Traffic Flow Theory & Simulation

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Lecture 12
Pedestrian Flow Theory

TU Delft

Pedestrian Flow Theory

An Introduction

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TUDelft Delft University of Technology

Challenge the Future

State-of-the-art Pedestrian Research

Introduction

- Key differences between car traffic and pedestrian traffic?

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Aspect

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Aspect	Cars

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Dimensionality		

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Anisotropy	Strongly anisotropic	Mildly anisotropic

Aim of this lecture

- Revisit concepts introduced for car traffic and discuss applicability (required modifications) for pedestrian flow

- After lecture you should be able to:
  - Understand key differences between pedestrian and vehicular flow
  - Understand / apply concepts of flow, density, speed to ped flows
  - Interpret and use pedestrian fundamental diagrams
  - Apply shockwave theory to simple situations
  - Know key self-organized features in pedestrian flow
  - Understand key features of microscopic pedestrian models and interpret equations

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Pedestrian data collection

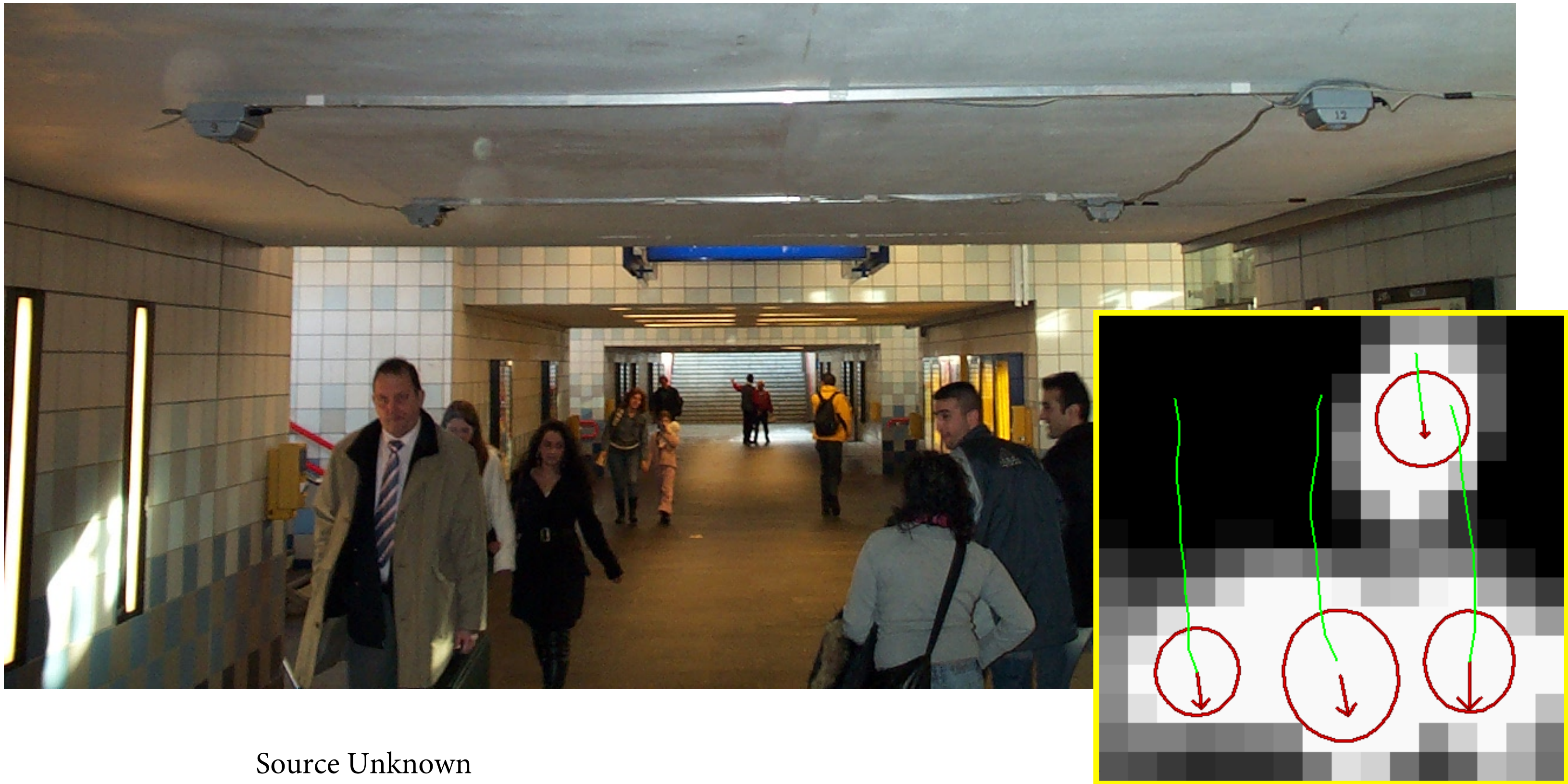
Some approaches...

Issues in pedestrian data collection

- Many traditional observation techniques are not suitable for pedestrian flow observation (inductive loops, pneumatic tubes)

- Which techniques would be suitable?
- Which issues do you still see?

Examples of ped data collection



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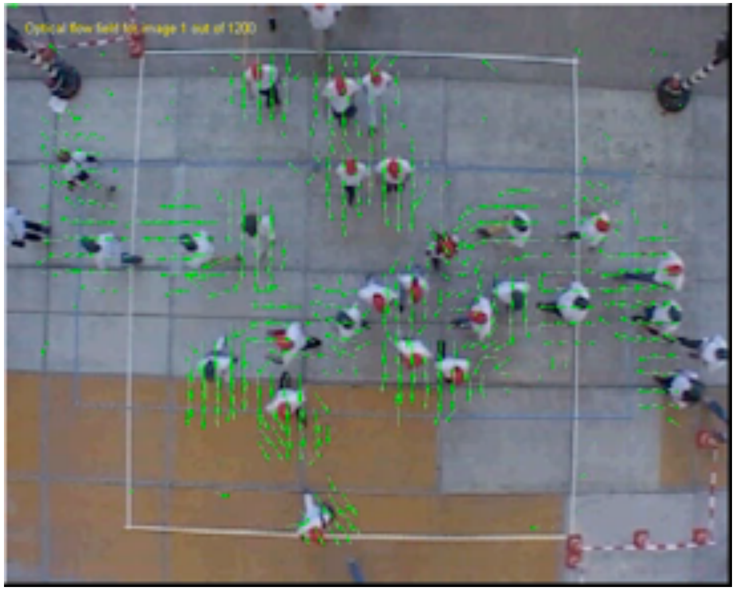
Examples of ped data collection

- Use of video detection + tracking software
- Relatively easy for controlled experiments
- More comprehensive for field tests (e.g. Lowlands)



Pedestrian tracking software

- Major problems due to occlusion, shape deformation, etc.
- Fusion of different data sources (multiple cameras, different types of cameras) seems appropriate direction (e.g. http://www.youtube.com/watch?v=otYOKYrZ6r4&feature=related)
- New data collection techniques (UAV's) will allow for more data on pedestrian behavior in the field

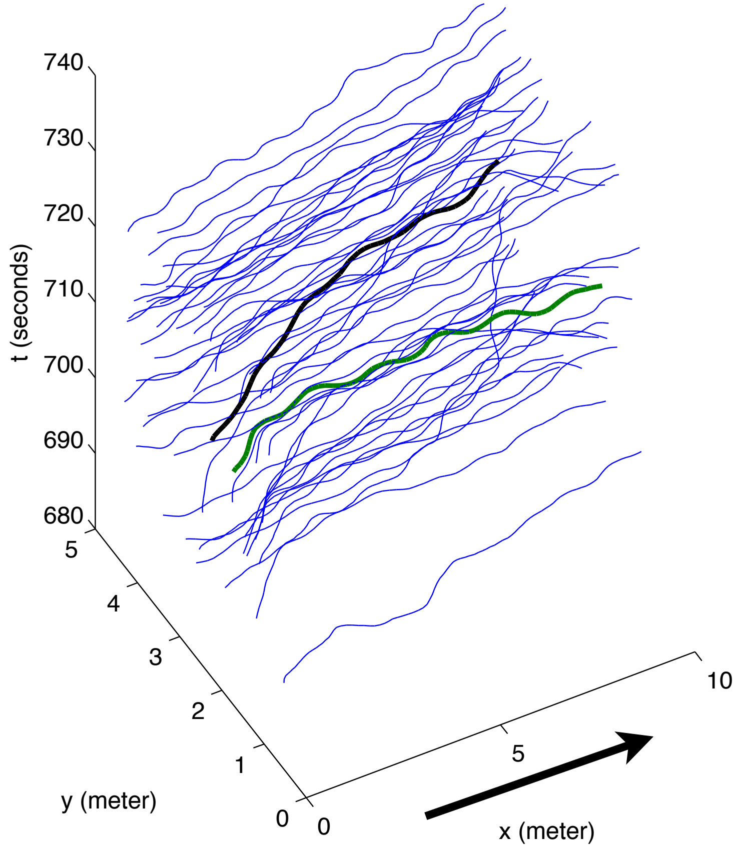
1.

Pedestrian Flow Variables

...flows, densities, speeds...

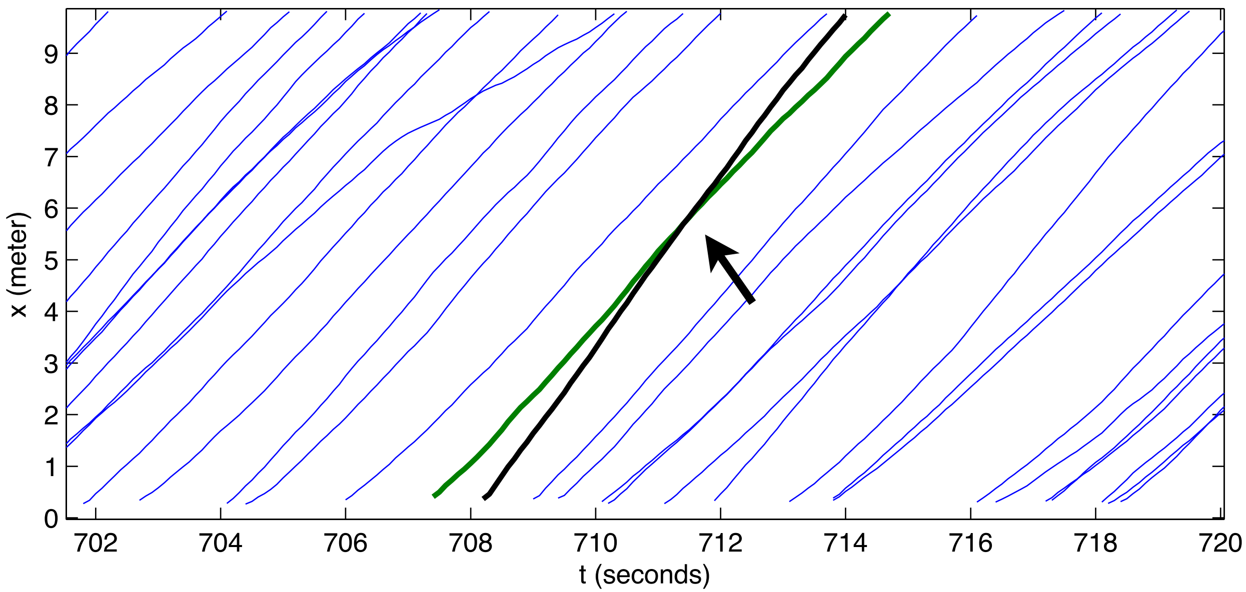
Microscopic flow variables

- Pedestrian trajectories $\vec{x}(t)$ describe position of a pedestrians as a function of t
- Example taken from TUD pedestrian experiments
- Projection of 2D movement onto main direction of motion yields regular trajectories in which overtakings / passings etc can be identified

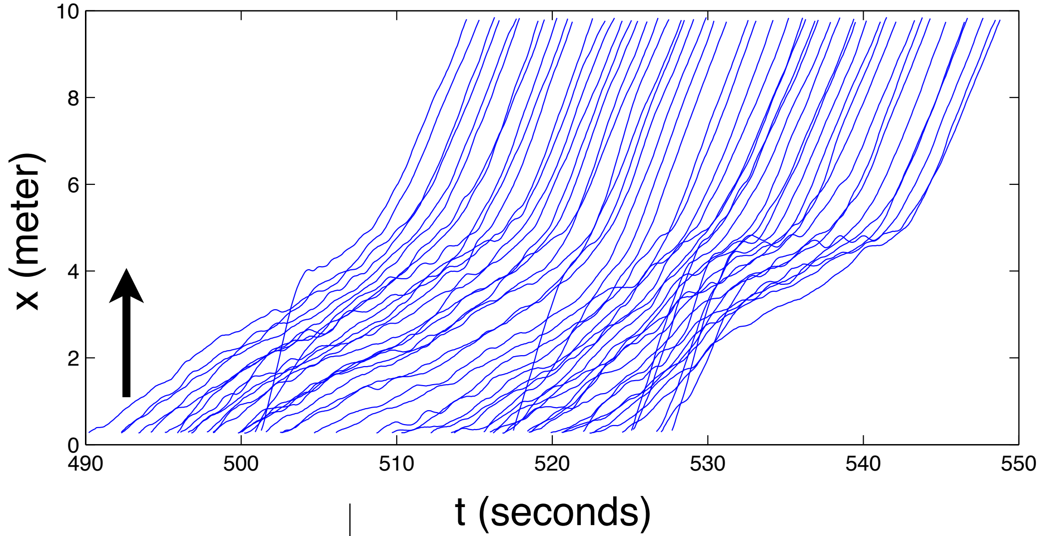


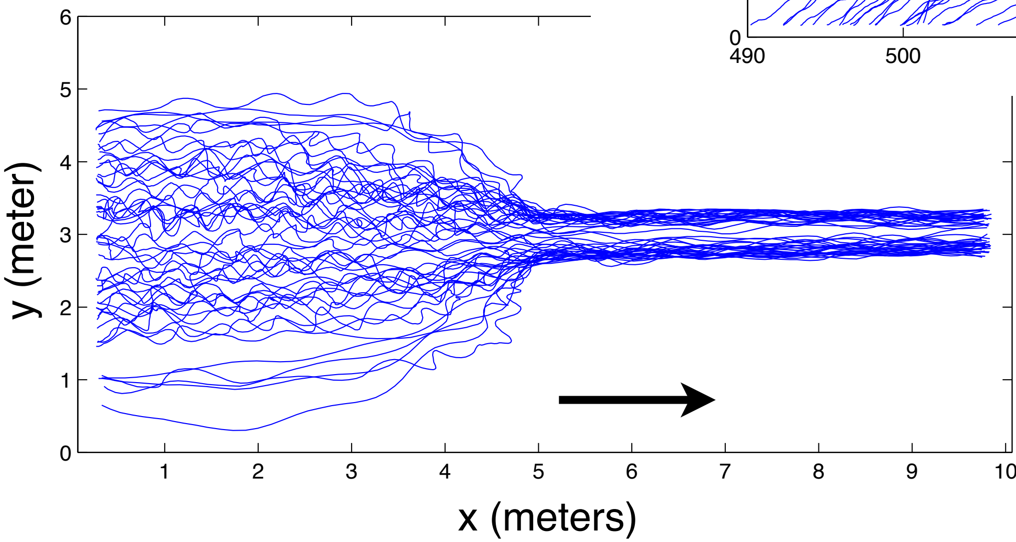
Microscopic flow variables

- Passing maneuver in xt-plane



Interpret the following projections





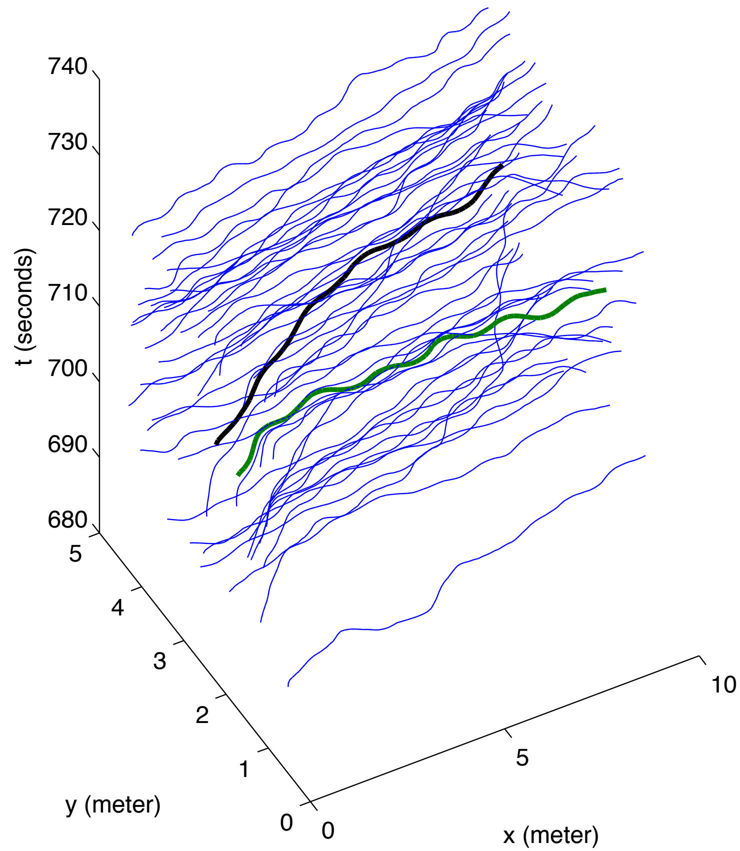
Microscopic flow variables

- How to define the following microscopic characteristics?
  - Speed (or velocity) of a pedestrian
  - Acceleration of a pedestrian
  - Time headway
  - Distance headway

- Can all of them be defined in a sensible way under all circumstances / in all situations?

Macroscopic flow variables

- **Density** is an instantaneous variable describing number of pedestrians in an area per unit area (P/m2)
- Which ‘cut’ to take?
- What are reasonable ranges for the density?
- Lets do a small experiment...



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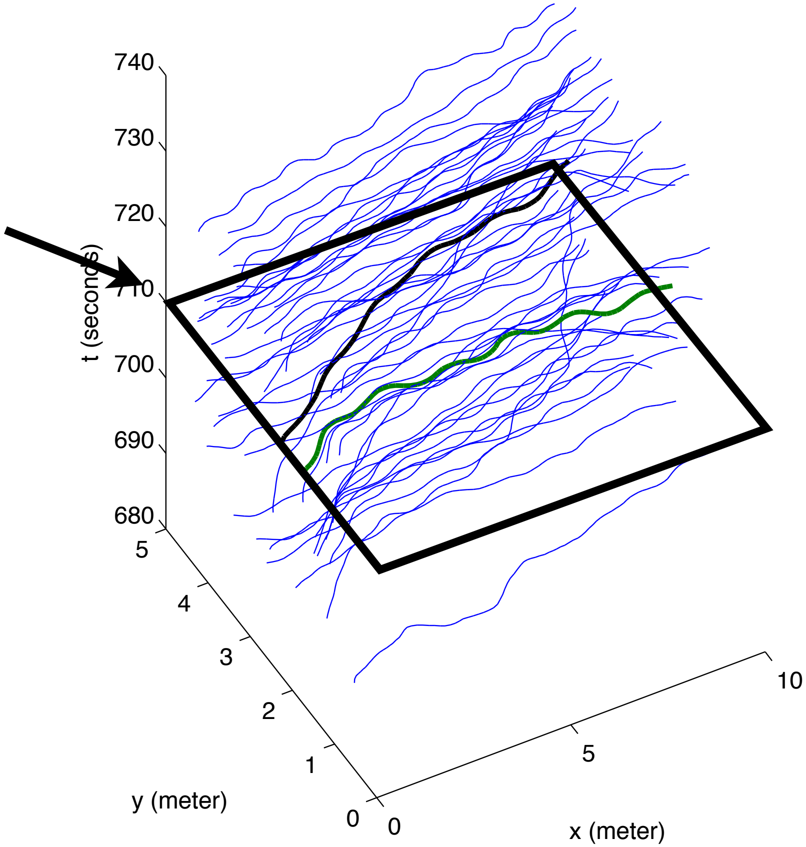
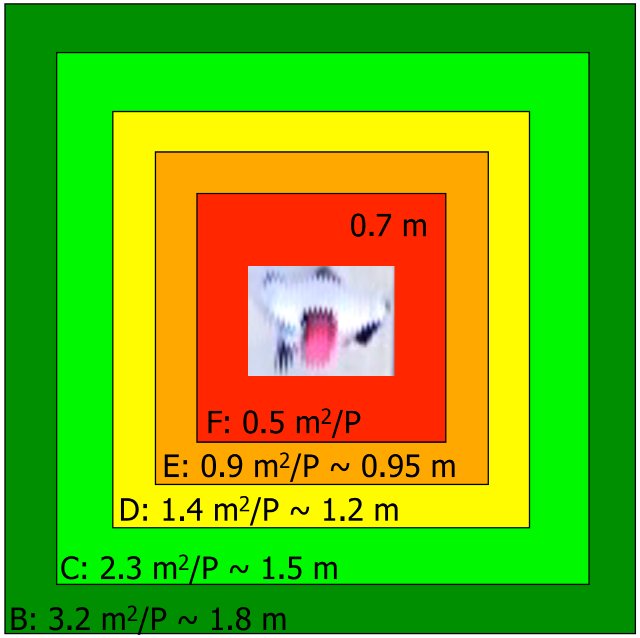
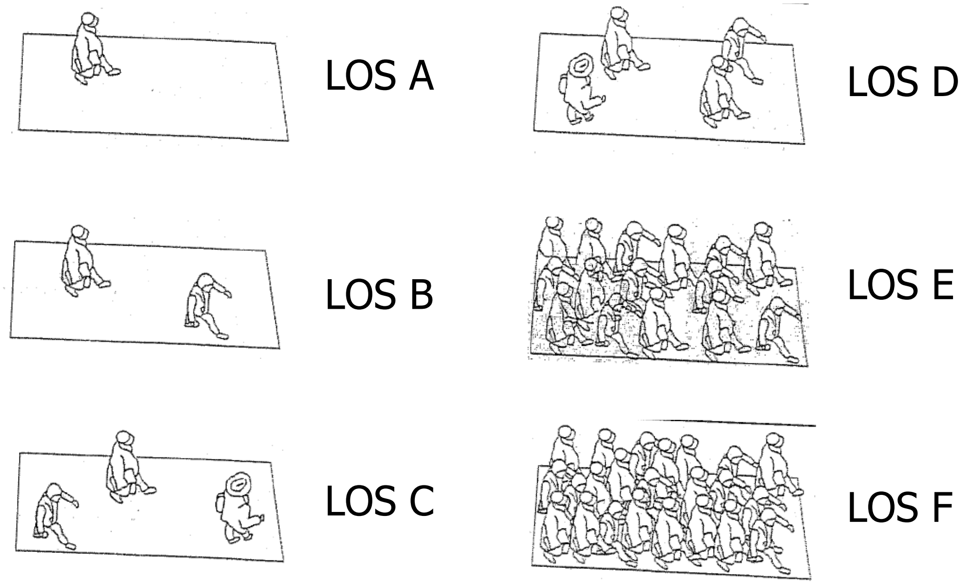


Use of Fundamental Diagram

- Service levels identification



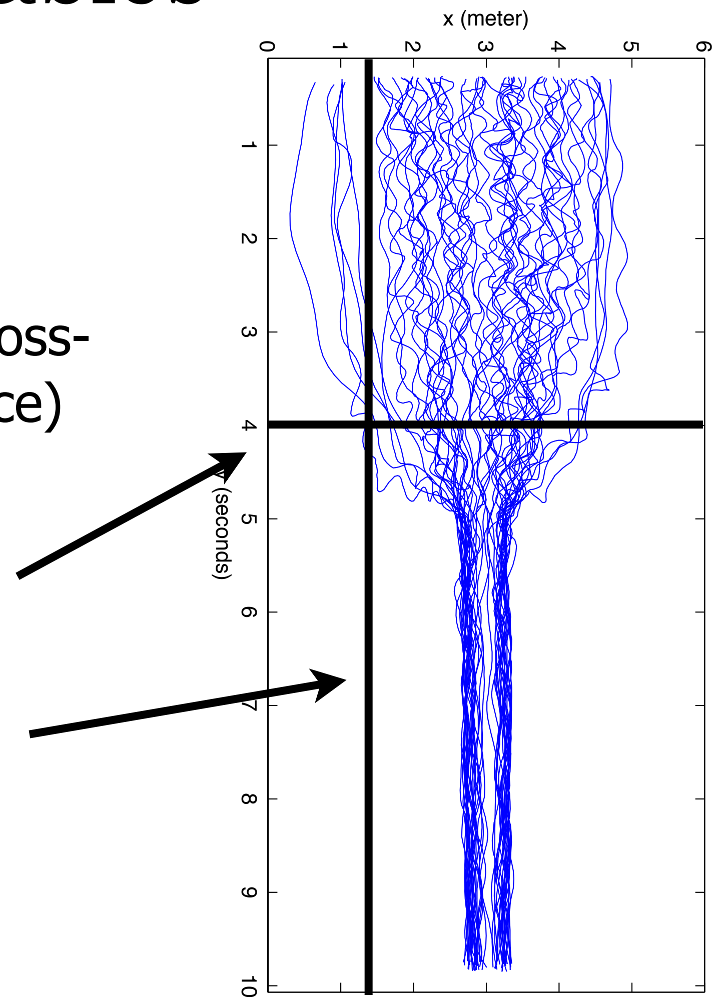


Macroscopic flow variables

- How can **flow** be defined?

Macroscopic flow variables

- How can **flow** be defined?
- Flow can be defined in relation to a cross-section (a line in two-dimensional space)
- Examples:
  - Flow in x-direction measured at cross-section at certain y
  - Flow in y-direction measured at cross-section at certain x
- Same definition as as for car traffic (# passages / time interval)



Macroscopic flow variables

- Flow at a location (x,y) thus has direction

$$\vec{q} = \begin{pmatrix} q_x \\ q_y \end{pmatrix} = q \cdot \vec{e}$$

- Questions:
  - How to interpret q_x and q_y?
  - Can flows be negative?
  - Does q = ku apply?
  - So, what about the speeds?
- What about two-dimensional or crossing flows?

Short note on directions...

- Pedestrian flows are multi-directional
- Per direction: flows, speeds, and densities can be determined sensibly according to the previous definitions

- Aggregation over directions is not trivial!
- Example:
  - Consider bi-directional flow with d = 1 (right to left), 2 (left to right)
  - We have determined flows for both direction
  - How can we determine the gross flow?

$$\vec{q} = \sum_{d=1,2} \vec{q}_d \,? \quad \text{or} \quad \vec{q} = \sum_{d=1,2} \left|\vec{q}_d\right| ? \quad \text{or} \quad ???$$

Micro-macro relation: exercise

- For car traffic, there is a strong relation between (average) micro and macro flow characteristics
- Do these relations also hold for pedestrian flows?

- How does $s = 1/k$ (average distance headway = 1 over density) translate to a pedestrian flows?

- What about $h = 1/q$ (average time headway = 1 over flow)?

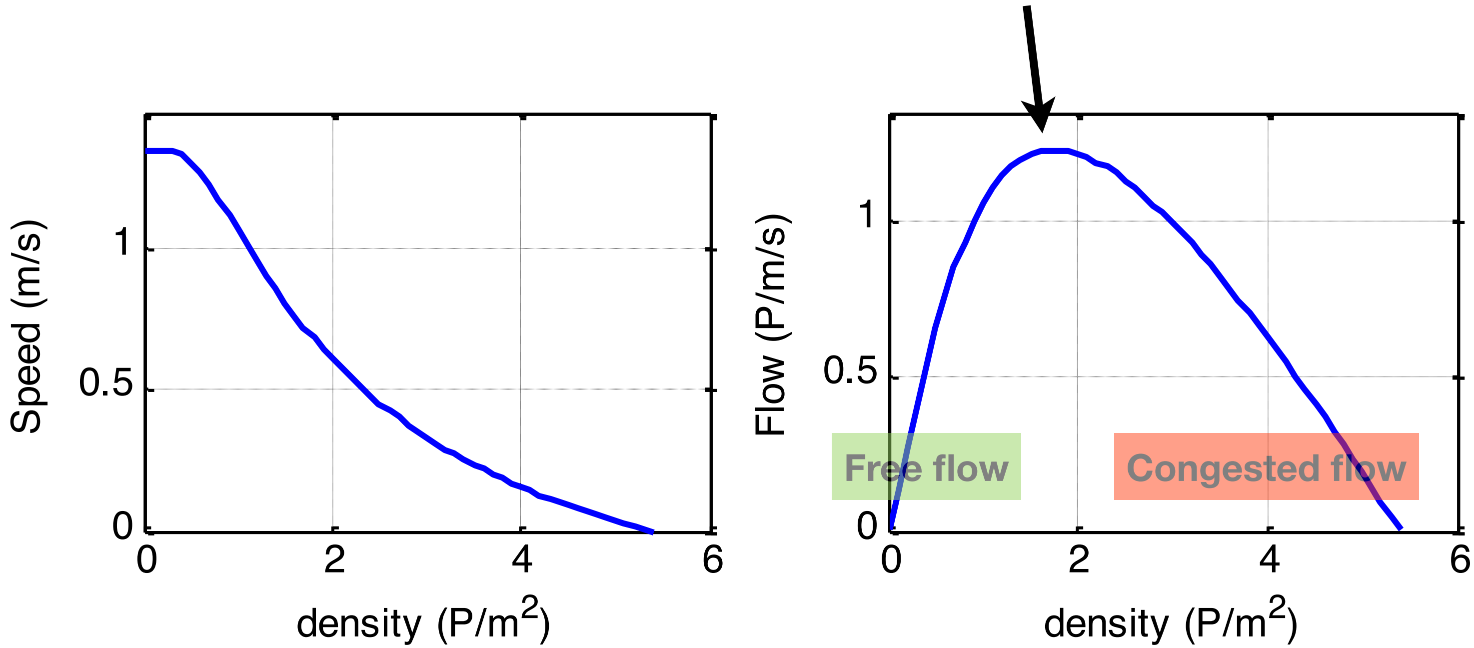
2.

Pedestrian Flow Characteristics

Capacity and Fundamental Diagram

Fundamental diagram of Weidmann

- Relation between (absolute) speed / flow and density
- How to interpret the maximum flow (1.22 P/m/s)?



Behavioral interpretation of FD?

- Car fundamental diagram has a ‘clear’ microscopic interpretation:
  - The larger the speed, the more distance drivers maintain with respect to each other, e.g.:

$$\frac{1}{k} = s(v) = s_0 + T \cdot v$$

- What about the pedestrian fundamental diagram?

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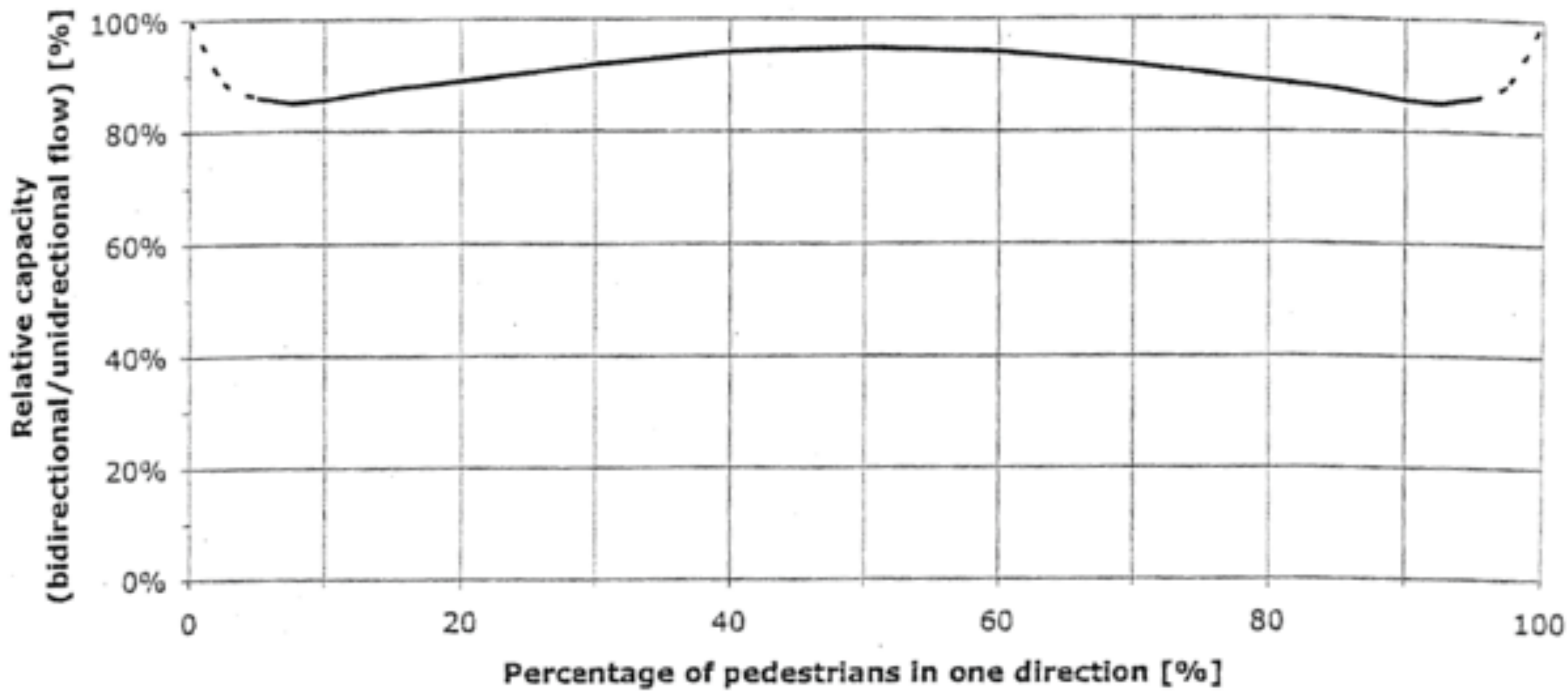
- What about the pedestrian fundamental diagram?
- Let A be the average area needed by a pedestrian walking at speed v, then:

$$\frac{1}{k} = A(v) = A_0 + T \cdot v$$

Impact of direction on capacity

- Effect of directional composition on capacity is small (<16%)



Factors affecting the FD?

- Which other factors will influence the fundamental diagram and its parameters (capacity, jam-density, etc.)?

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- Flow composition
  - Age, gender,
  - Walking purpose (e.g. leisure, commuting, shopping)

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- Flow composition
  - Age, gender,
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- Walking infrastructure
  - Surface inclination
  - Stairs

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  - Age, gender,
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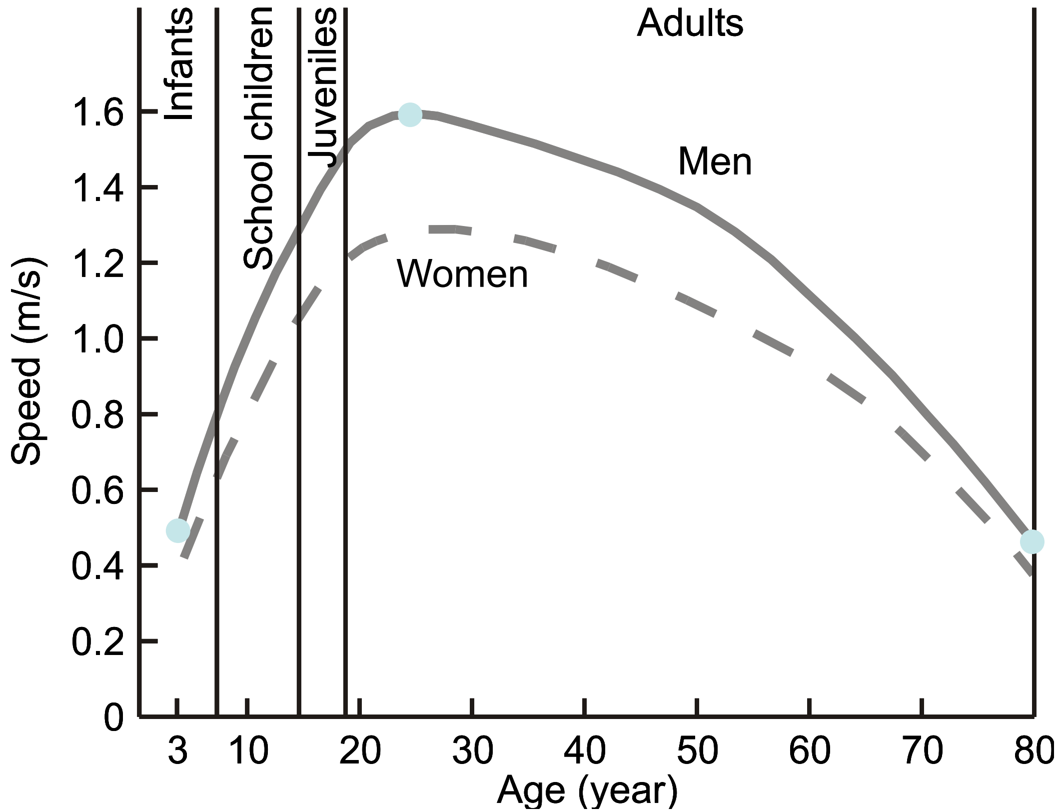
- Walking infrastructure
  - Surface inclination
  - Stairs
- Environment
  - Temperature, weather conditions

Example: impact of gender and age



Example: capacity analysis

- Investigate door capacity values for building regulations
- Performed controlled experiments to investigate impact of flow composition, ambient conditions, width of opening, presence of door, time pressure, etc
- Capacity relation determined:

$$C = 2.69 + 1.06 \cdot P_C - 0.21 \cdot P_E - 2.13 \cdot P_D$$
$$-0.01 \cdot \text{Stress} - 0.12 \cdot \text{Width} - 0.18 \cdot \text{Door} + 0.09 \cdot \text{Light}$$

Fundamental diagram Hajj

- Measured flow-density relation at Jamarat bridge

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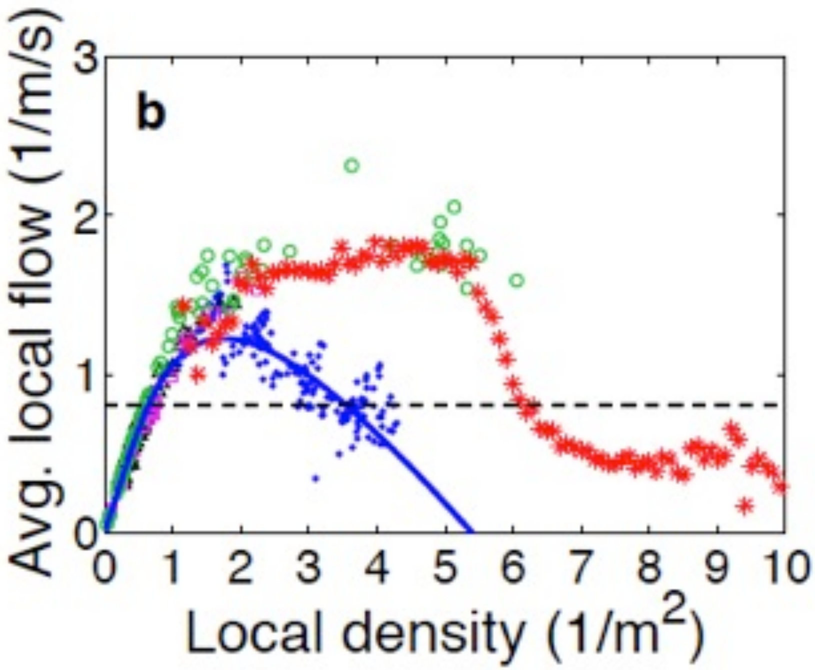
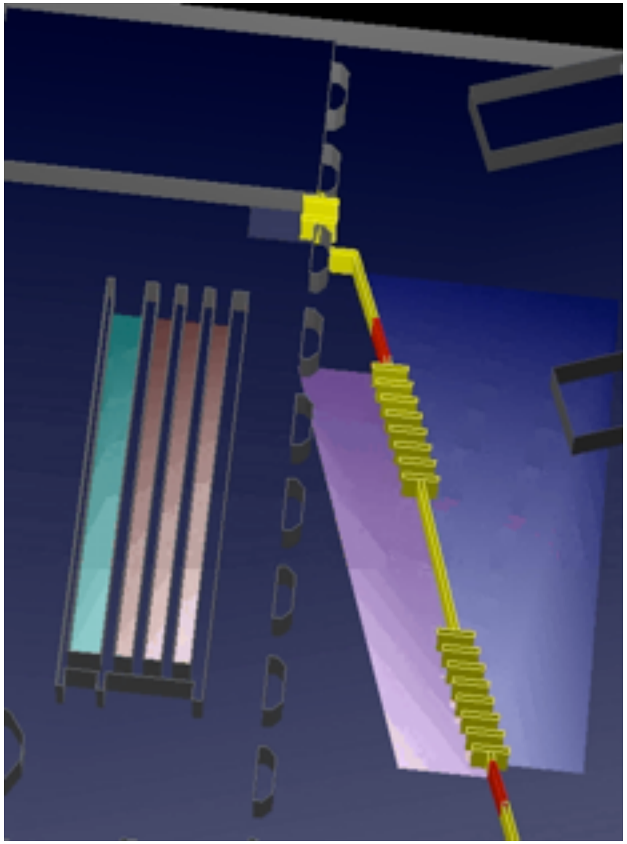


Pedestrian crowds

- Existence of new ‘turbulent’ traffic state:
  - Dynamics of flow are governed by physical interactions
  - Density is extremely high (8-10 P/m2)
  - Pedestrians move uncontrolled in multiple directions
  - Pressure on pedestrians can be very high, situation is very dangerous

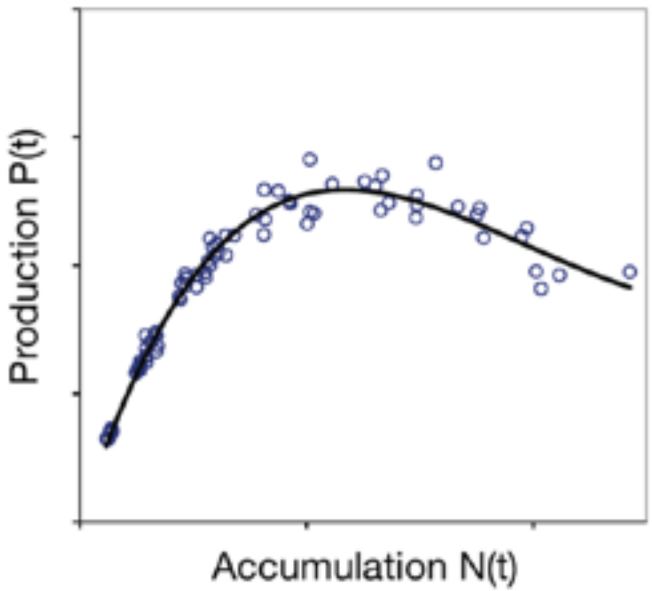
Photo by James Cridland on Flickr.com / CC BY

Network fundamental diagram?



NOMAD Animatiion by verkeerskunde.nl

- Behavior of ped flows in networks
- Relation between production and accumulation



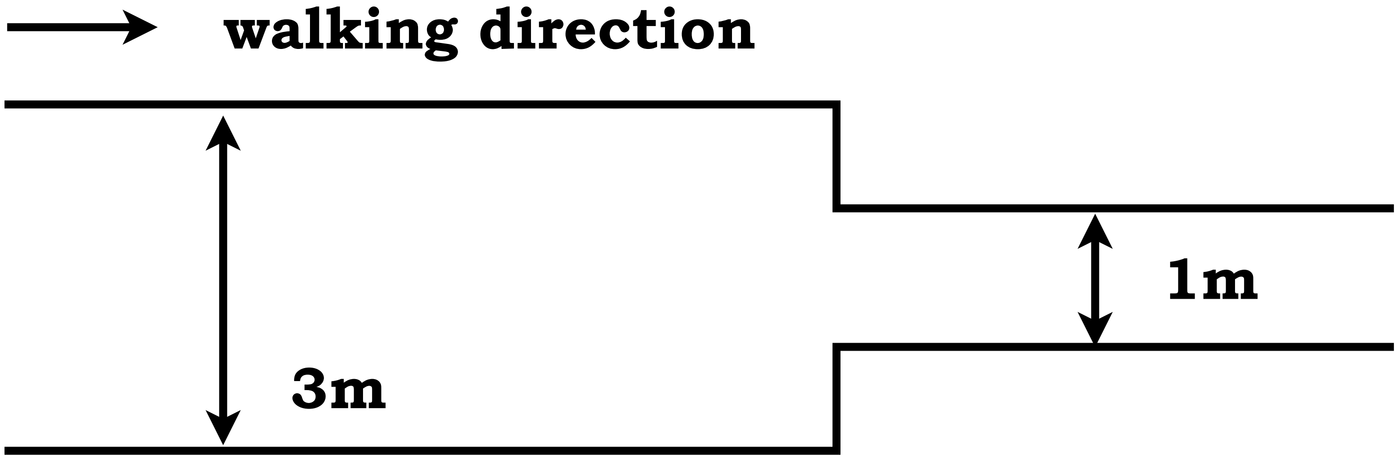
3.

Macroscopic Flow Models

...shockwave and kinematic wave theory...

Overloaded narrow bottleneck

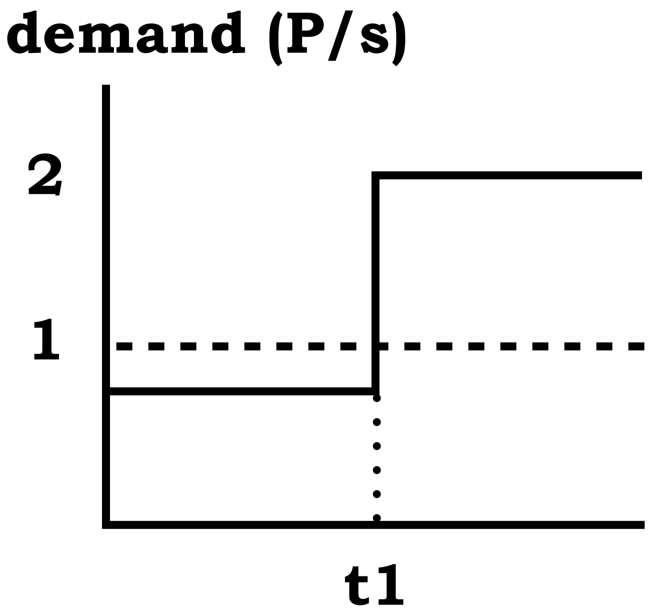
- Consider a narrow bottleneck situation (similar to experiments)



- Daganzo FD with $C = 1$ P/m/s, $v^0 = 1$ m/s and $k_{jam} = 5$ P/m^2
- Assume homogeneous distribution of density over width of area

Overloaded narrow bottleneck

- Assume following demand profile
- What happens when bottleneck is oversaturated?
- Sketch some pedestrian trajectories
- Can you also plot there y-position as a function of time?



Conservation of pedestrians

- Derivation of conservation equation is equivalent to one dimensional car flow
- Conservation of pedestrian equation (possibly per direction d):

$$\frac{\partial k}{\partial t}+\frac{\partial \vec{q}}{\partial x}+\frac{\partial \vec{q}}{\partial y}=0$$

- First-order pedestrian theory: pedestrians behave according to the fundamental diagram, i.e.:

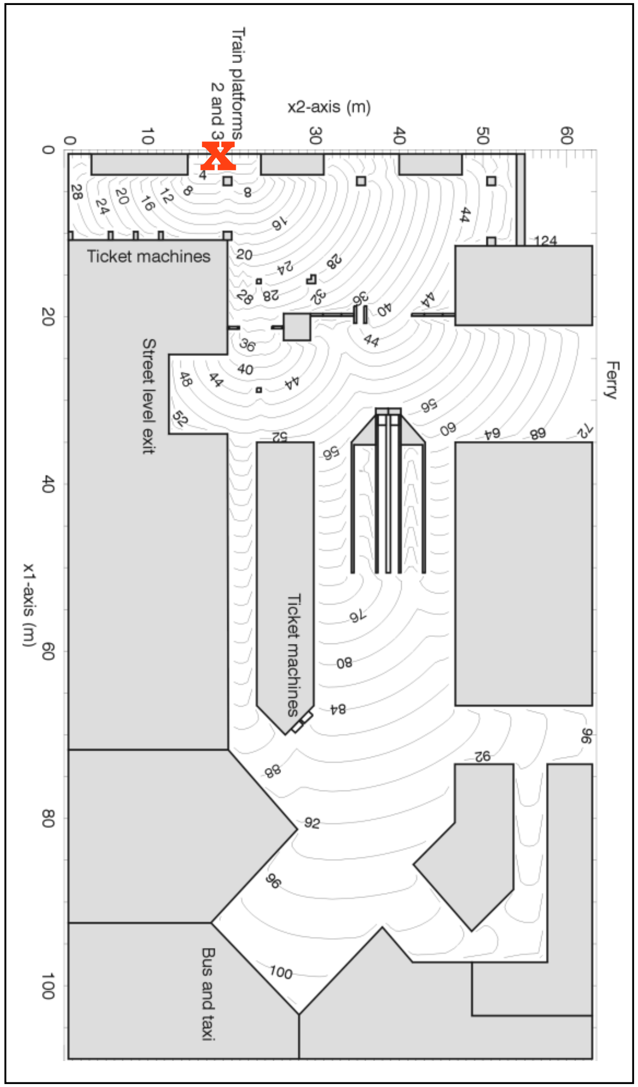
$$q=Q(k)=k\cdot U(k)$$

- Is this a complete model?

Including direction

- Additional assumption: direction at (x,y) determined by minimizing distance / walking time to destination
- Example shows iso-walking time curves to location ‘x’
- Direction perpendicular to these lines (steepest descent path)
- For all math lovers:

$$\vec{e}(x,y) = \frac{\nabla D(x,y)}{\| \nabla D(x,y) \|}$$



Completing the KW model for peds

- Information about the walking direction completes the pedestrian Kinematic Wave model:

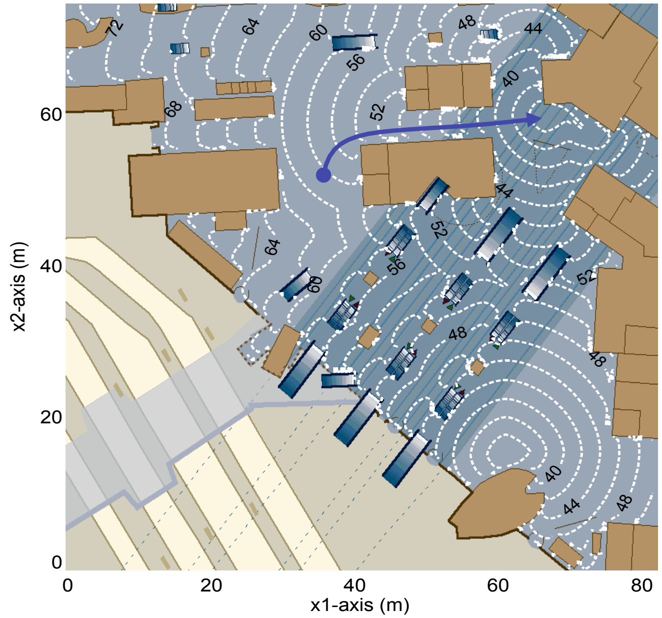
$$\frac{\partial k}{\partial t} + \frac{\partial \vec{q}}{\partial x} + \frac{\partial \vec{q}}{\partial y} = 0 \quad \text{with} \quad \vec{q} = Q(k) \cdot \vec{e}(x,y)$$

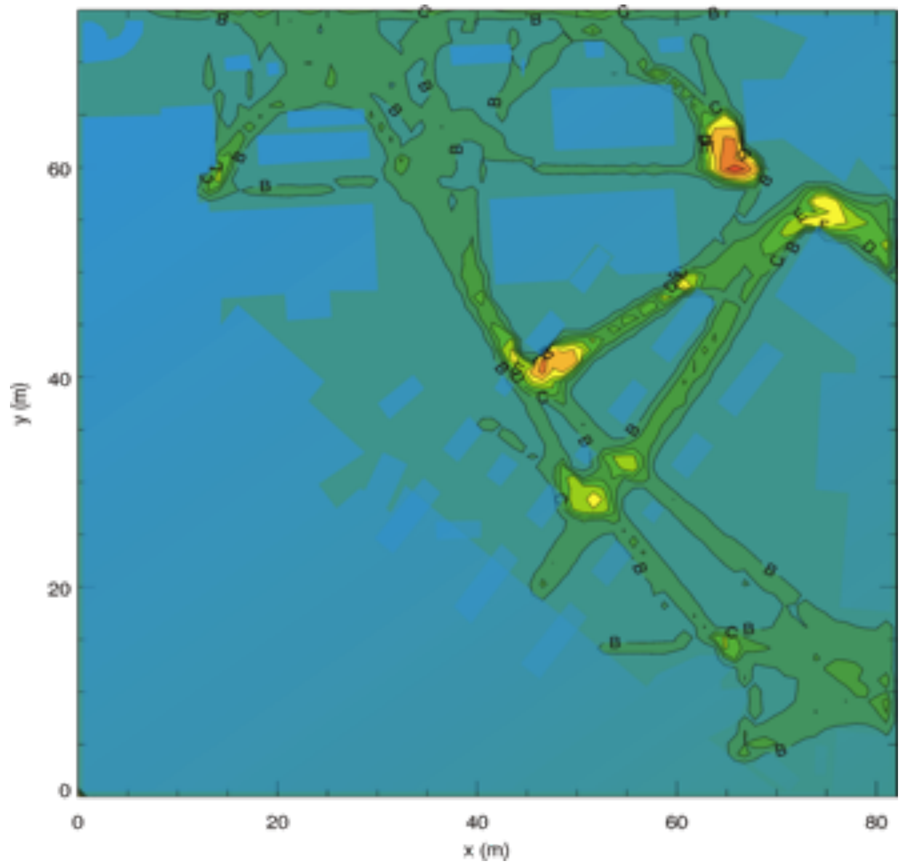
- Additional PDE describing the optimal direction

- Basis for DTA model describing optimal direction as a continuous function of time and space (Hughes,2004), (Hoogendoorn,2004)

Example application

- Pedestrian flows in Schiphol Plaza





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Empirical features of pedestrian flow

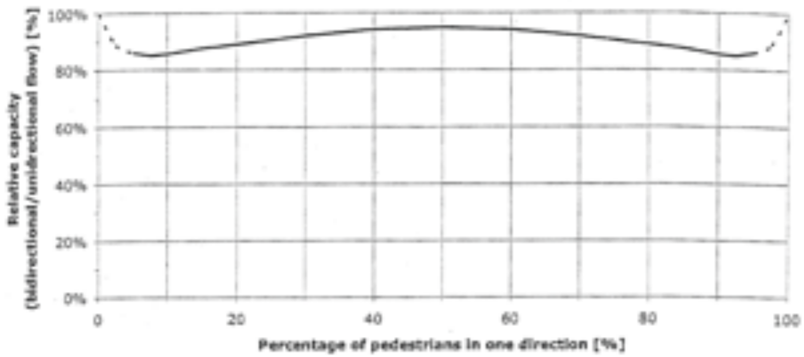
...self-organized features

Capacity for bidirectional flows...

- Would you expect the capacity reduction to be so small?

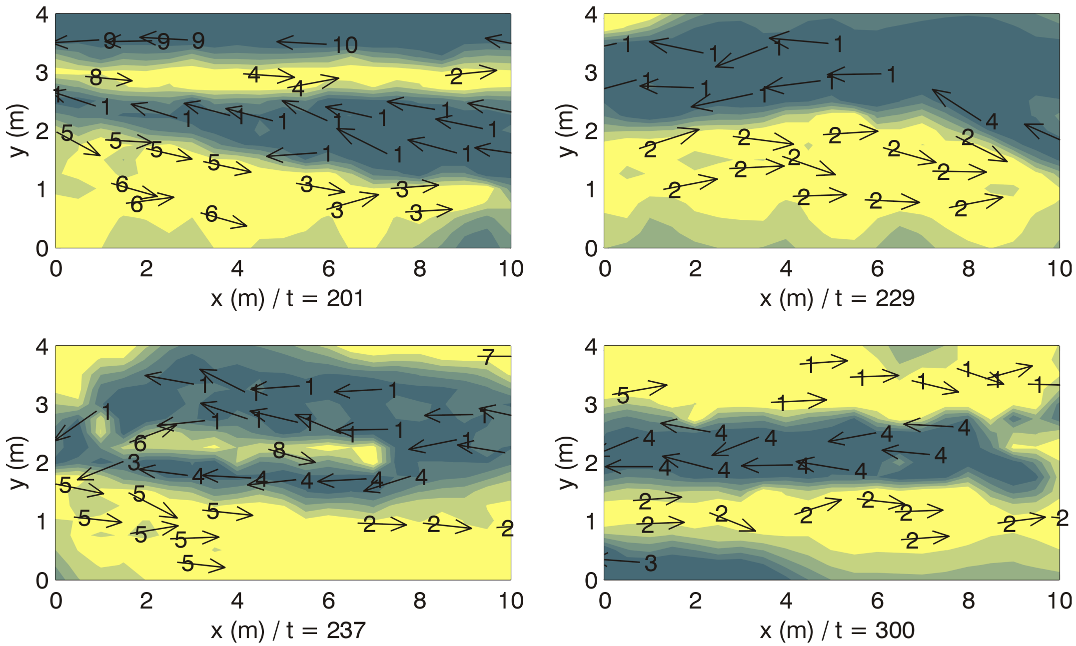
- Lets discuss an explanation...

- What can we observe in our experiment?



Self-organization in pedestrian flow

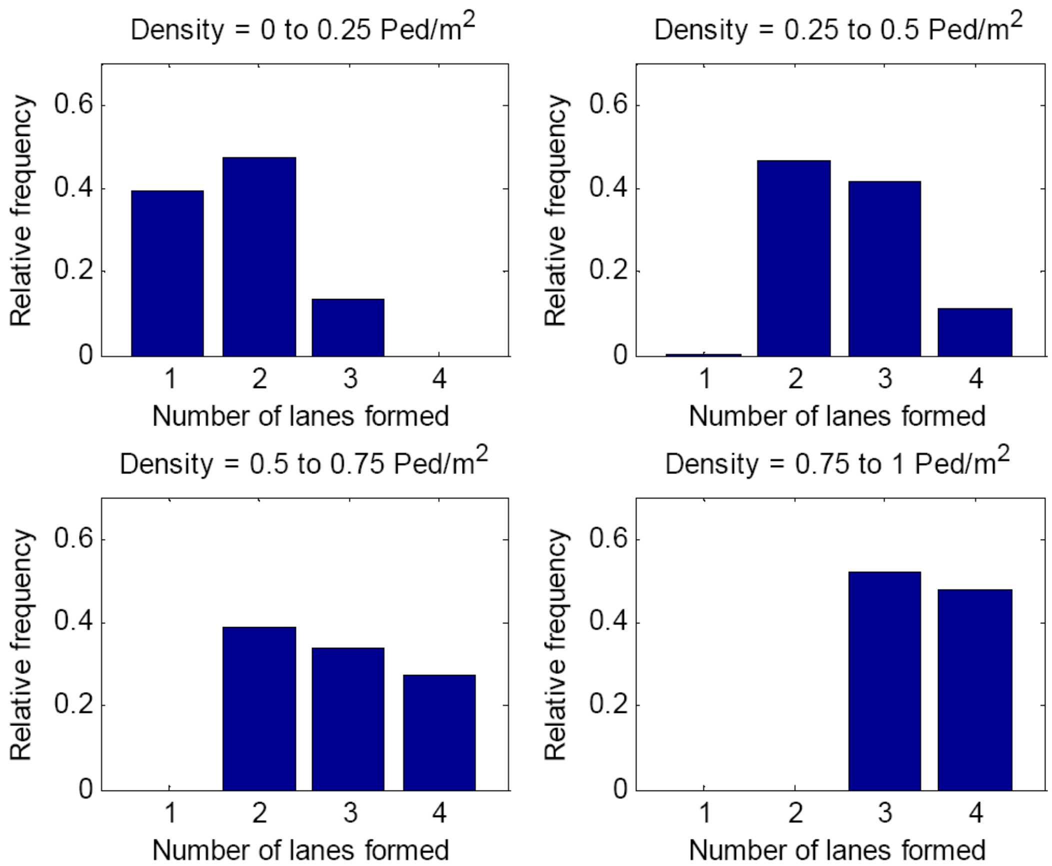
- Specific traffic states appear to self-organize in pedestrian flow
- Example: self-organization of lanes in bi-directional flows



Lane formation process

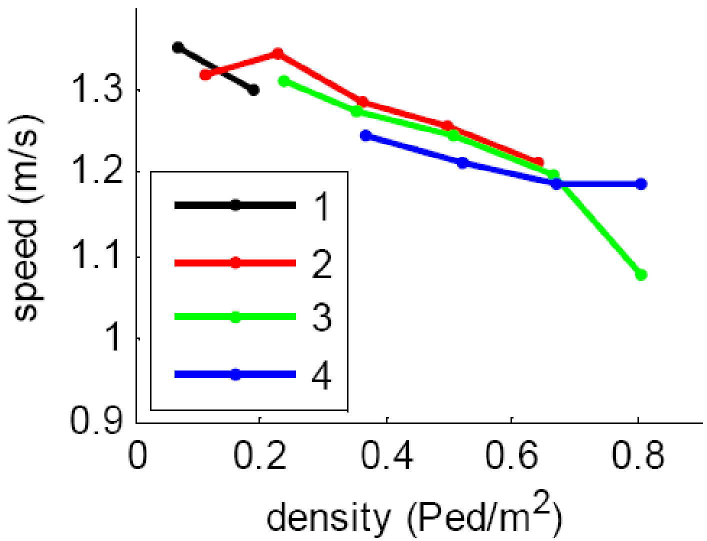
- Number of lanes formed depends on density
- Example shows probably of n-lanes being formed for different density regimes

- What happens at very high densities?



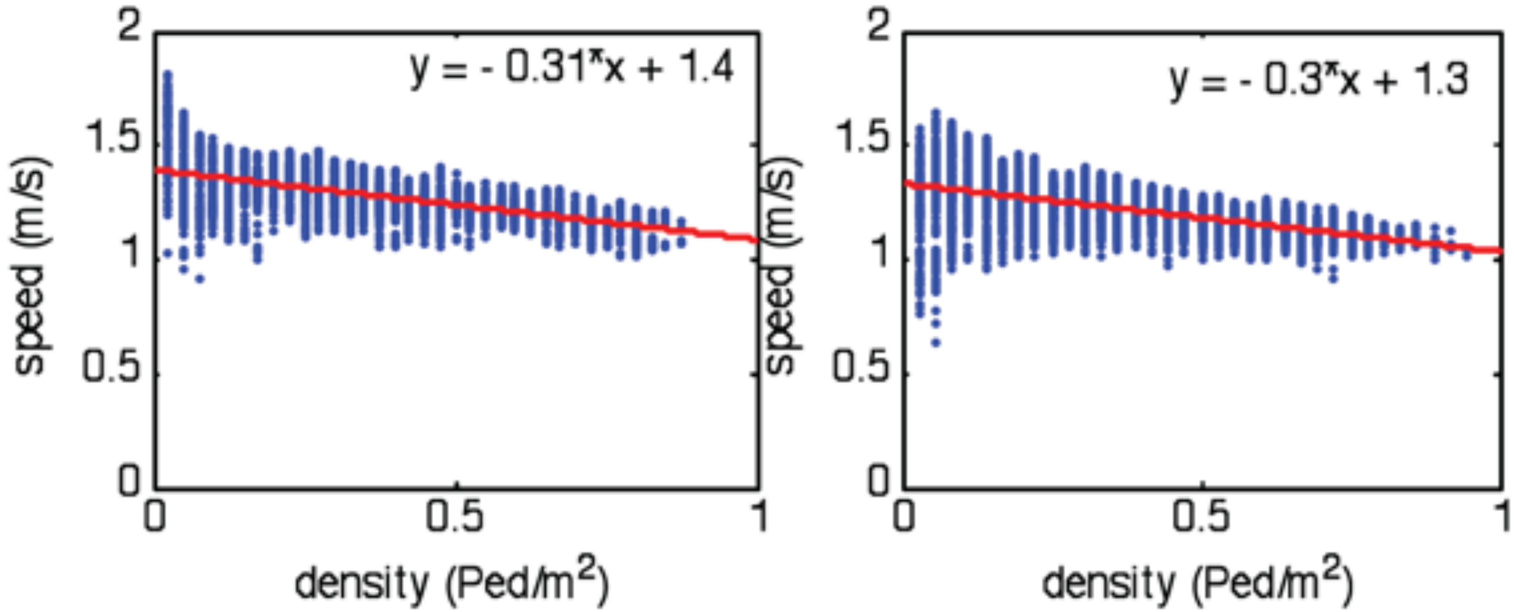
Efficiency of self-organized patterns

- Speed-density relation for different # lanes
- Small reduction in average speed visible for larger lane number

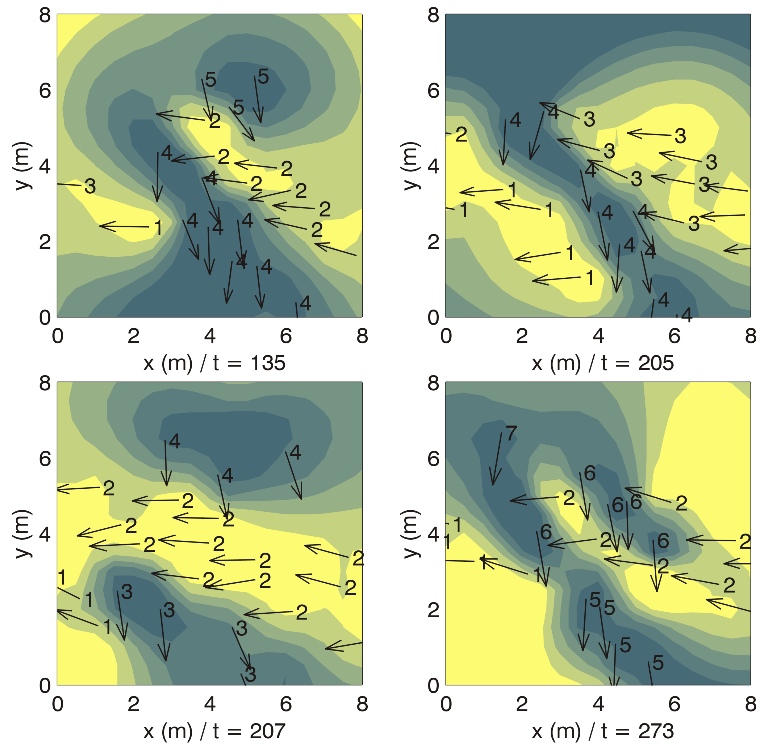


Efficiency of self-organized patterns

- Fundamental diagrams for uni-directional and bi-directional flows
- Which is which?



Crossing flows: diagonal stripes



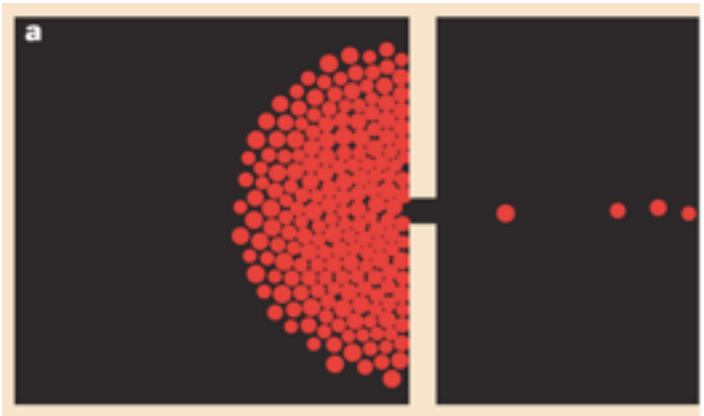
End to efficient self-organization

- When density becomes too large, self-organization stagnates
- Phase transition occurs from efficient free flow to congested flow

Photo by Henk-Jand van der Klis on Flickr.com / CC BY NC ND

Faster is slower effect

- Increasing (time-) pressure causes severe reduction in capacity due to arc formation
- Keep density below critical density to keep flow running smoothly



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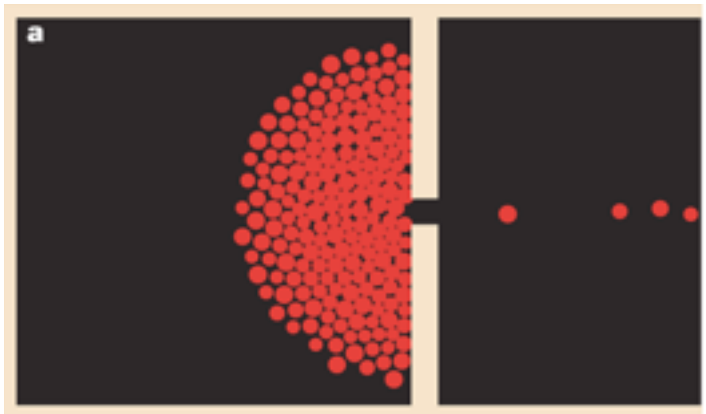

Preventing the capacity drop

- Main cause of capacity drop for pedestrians is arc formation due to high pressure
- How to reduce this effect?

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5.

Microscopic Simulation Models

...Social Forces and other models

Developing walker models

- Suppose we want to develop a model describing the acceleration as a continuous function of time, i.e.

$$\vec{a}_i(t) = \vec{f}(\ldots)$$

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- Considered aspects in Social Forces model:
  - Pedestrians aim to walk at free speed into their desired direction
  - Pedestrians try to maintain sufficient distance from the pedestrian in front of them

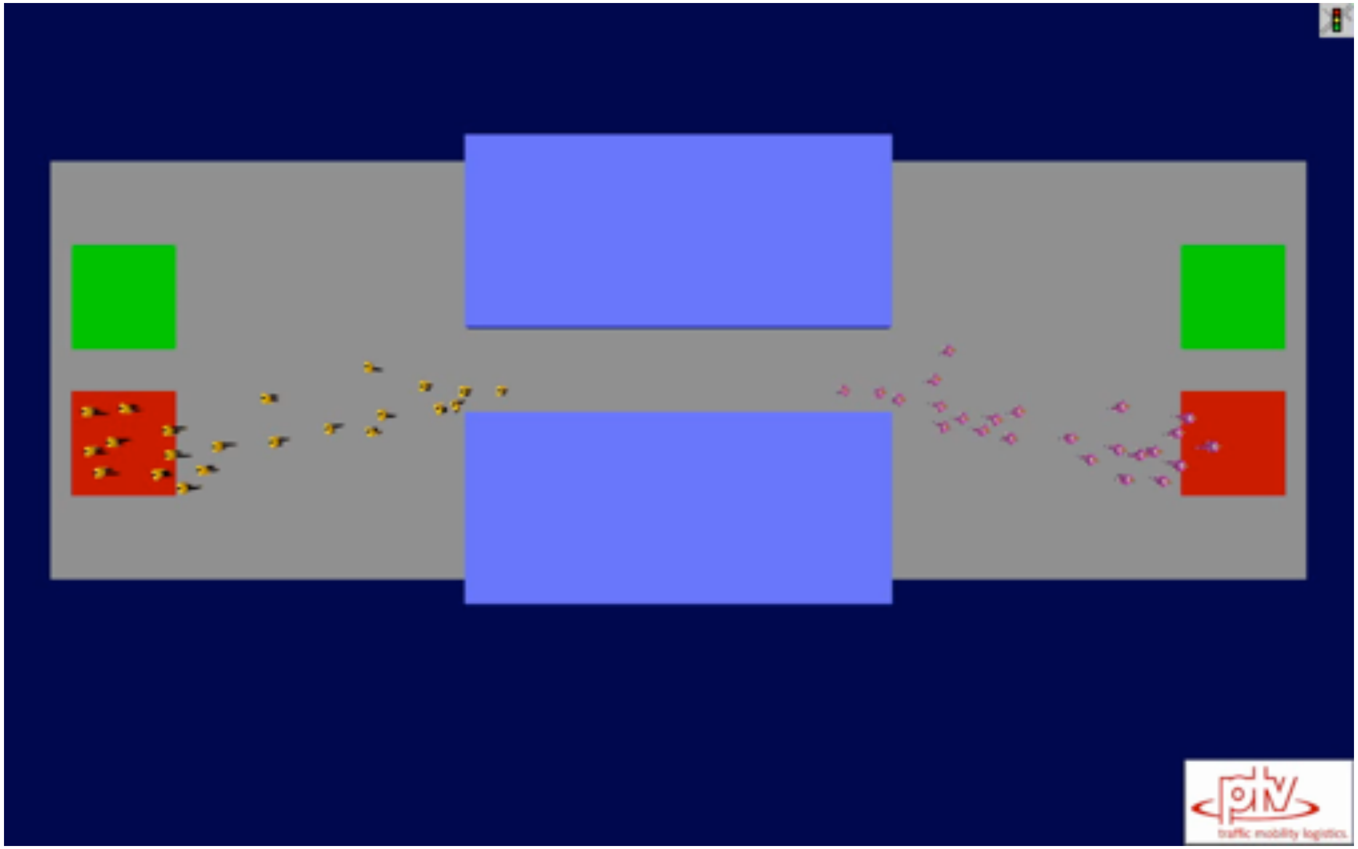
Basic social forces model

- Acceleration can be written as following function:

$$\vec{a}_i(t) = \frac{\vec{v}^0 - \vec{v}_i(t)}{\tau} + A_0 \sum_{j \text{ in front of i}} \frac{\vec{x}_j - \vec{x}_i}{\| \vec{x}_j - \vec{x}_i \|} e^{-\frac{\| \vec{x}_j - \vec{x}_i \|}{R_0}}$$

- Interpret the two main terms
- Desired properties of the model?
  - What will happen when differences between desired speed and actual speed becomes larger?
  - What will happen when the distance between two pedestrians becomes very small?

Model validity



Extented social forces model

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- Pedestrians are described like 'squash balls'
  - They are compressible!
  - When compressed, strong forces are exerted in normal direction
  - Strong frictional forces apply in case of speed differentials

Extented social forces model

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  - Strong frictional forces apply in case of speed differentials

Extented social forces model

- What is missing in the model?

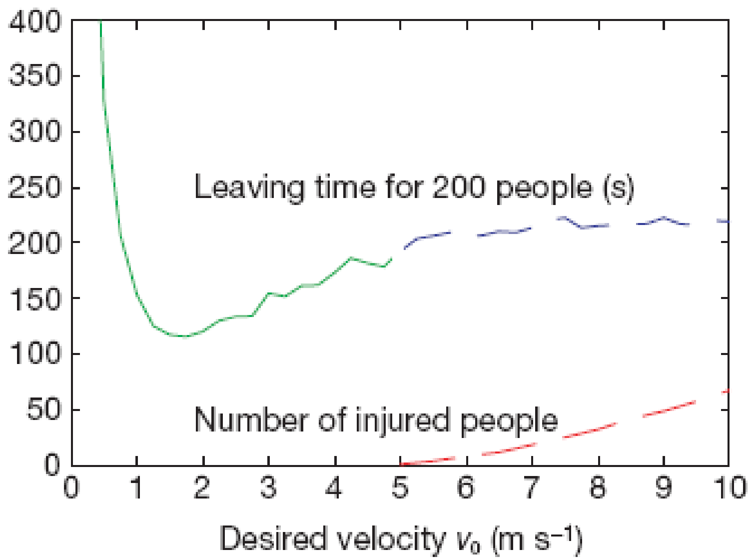
- Inclusion of physical interactions

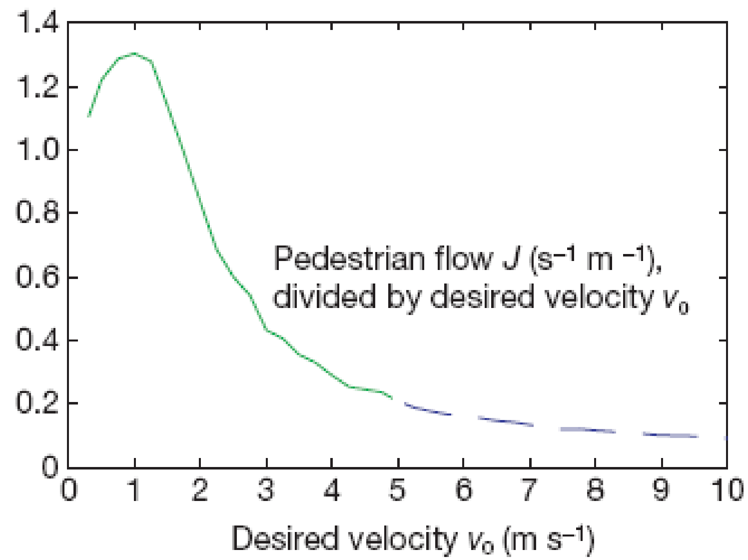
- Pedestrians are described like ‘squash balls’
  - They are compressible!
  - When compressed, strong forces are exerted in normal direction
  - Strong frictional forces apply in case of speed differentials

- Inclusion of physical forces results in ‘faster-is-slower’ effect (Nature paper of Helbing)

Evacuation from a room

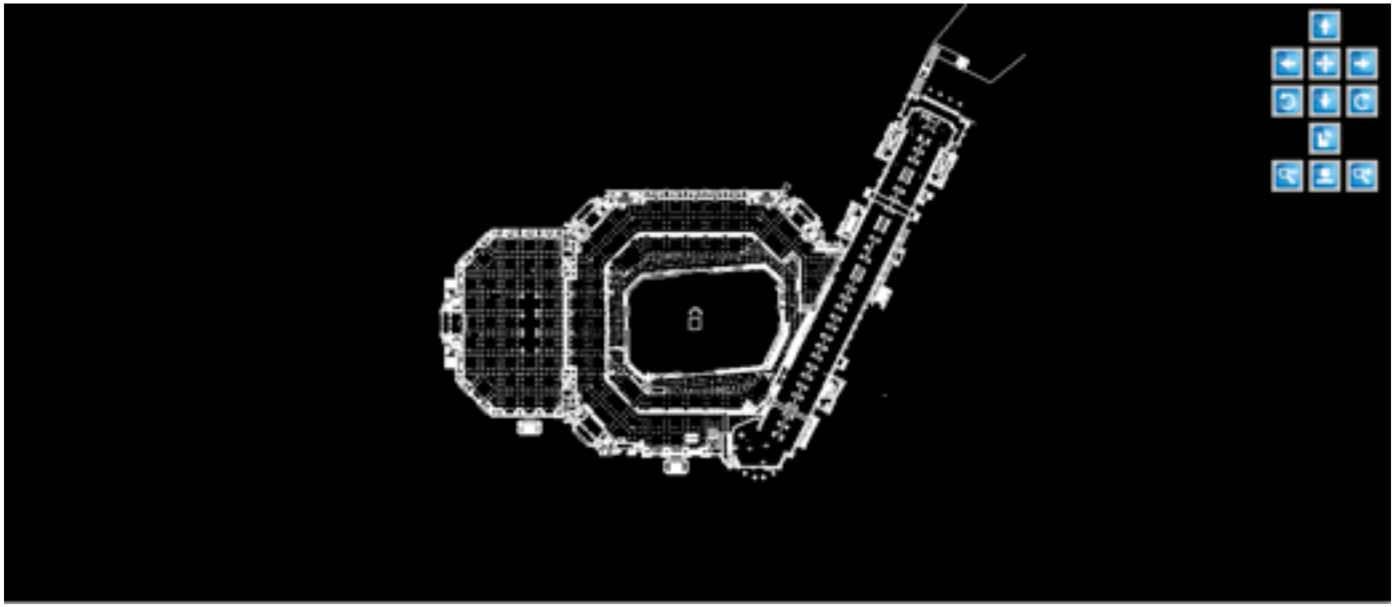
- Results from evacuation simulation experiment using social forces model show impact of arc formation of evacuation times
- Note: free speed = proxy for haste





Alternative microscopic models

- NOMAD model based on pedestrian economicus (Hoogendoorn)
- Models based on discrete choice approach (Bierlaire)
- Cellular Automata models (Mahmassani)



Aim of this lecture

- After lecture you should be able to:
  - Understand key differences between pedestrian and vehicular flow
  - Understand / apply concepts of flow, density, speed to ped flows
  - Interpret and use pedestrian fundamental diagrams
  - Apply shockwave theory to simple situations
  - Know key self-organized features in pedestrian flow
  - Understand key features of microscopic pedestrian models and interpret equations

- Interested in pedestrian flow? Check http://www.uitzendinggemist.nl/afleveringen/1114481/afleveringen?page=9