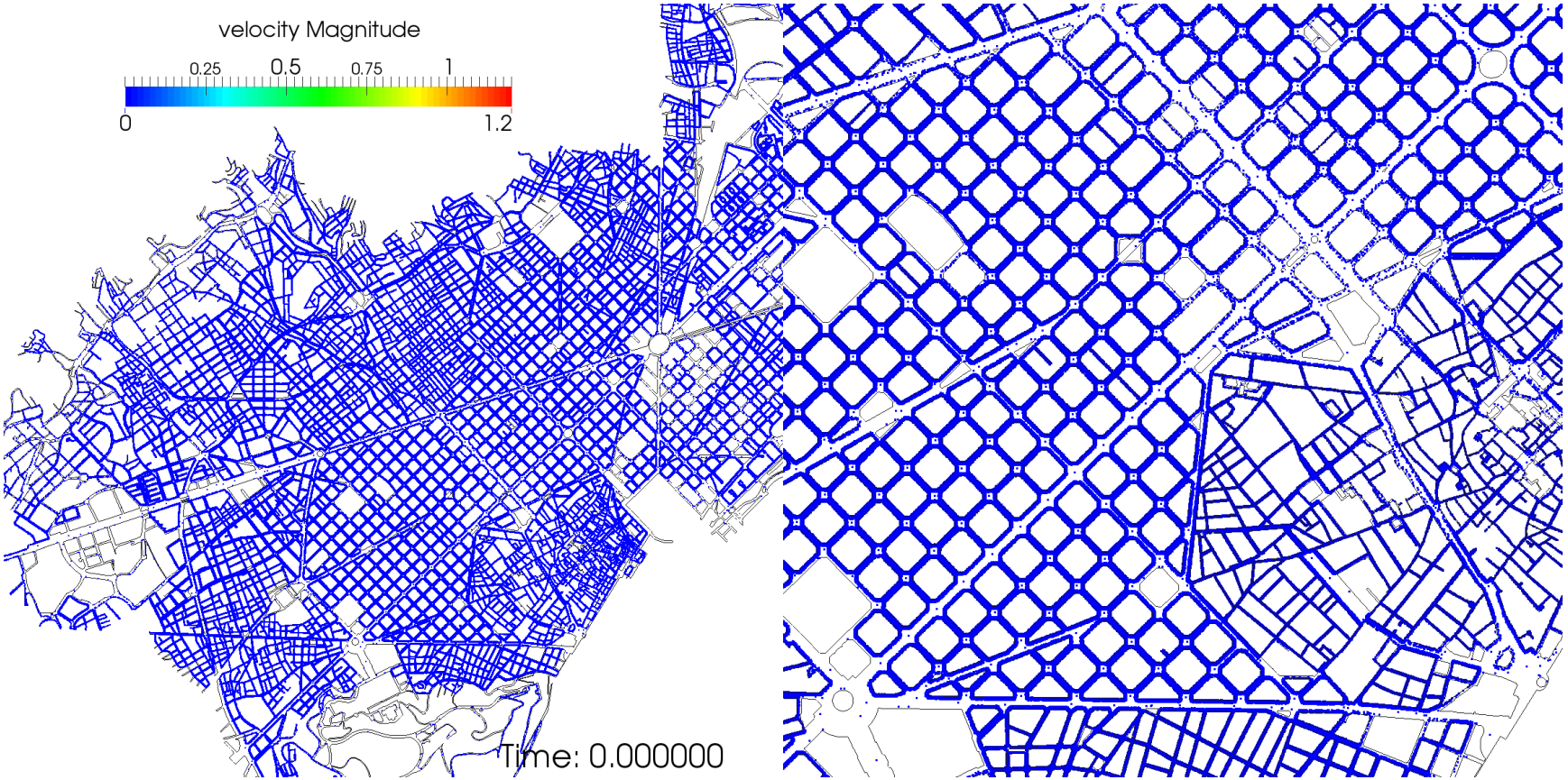
Evacuation of BCN



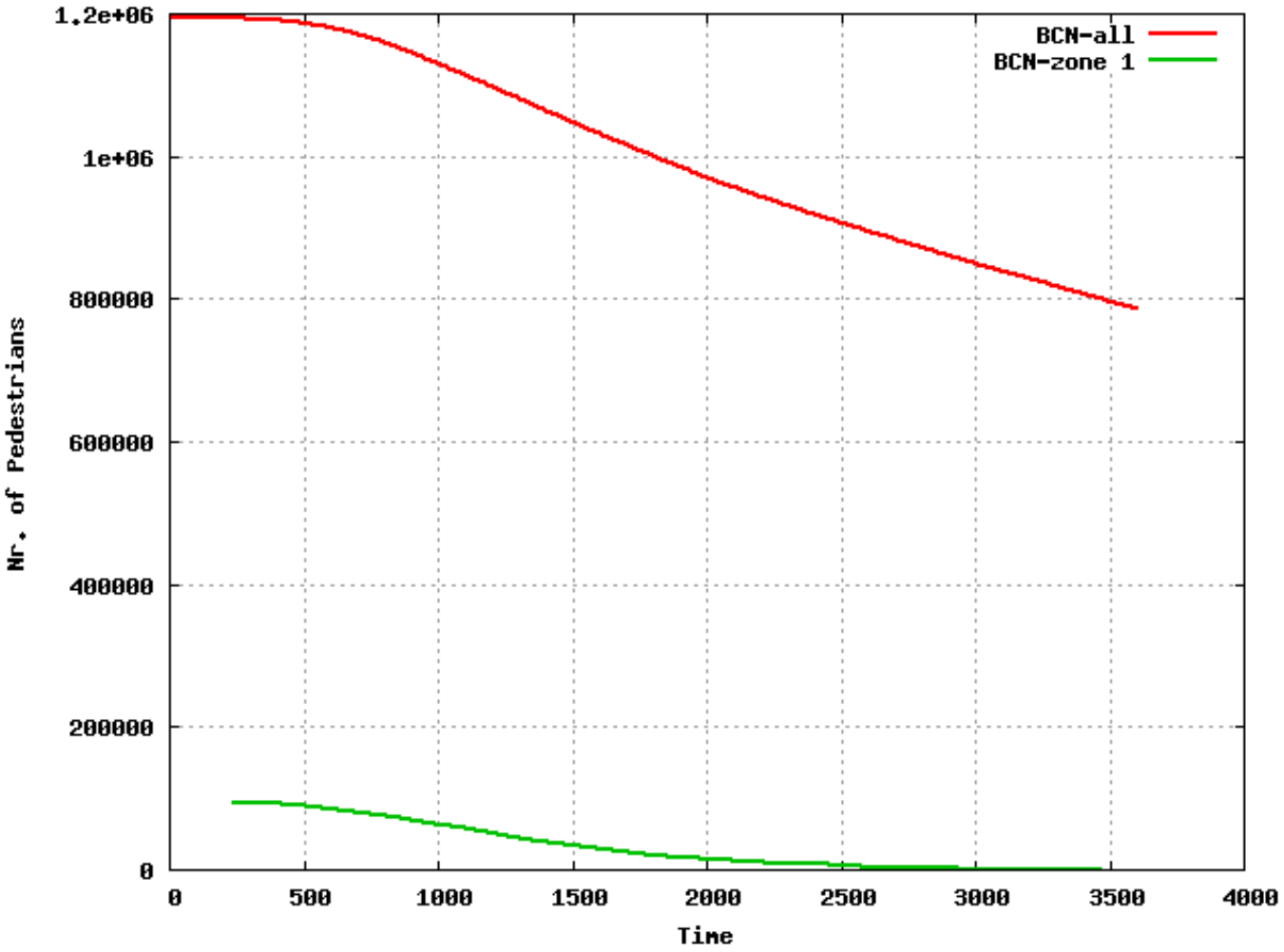
Evacuation of BCN



Evacuation of BCN



Evacuation Times



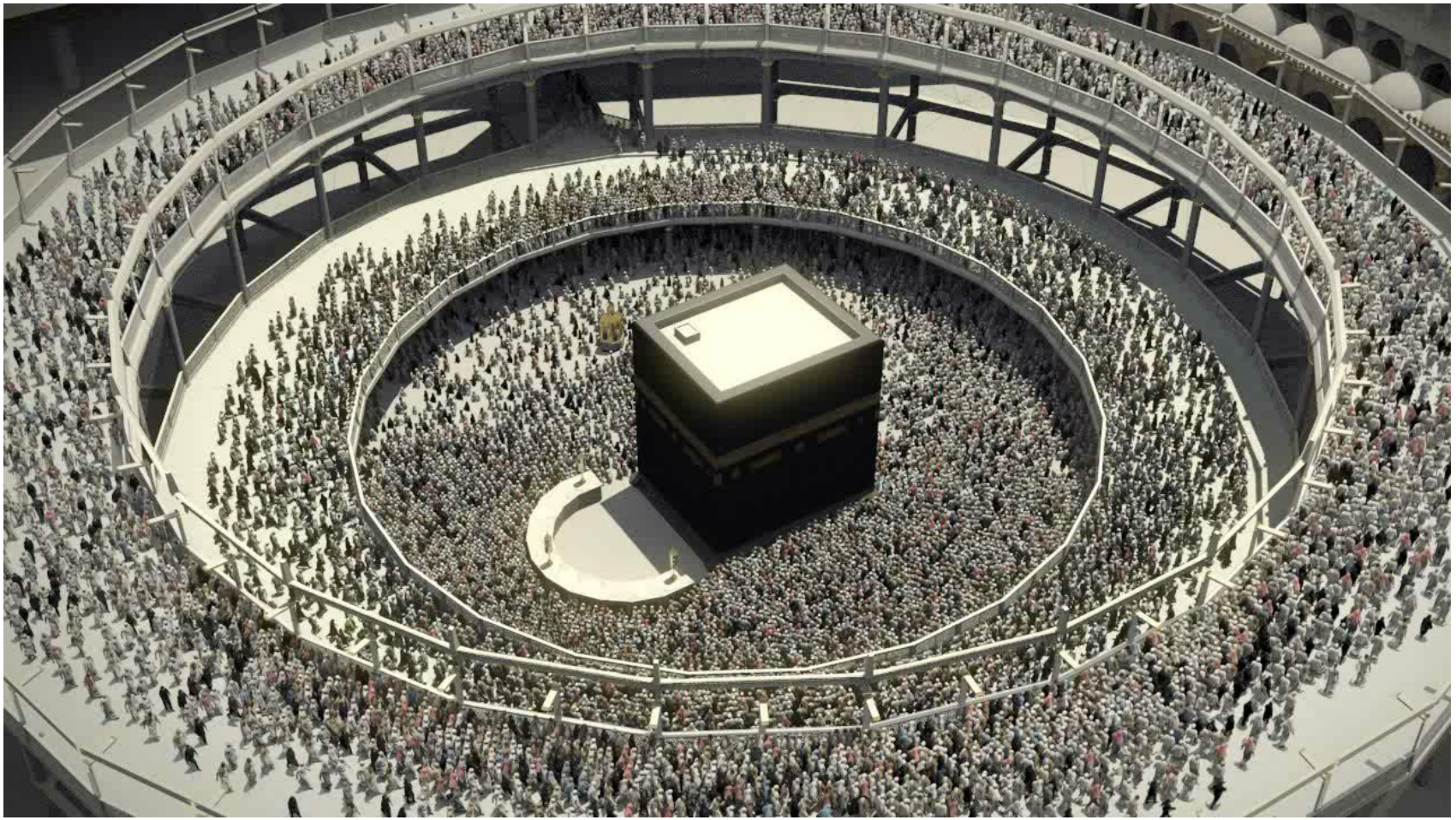
Evacuation of BCN

Number of Pedestrians : 1.2 M
Integration Time : 1.0 hr

ndomn	nprol	ncore	runtime	run/real time
128	4	512	3379	0.94
256	2	512	3492	0.97
128	8	1024	2461	0.68

Photo-Realistic Rendering Based on PEDFLOW Calculations

Rendering via 3-D Studio Max

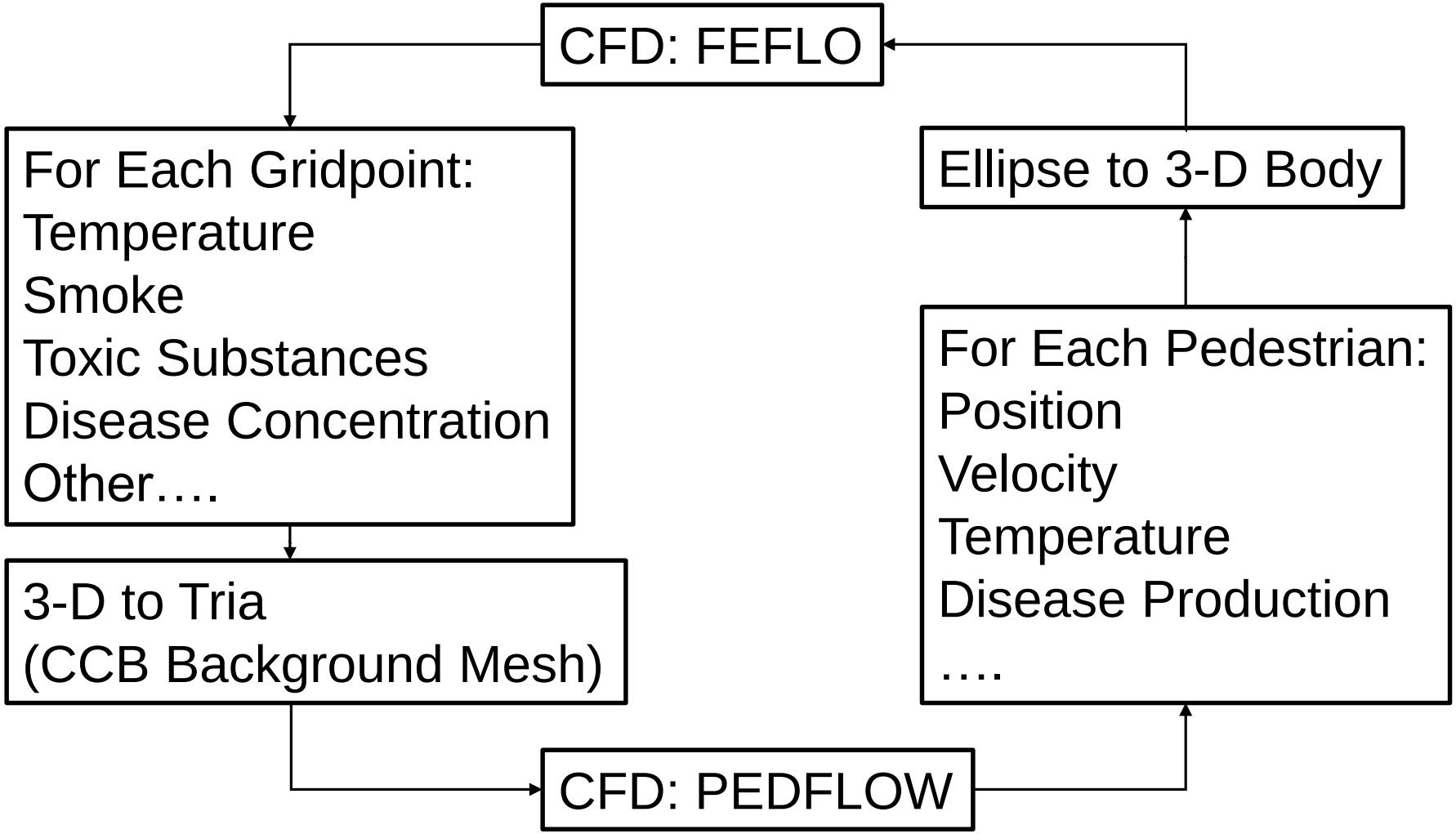


Coupling of CFD and CCD

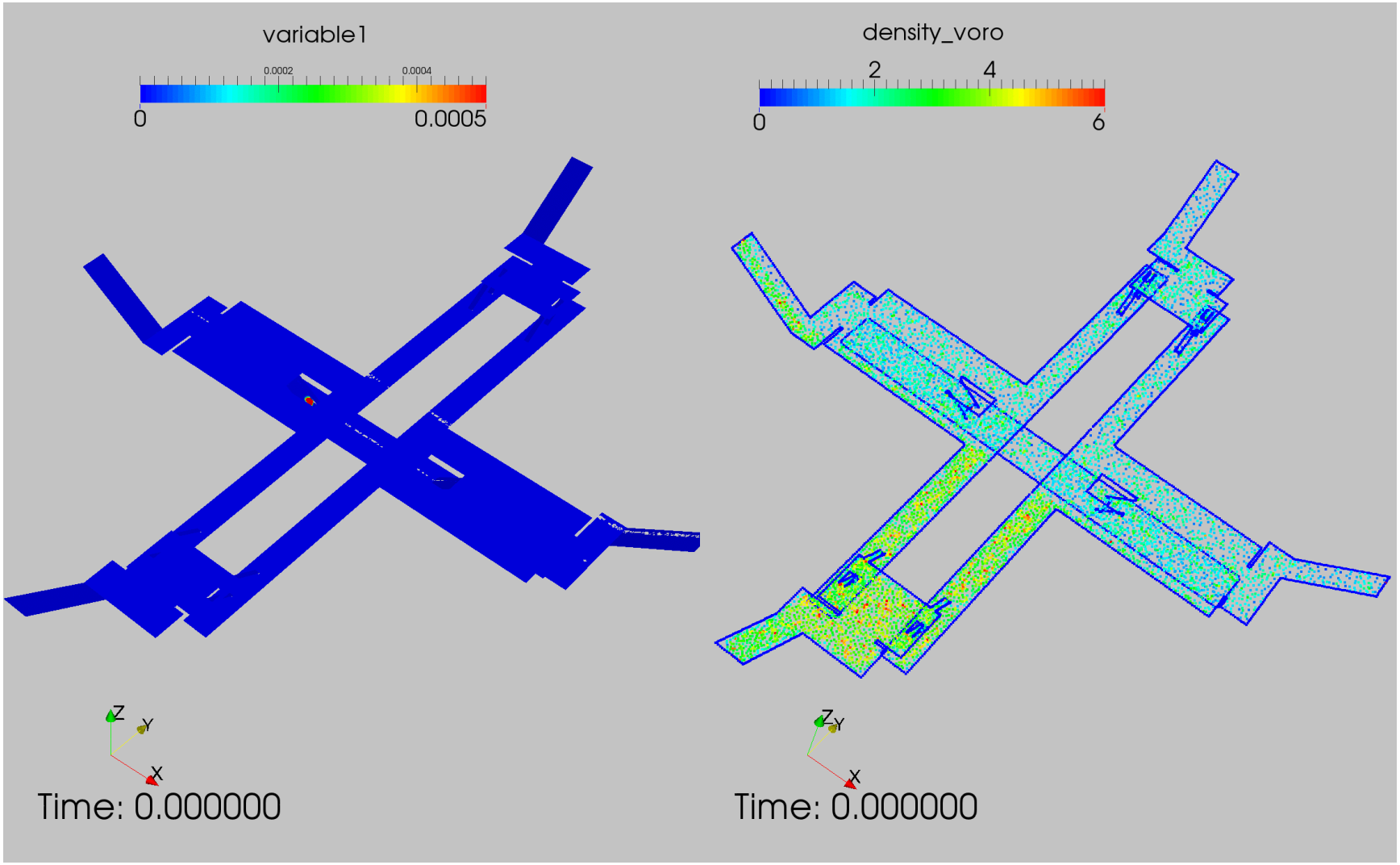
Coupling of CFD and CCD

- Flow May Influence Motion of Pedestrians
  - Smoke, Toxic Materials, Fire, …
- Motion (Presence) of Pedestrians May Influence Flow
  - Narrow Passages in Subways
- Flow May Also Influence Spread of Diseases
  - Flu, SARS, Coronavirus, …
- ➔ Need Coupled CFD/CCD

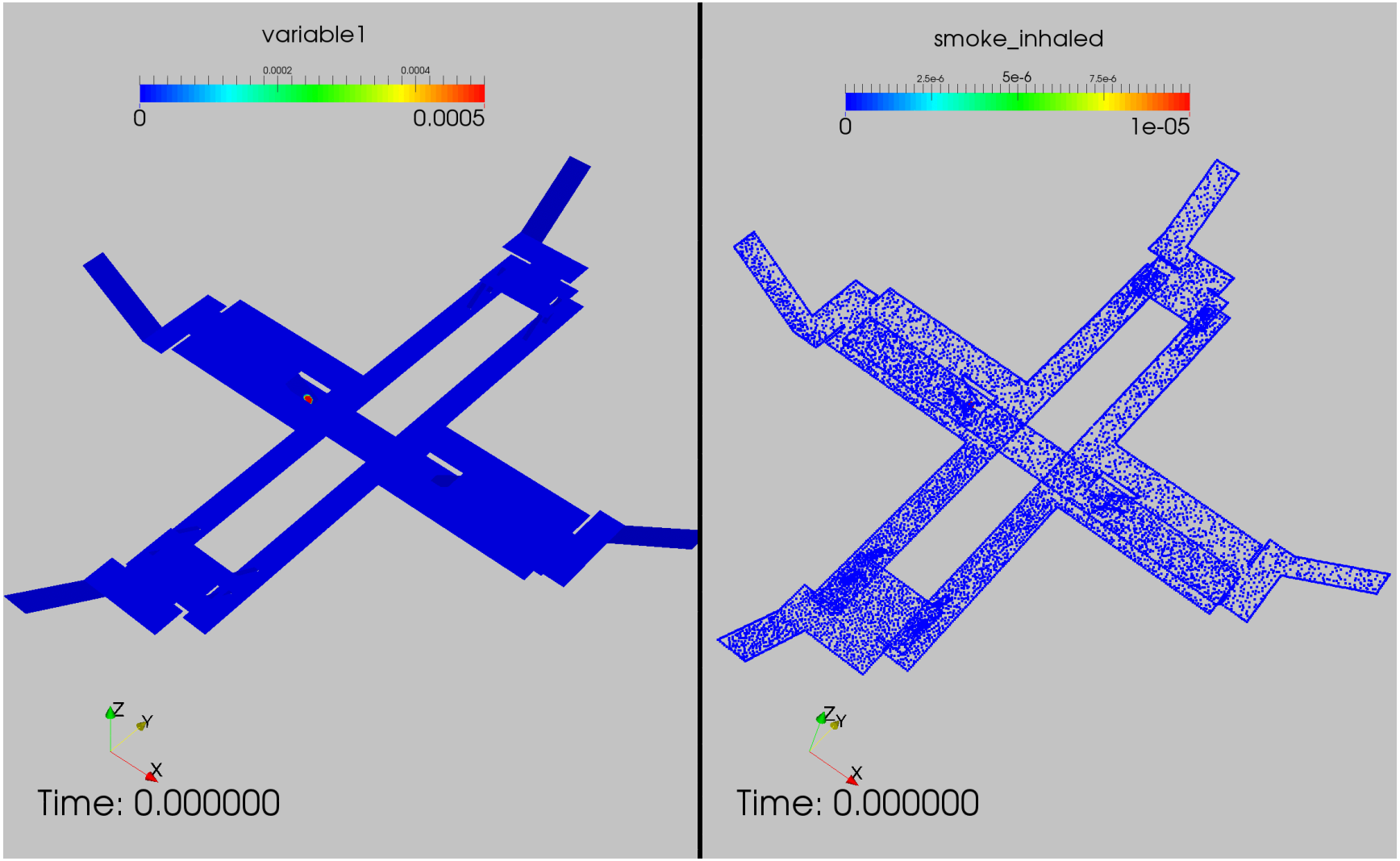
Coupling of CFD and CCD



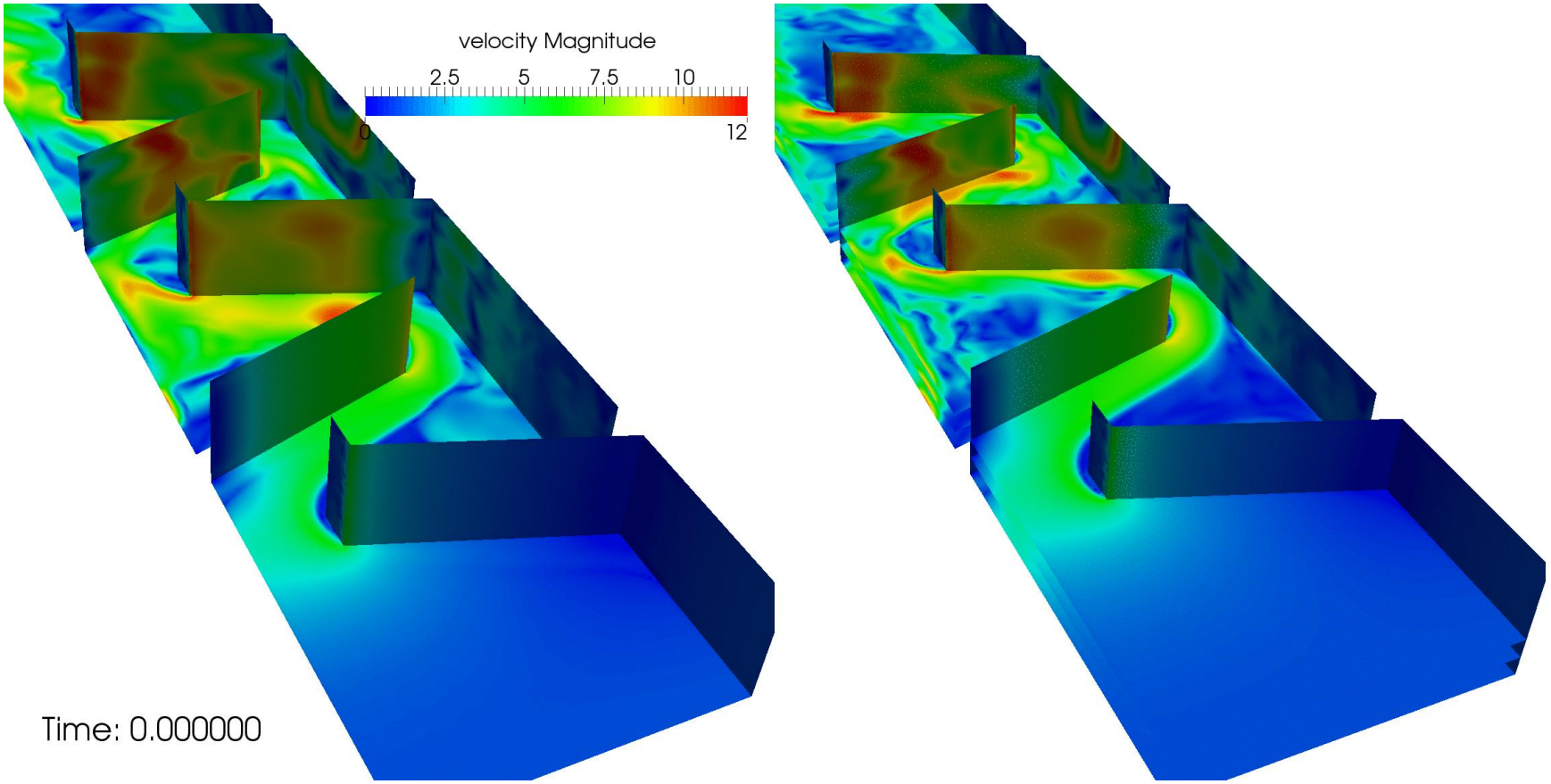
Metro Evacuation



Metro Evacuation



Pedestrians in Passage



Conclusions and Outlook

Conclusions and Outlook (1)

- Developed Efficient Code for the Simulation of Pedestrian Flows and Crowd Dynamics
- Basis:
  - Global (Overall) Direction: Desired Location/Time
  - Local Obstacle / Pedestrian Avoidance
- Results Obtained to Date:
  - Correct Crowd Dynamics, Lane Forming, Overtaking, Avoidance of Obstacles, …
- Results Promising
- Validation, Validation, Validation …
  - Video Footage

Conclusions and Outlook (2)

- Incorporate More Realism
  - Queing in Certain Locations
    - Tellers, Train Stations, Bus Stops, …
  - Moving in Walkways and Escalators
  - In/Outflow Behaviour
    - Elevators
    - Trains/Subways
  - Panic Behaviour
  - Fallen Pedestrians
  - …

Conclusions and Outlook (3)

- Link to Other Disciplines:
- PEDPRESS: Asphyxia, Collapse, …
  - Ongoing Experiments
- CFD: Smoke/Comfort
  - Working
- CFD: Spread of Diseases
  - Need Medical Data / Spread Factors
- CSD: Loading of Structures
  - Working

Conclusions and Outlook (4)

- Ongoing Theoretical Studies
  - Entry Into Incoming Crowd (Emergency Personnel)
  - Density-Velocity Diagrams (PM/Helbing/Seyfried/…)

- Overall: Young Discipline, Exciting Area !
- Lots of Work to be Done !

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