Pedestrian Flow Modelling

From data to models, from micro to macro...

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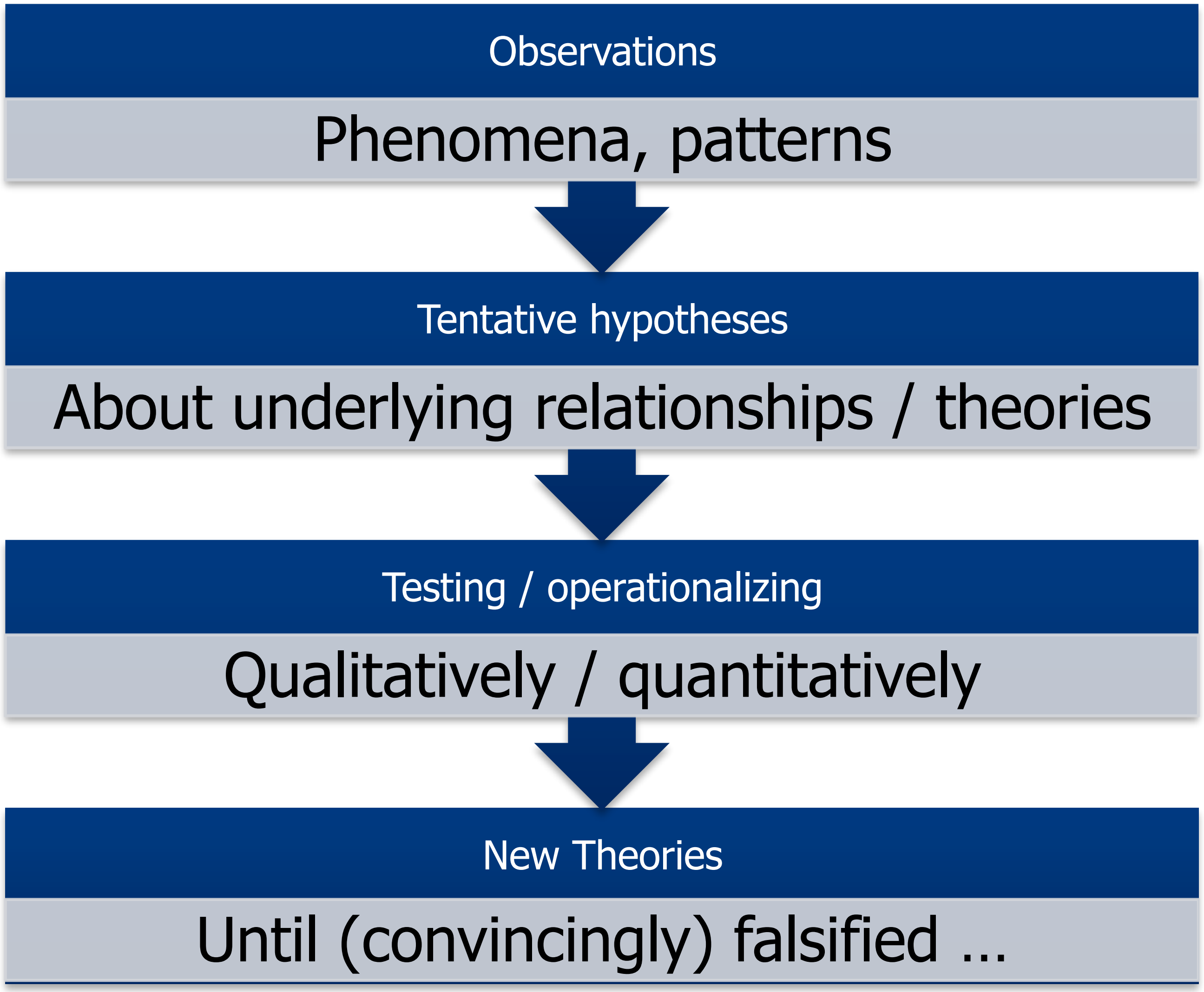
Importance of data!

- Pedestrian flow theory is by and large an inductive science
- Importance of data (and data collection) cannot be overstated
- Collect data to:
  - Identify key features, **phenomena (queuing, lane formation, etc.)** in pedestrian flow operations
  - Quantify **flow characteristics and relations (e.g. FD)**
- These form basis for theories, mathematical models & simulation

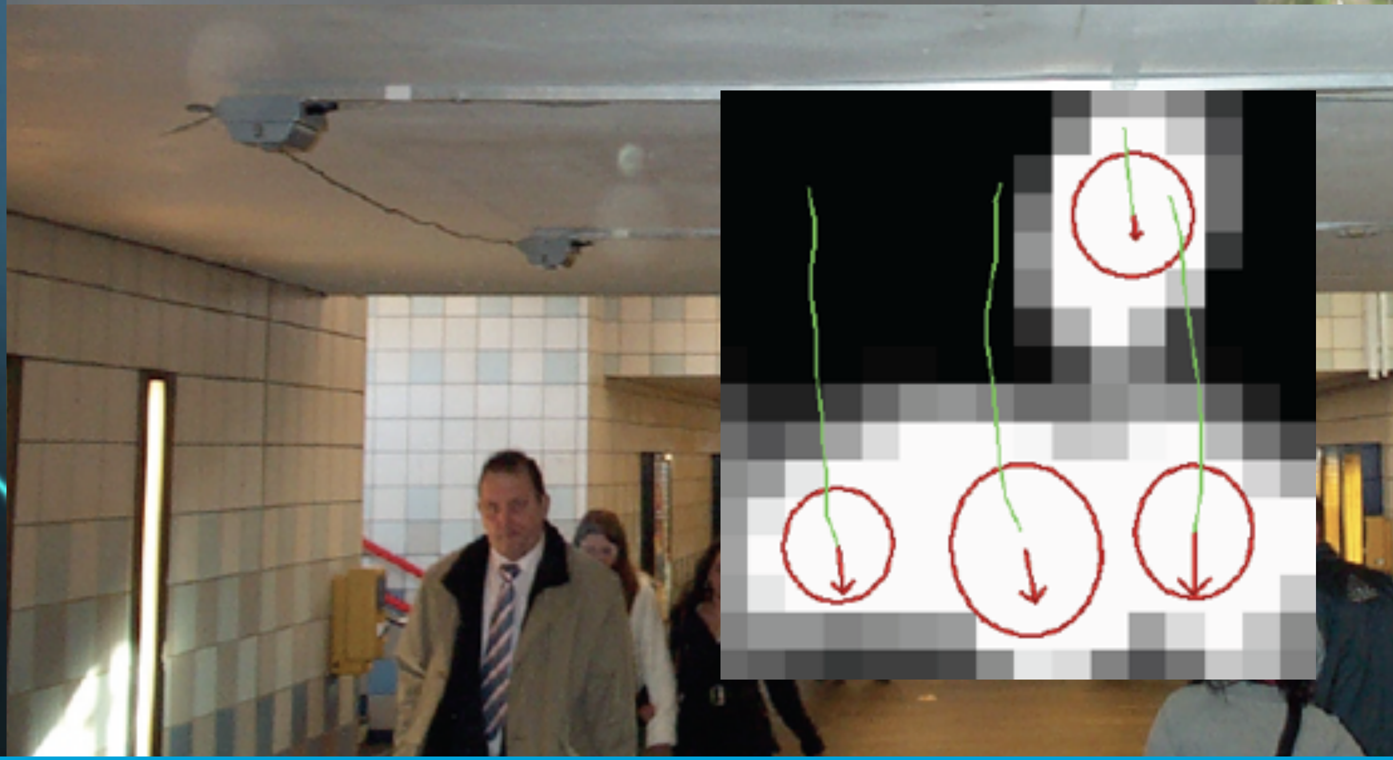


Pedestrian Flow Theory

From empirical facts to theory

Importance of data collection in inductive sciences…





Examples data collection efforts TU Delft

Field observations, controlled experiments, virtual laboratories

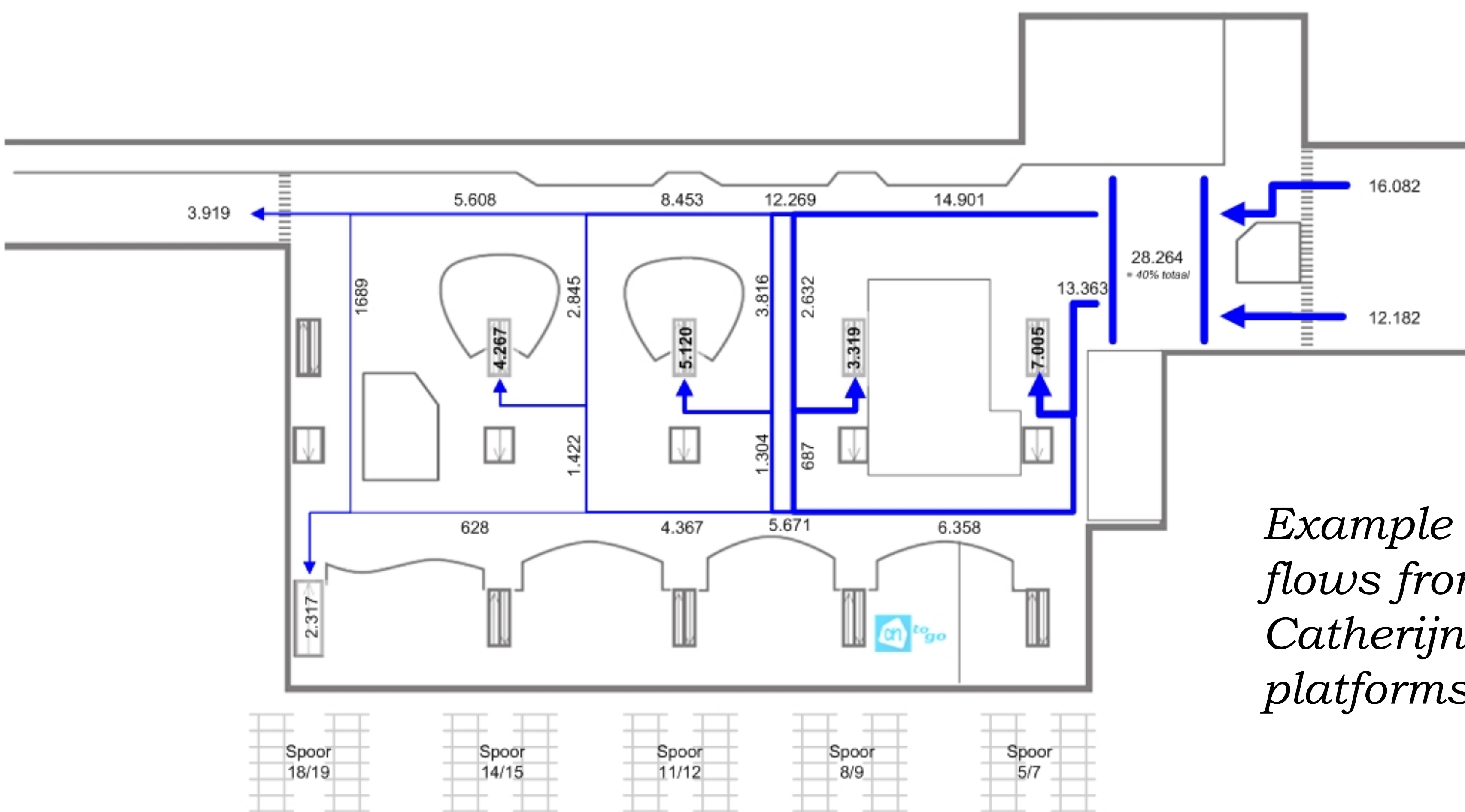
Data collection remains a challenge, but many new opportunities arise!

New Technology for Data Collection

Combination of data sources lead to new insights!

SmartStation concept (Jeroen vd Heuvel, NS Stations)

- Combination of cameras and BT/Wifi scanners to monitor pedestrian flows
- First results on using these data for route / location choice modelling



Example shows route flows from Hoog Catherijne to train platforms and exit

Empirical characteristics and relations

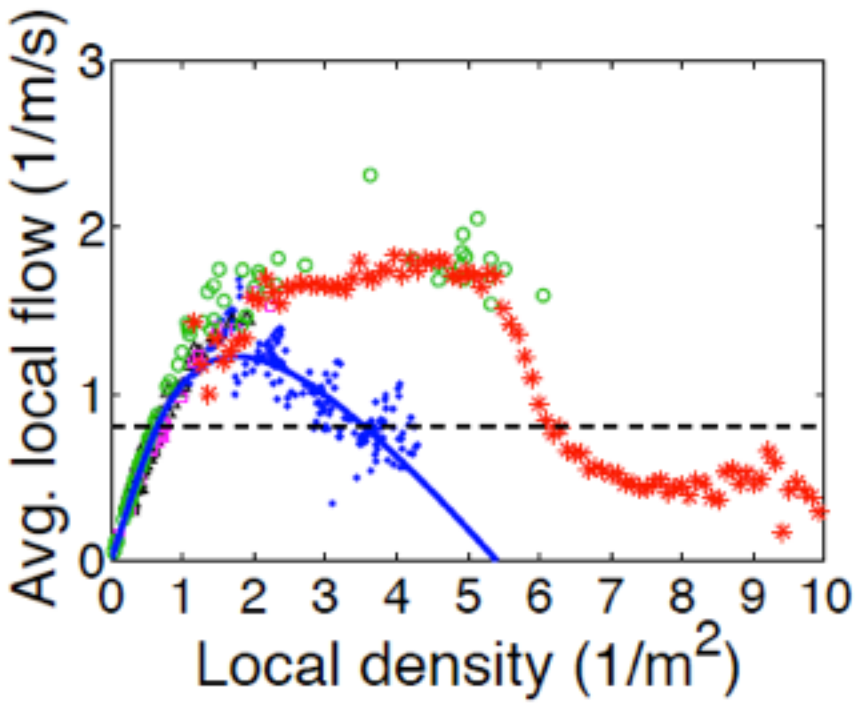
- Experimental research capacity values:

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

- Strong influence of composition of flow
- Importance of geometric factors

Fundamental diagram pedestrian flows

- Relation between density and flow / speed
- Stems directly from walking behaviour and relates to space pedestrian needs for walking at certain speed
- Big influence of context!

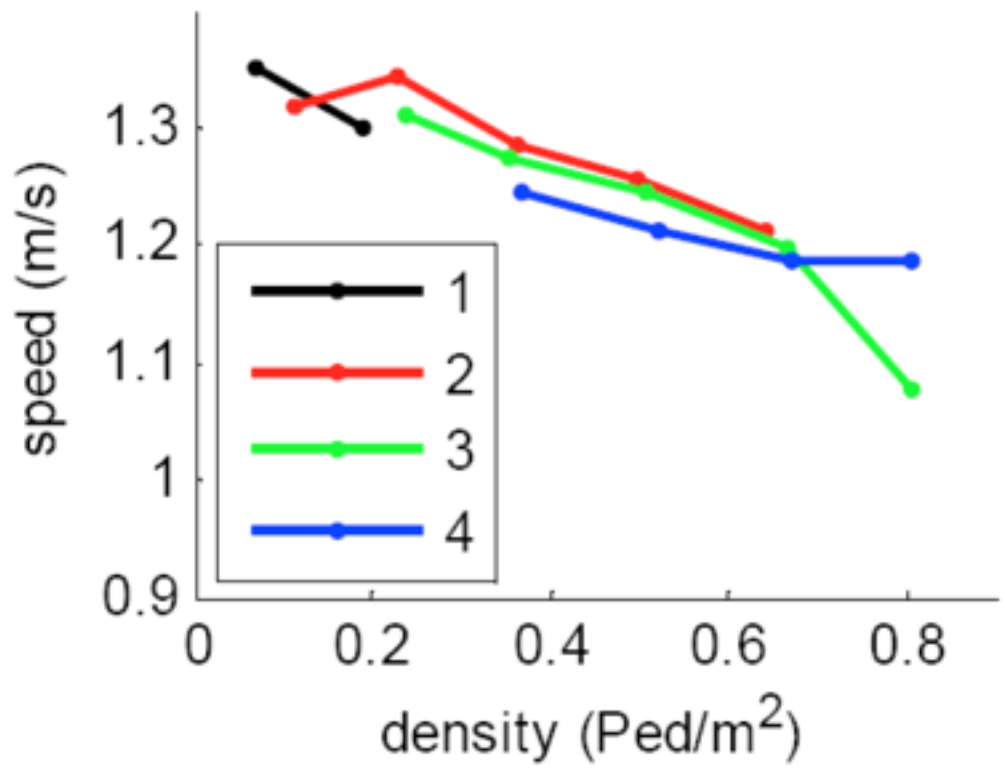


Traffic flow characteristics for pedestrians...

Capacity, fundamental diagram, and influence of context

Phenomena in pedestrian flow operations

Fascinating worlds of pedestrian flow dynamics!



Characteristics:

- Self-organisation yields moderate reduction of flow efficiency
- Chaotic features, e.g. multiple 'stable' patterns may result
- Limits of self-organisation

Limits to efficient self-organisation

Overloading causes phase transitions

Examples self-organisation

- When conditions become too crowded efficient self-organisation ‘breaks down’
- Flow performance (effective capacity) decreases substantially, causing cascade effect as demand stays at same level
- New phases make occur (start-stop waves, turbulence)

Network level characteristics

- Network fundamental diagram captures this flow deterioration

The Modelling Challenge

Reproducing key phenomena in pedestrian dynamics

Towards useful pedestrian flow models…

Challenge is to come up with a model that can predict pedestrian flow dynamics under a variety of circumstances and conditions

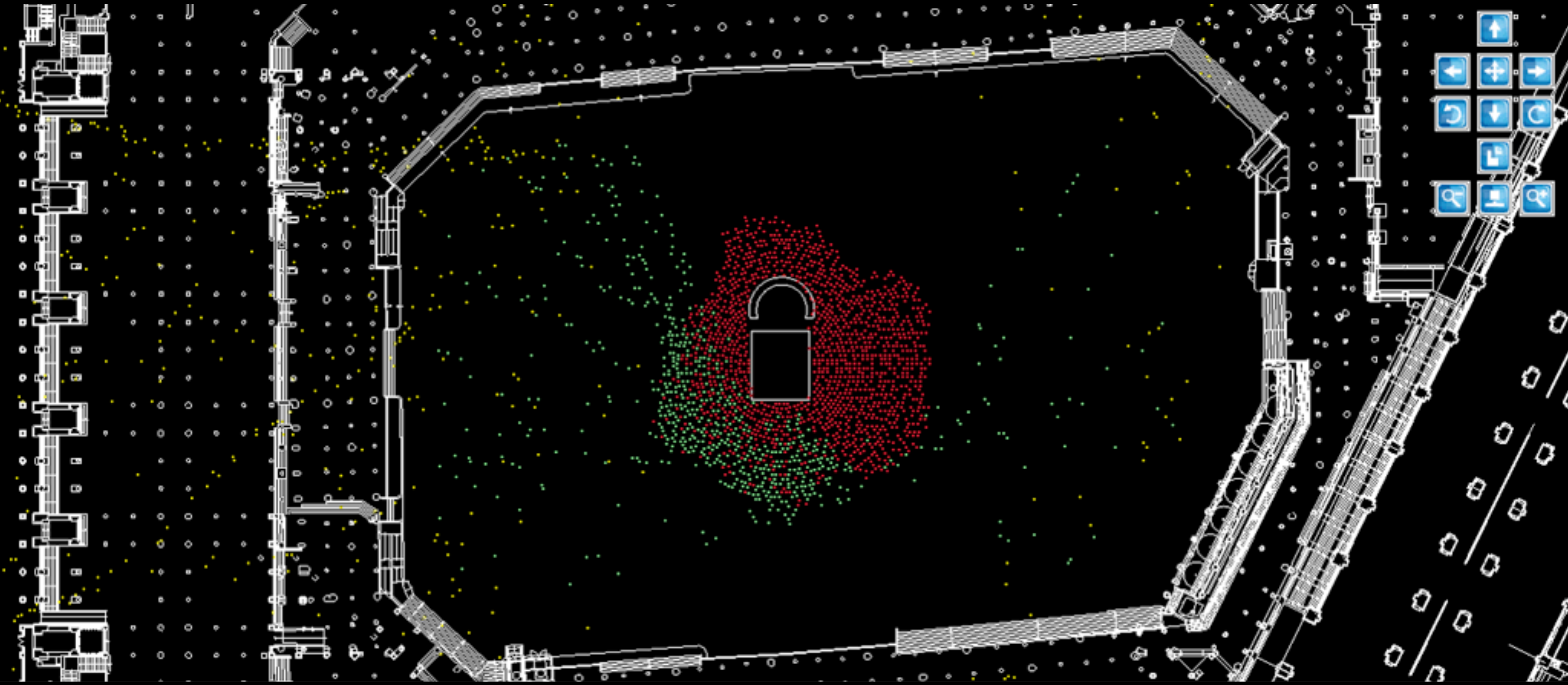
Inductive approach: when designing a model, consider the following:

- Which are the key phenomena / characteristics you need to represent?
- Which theories could be used to represent these phenomena?
- Which mathematical constructs are applicable and useful?
- Which representation levels are appropriate
- How to tackle calibration and validation?

Modelling

Mathematical approaches to Simulating Crowds

Example redesign of the Masjid al-Haram Mosque



Courtesy of Prof. H. Mahmassani

NOMAD Game Theoretical Model

Interaction modelling by using differential game

Or: Pedestrian Ecomicus as main theoretical assumption…

- Game theory turns out to be suitable to model multi-actor systems where actors are interacting and…
- where actors try to optimise their own situation…
- are (thus) competing over a scarce resource (in this case space)

- Self organisation occurs often under these conditions

Main behavioural assumptions (loosely based on

- Pedestrian can be described as optimal, predictive co… term predictions of prevailing conditions, including a… er pedestrians (opponents)
- Pedestrians minimise walking effort caused by dista… ns from desired speed / direction, and acceleration
- Costs are discounted over time, yielding:

$$J = \int_t^{\infty} e^{-\eta t} \left[\frac{1}{2}\mathbf{a}^T\mathbf{a} + c_1 \frac{1}{2}(\mathbf{v}^0 - \mathbf{v})^T(\mathbf{v}^0 - \mathbf{v}) + c_2 \sum_q e^{-\frac{\|\mathbf{r}_q - \mathbf{r}\|}{R_0}} \right]$$

Use of **differential game theory** to determine the pedestrian acceleration behaviour (i.e. the acceleration a) for different types of assumed behaviour opponents (neutral, cooperative, aggressive)

NOMAD Game Theoretical Model

Interaction modelling by using differential game theory

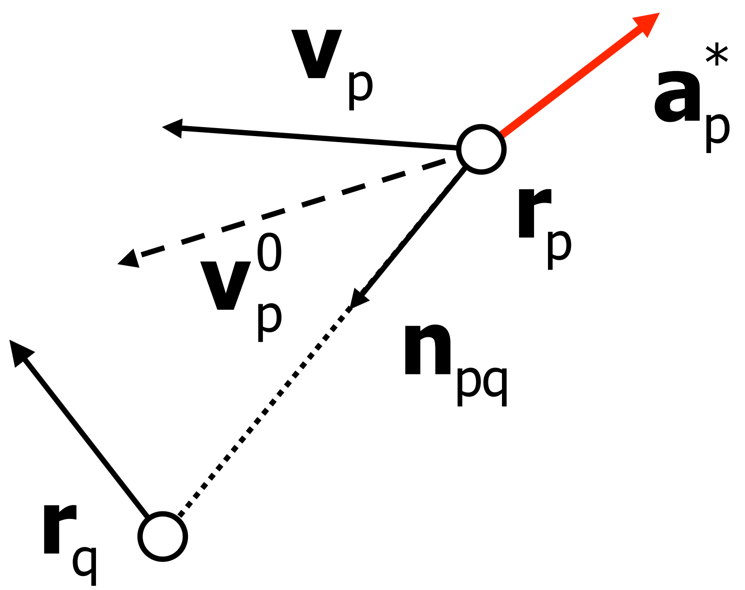
Or: Pedestrian Ecomicus as main theoretical assumption…

Resulting optimisation problem:

$$\mathbf{a}^*_{[t,\infty)} = \arg\min J$$

subject to

$$\frac{d}{dt}\mathbf{x} = \mathbf{f}(t,\mathbf{x},\mathbf{a})$$



- Here, **f** denotes the dynamics of the system state **x** describing the positions **r** and velocities **v** of all pedestrians relevant for the considered pedestrian p
- Pedestrian p makes assumptions on behaviour of the other pedestrians (opponents q): neutral, cooperative, or risk-seeking
- Simplest assumption ($\mathbf{a}_q = 0$) yields **closed-form** expression for $\mathbf{a}_p^*$ when using Pontryagin's minimum principle (which is very familiar!)

NOMAD Game Theoretical Model

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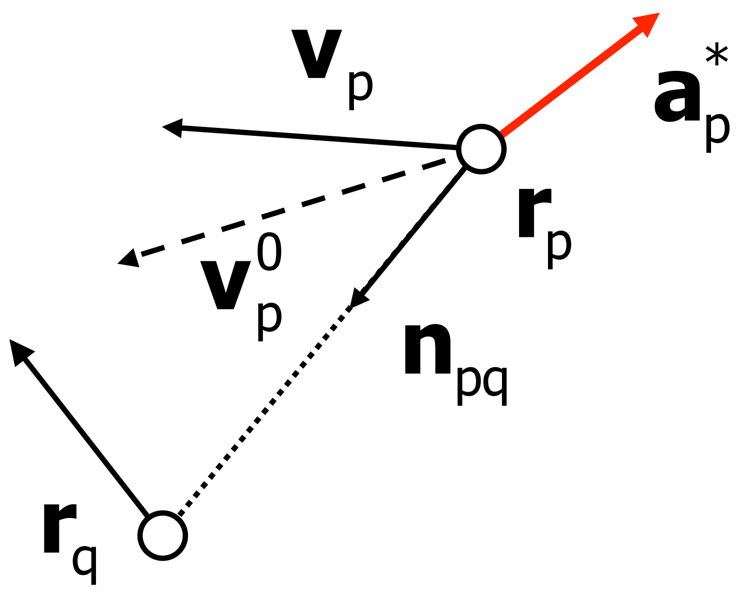
Resulting optimal acceleration:



- Under the assumption that the opponent peds do not anticipate on behaviour of considered ped, we find closed form expression for $\mathbf{a}_p(t)$:

$$\mathbf{a}_p(t) = \frac{\mathbf{v}_p^0 - \mathbf{v}_p}{\tau_p} - A_p^0 \sum_{q \neq p} \mathbf{n}_{pq} e^{-\|\mathbf{r}_p - \mathbf{r}_q\|/R_p^0}$$

- Resulting expression is same as **original Social Forces model** of Helbing

Face validity?

- How can we derive the fundamental diagram (and does it make sense)?
- Which phenomena are reproduced?

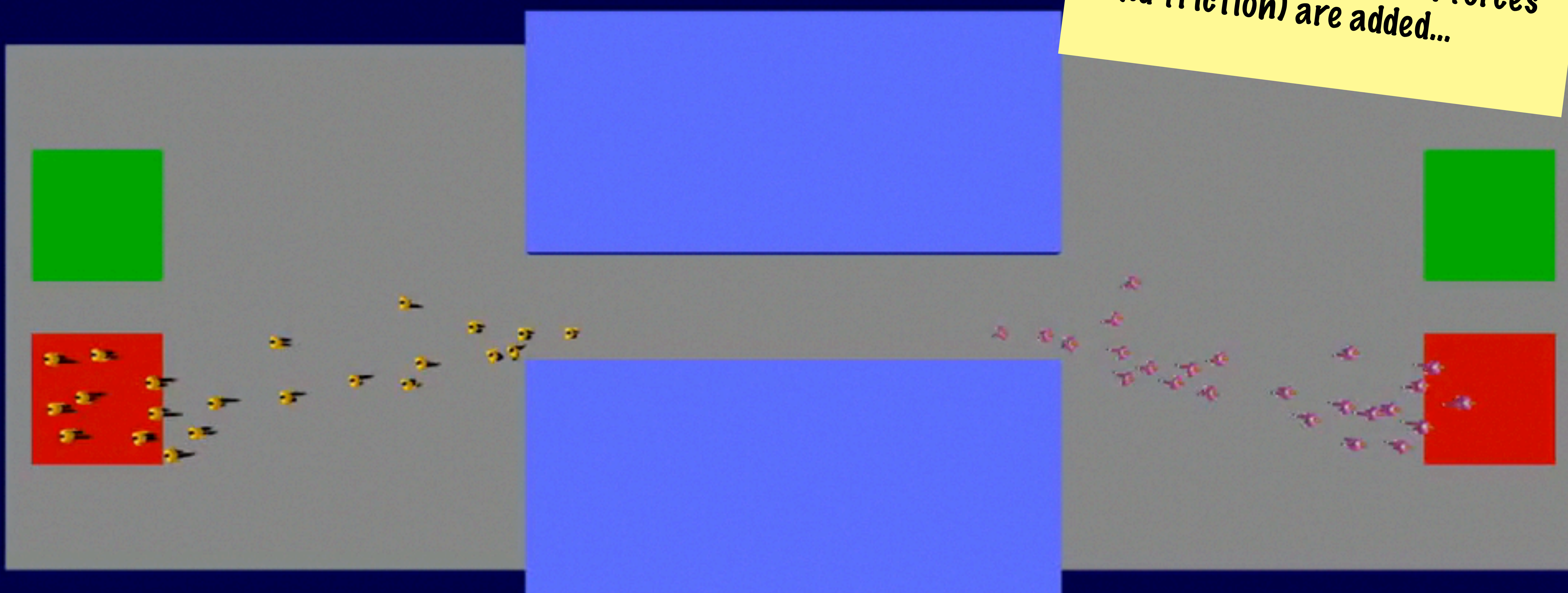
NOMAD Game Theoretical Model

Interaction modelling by using differential game theory

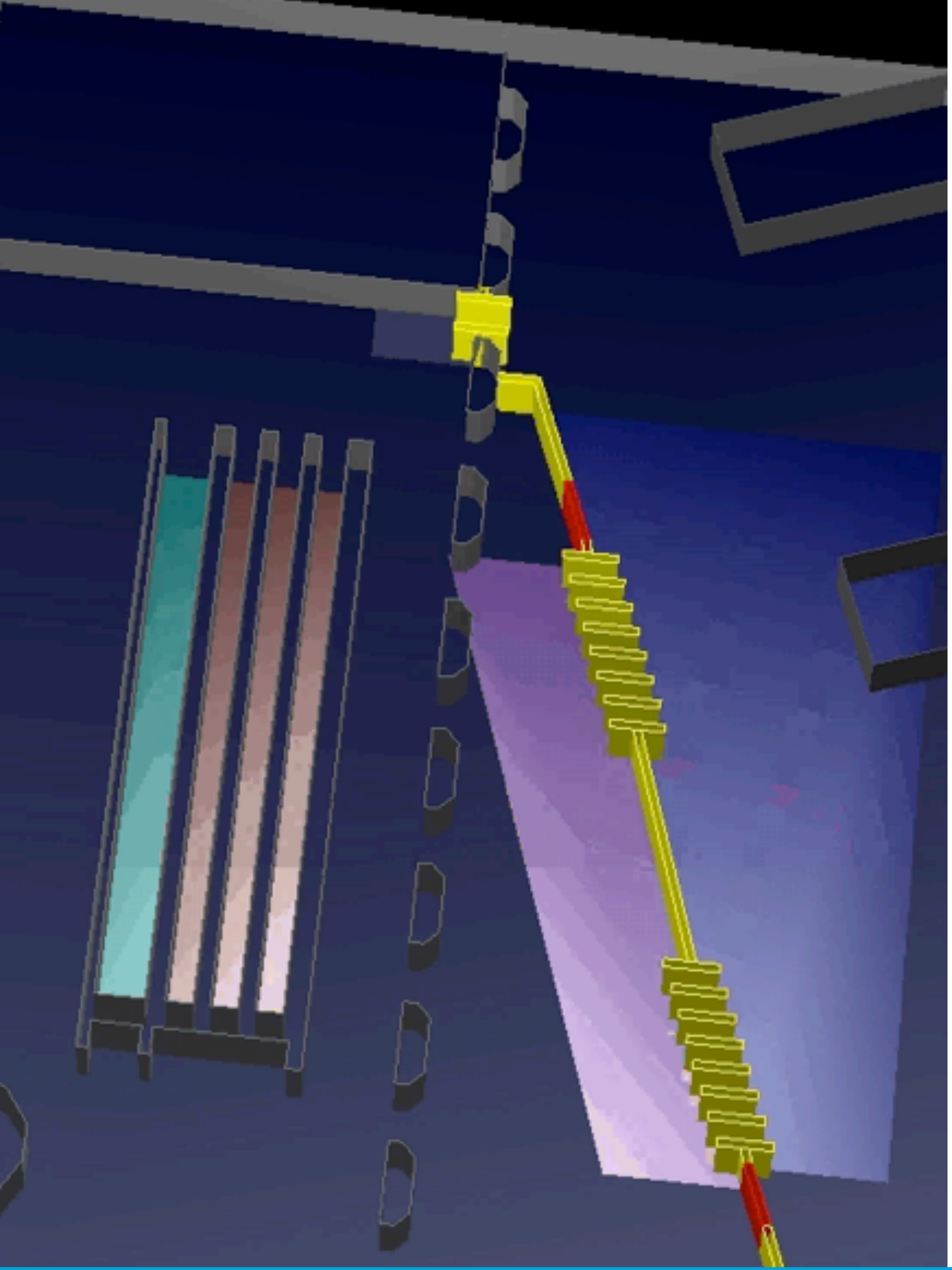
Or: Pedestrian Ecomicus as main theoretical assumption…

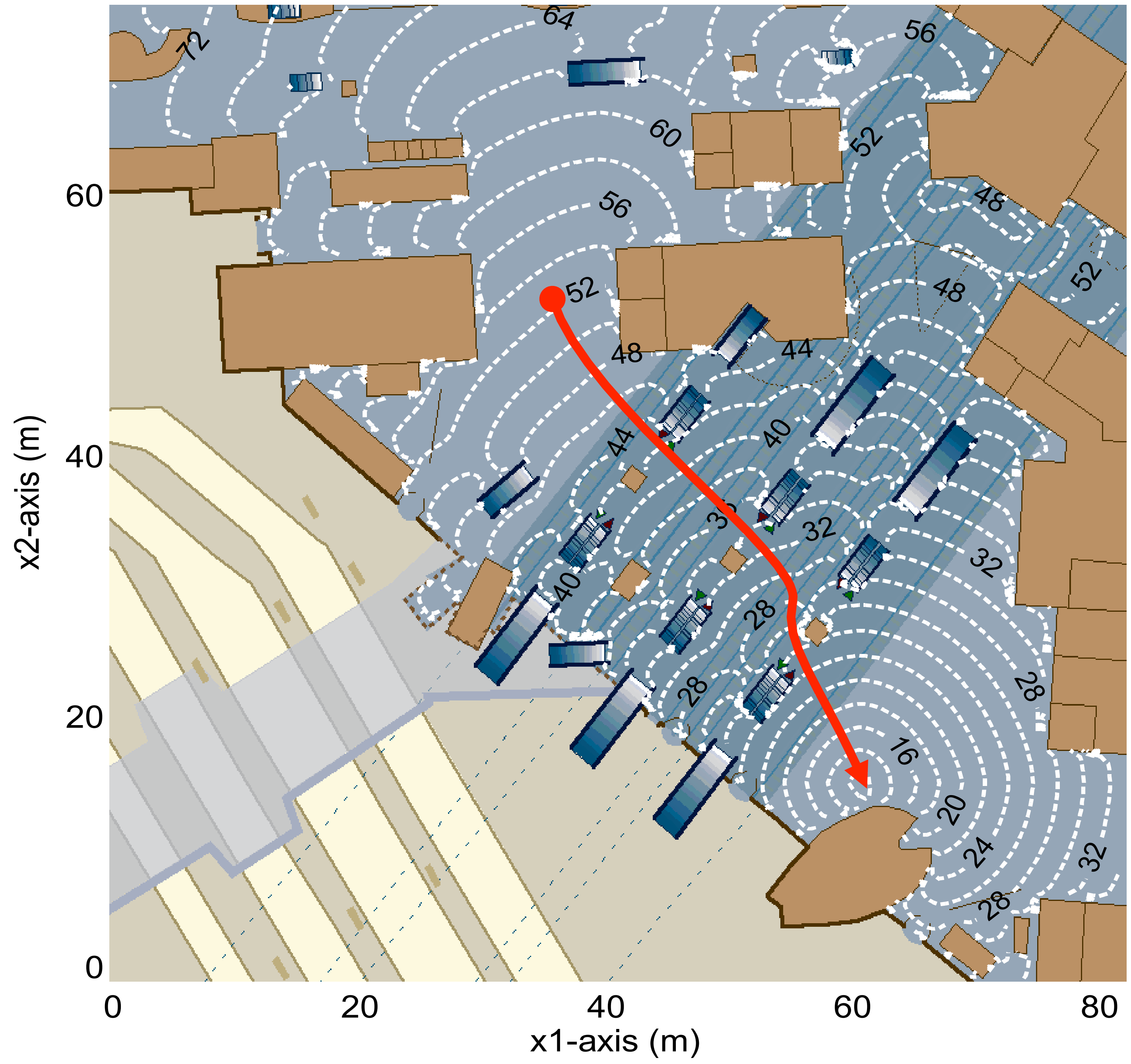
- Model qualitatively captures breakdown processes and 'faster = slower effect' if contact forces (normal forces and friction) are added…

Example shows lane formation process for homogeneous groups…



Heterogeneity yields less efficient lane formation (freezing by heating)





Completing the Model

Route choice modelling by Stochastic Optimal Control

Optimal routing in continuous time and space...

Continuum modelling

Dynamic assignment in continuous time and space

Macroscopic traffic flow modelling…

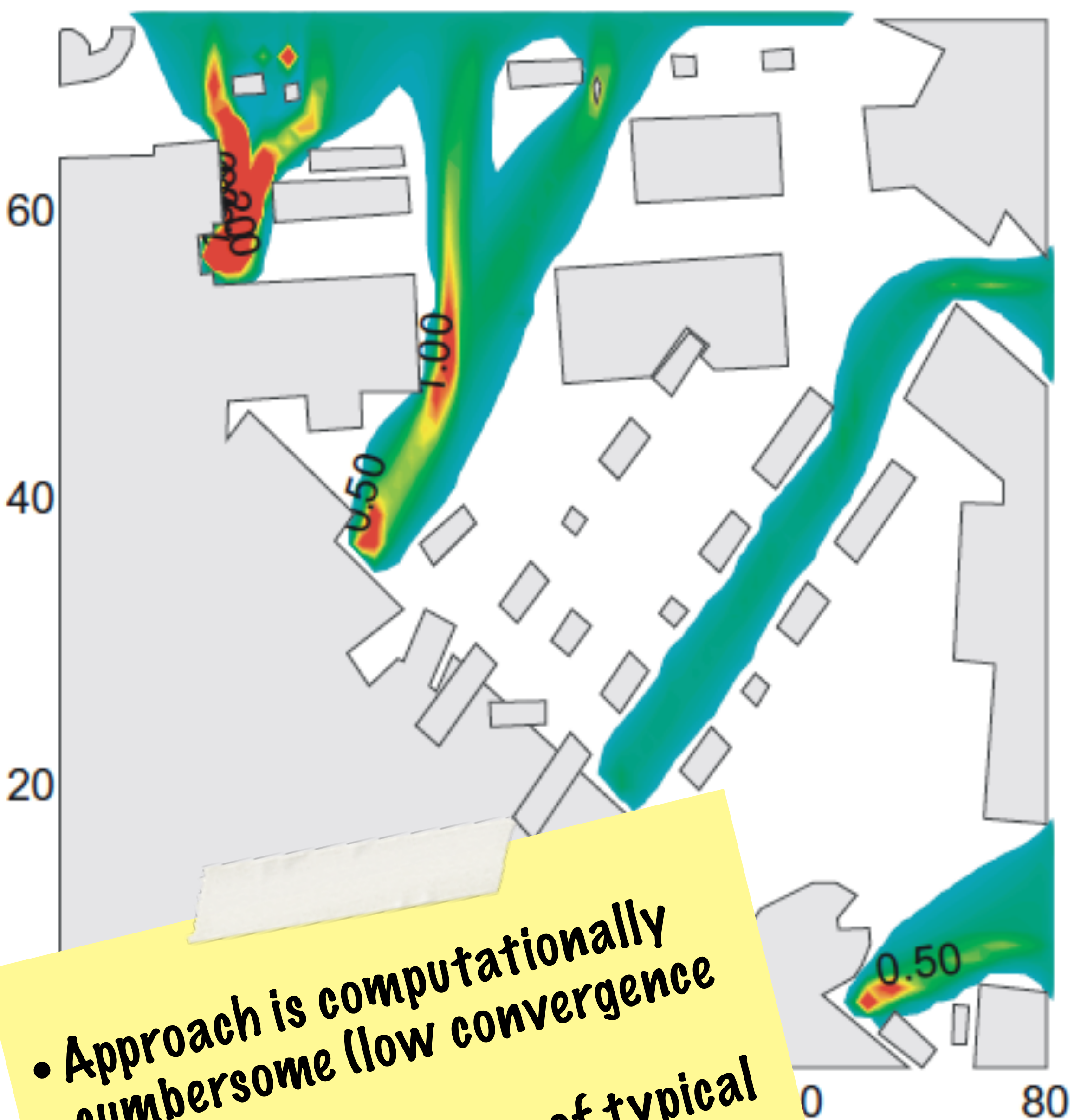
Multi-class macroscopic model of Hoogendoorn and Bovy (2004)

- Compute value function $W_d(t,\mathbf{x})$ for each (set of) destination(s) d
- Determine optimal direction: $\mathbf{e}_d^*(t,\mathbf{x}) = -c_0 \cdot \nabla W_d(t,\mathbf{x})$
- Apply conservation of pedestrian equation for each destination d

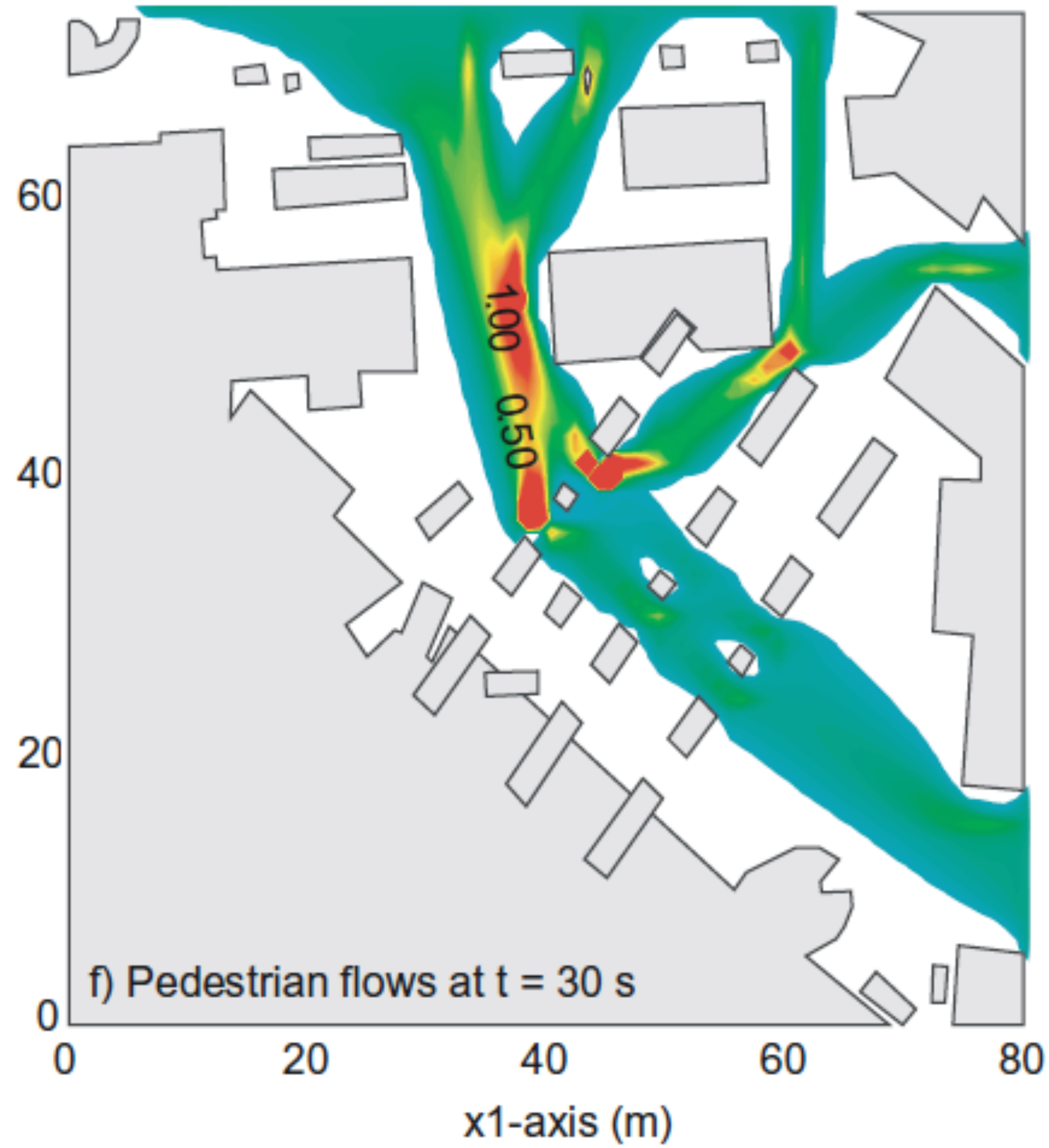
$$\frac{\partial}{\partial t}\rho_d + \nabla \cdot \mathbf{q}_d = r - s \quad \text{with} \quad \mathbf{q}_d(t,\mathbf{x}) = \mathbf{e}_d^* \cdot \rho_d \cdot V(\rho_1,\ldots,\rho_D)$$

- Is this a reasonable model? No, since there is only local (static) route choice, unrealistic features occur
- Bi-level optimisation solution approach:
  - use equilibrium speed in the HJB equation as maximum possible speed and re-calculate $W_d(t,\mathbf{x})$
  - Re-assign pedestrian flows using conservation of pedestrian equation

Pedestrian flows to exits



Pedestrian flows to escalators



- Approach is computationally cumbersome (low convergence rates)
- No self-organisation of typical pedestrian flow patterns...

Con… modelling

Dynamic assignment in continuous time and space

Macroscopic traffic flow modelling…

Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models...

Level of anisotropy reflected by this parameter

- NOMAD / Social-forces model as starting point:

$$\vec{a}_i = \frac{\vec{v}_i^0 - \vec{v}_i}{\tau_i} - A_i \sum_j \exp\left[-\frac{R_{ij}}{B_i}\right] \cdot \vec{n}_{ij} \cdot \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\phi_{ij}}{2}\right)$$

- Equilibrium relation stemming from model ($a_i = 0$):

$$\vec{v}_i = \vec{v}_i^0 - \tau_i A_i \sum_j \exp\left[-\frac{R_{ij}}{B_i}\right] \cdot \vec{n}_{ij} \cdot \left(\lambda_i + (1-\lambda_i)\frac{1+\cos\phi_{ij}}{2}\right)$$

- Interpret densities as a 'probability' of a pedestrian being present gives a **macroscopic equilibrium relation** (expected velocity), which equals:

$$\vec{v} = \vec{v}^0(\vec{x}) - \tau A \iint_{\vec{y}\in\Omega(\vec{x})} \exp\left(-\frac{||\vec{y}-\vec{x}||}{B}\right)\left(\lambda + (1-\lambda)\frac{1+\cos\phi_{xy}(\vec{v})}{2}\right)\frac{\vec{y}-\vec{x}}{||\vec{y}-\vec{x}||}\rho(t,\vec{y})d\vec{y}$$

- Combine with conservation of pedestrian equation yields complete model, but numerical integration is computationally very intensive

Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models...

- Taylor series approximation:

$$\rho(t,\vec{y}) = \rho(t,\vec{x}) + (\vec{y}-\vec{x}) \cdot \nabla\rho(t,\vec{x}) + O(||\vec{y}-\vec{x}||^2)$$

  yields a closed-form expression for the equilibrium velocity $\vec{v} = \vec{e} \cdot V$, which is given by the equilibrium speed and direction:

$$V = ||\vec{v}^0 - \beta_0 \cdot \nabla\rho|| - \alpha_0\rho$$

$$\vec{e} = \frac{\vec{v}^0 - \beta_0 \cdot \nabla\rho}{V + \alpha_0\rho}$$

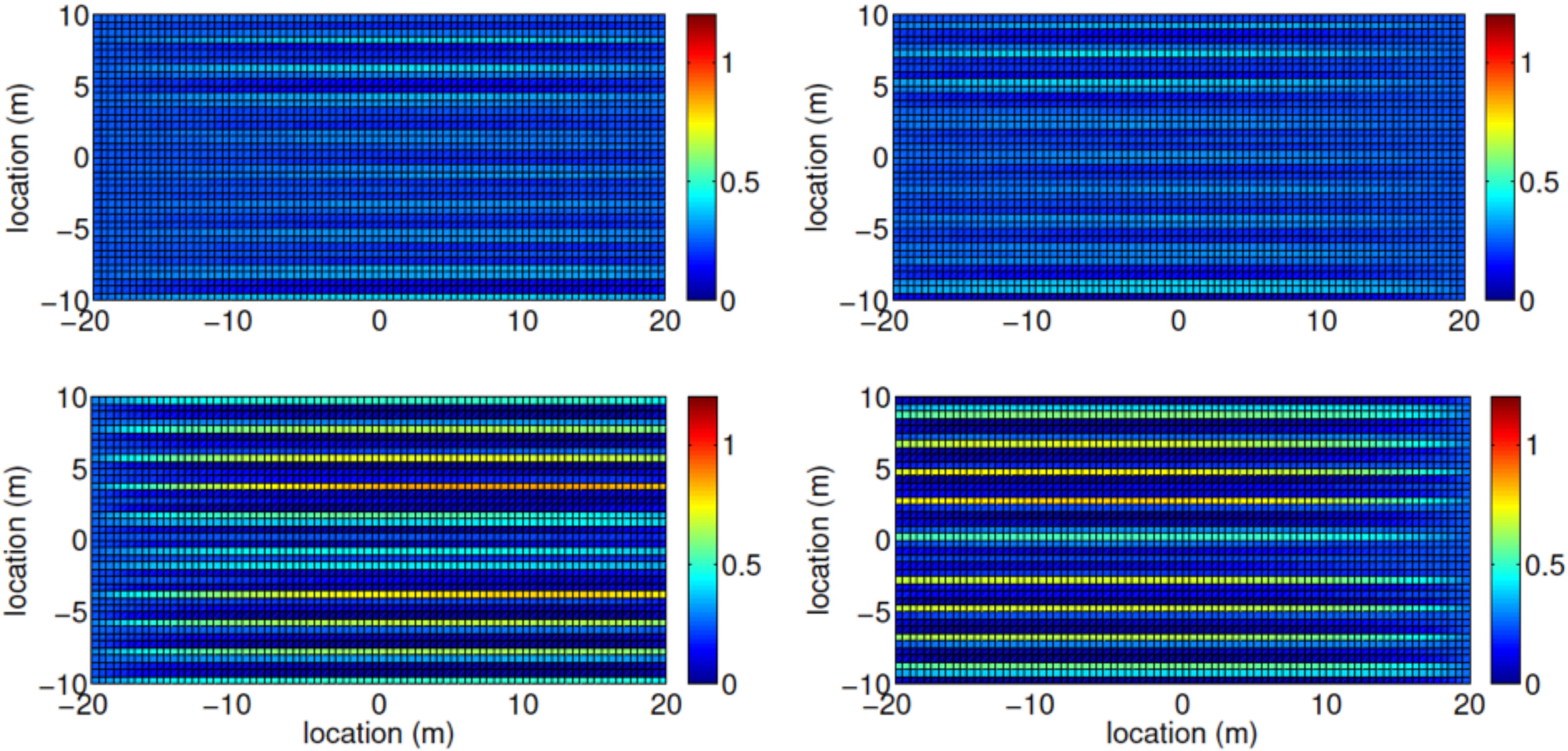
- with: $\alpha_0 = \pi\tau AB^2(1-\lambda)$ and $\beta_0 = 2\pi\tau AB^3(1+\lambda)$
- Check behaviour of model by looking at isotropic flow ($\lambda = 1$) and homogeneous flow conditions ($\nabla\rho = \vec{0}$)
- Multi-class generalisation + Godunov scheme numerical approximation

Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models…

- Model seems to reproduce self-organised patterns (e.g. example below shows lane formation for bi-directional flows)

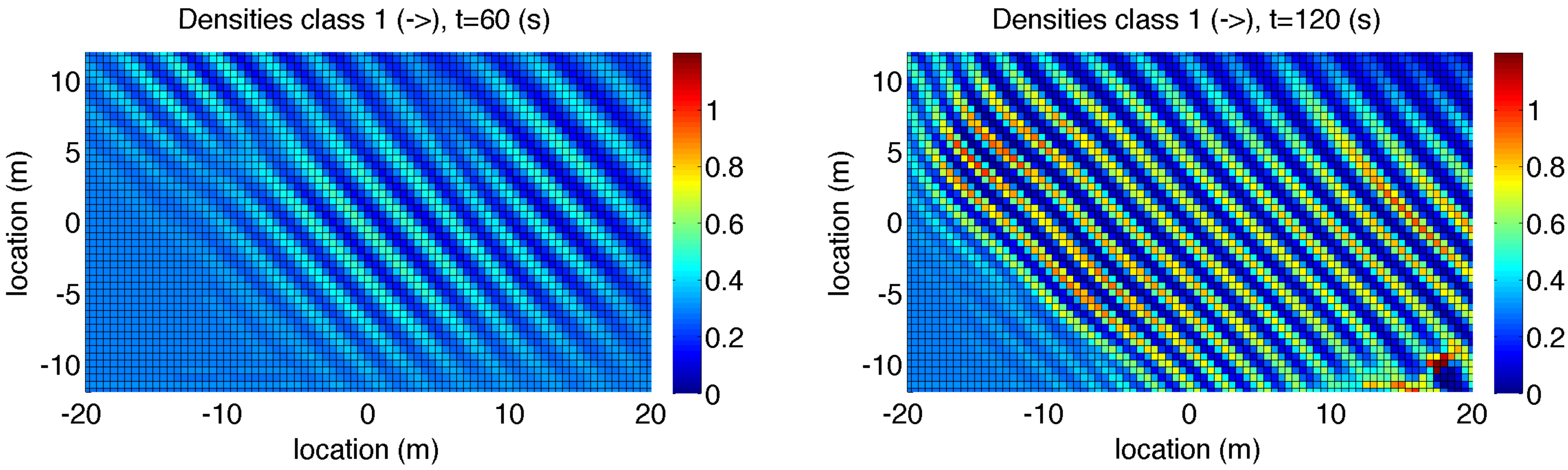


Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models…

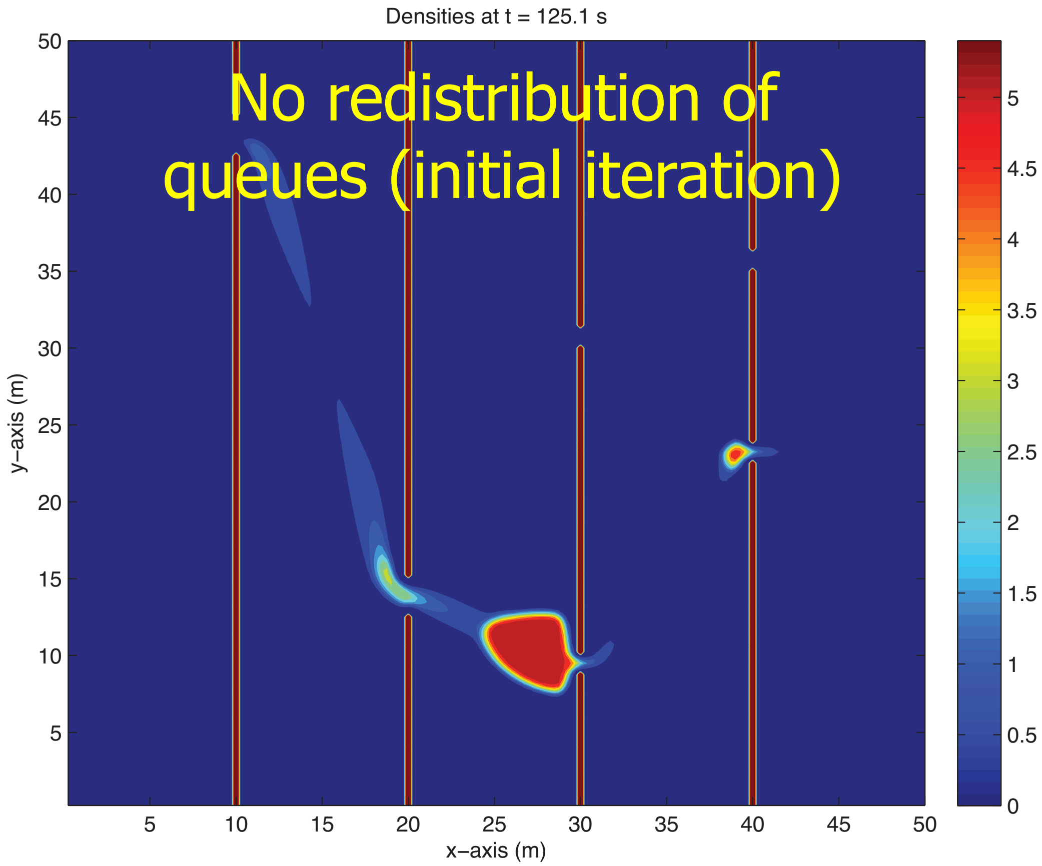
- First simulation results also show formation of diagonal stripes…
- Results provide indication of self-organisation (and even breakdown phenomena?)
- More investigations are required…

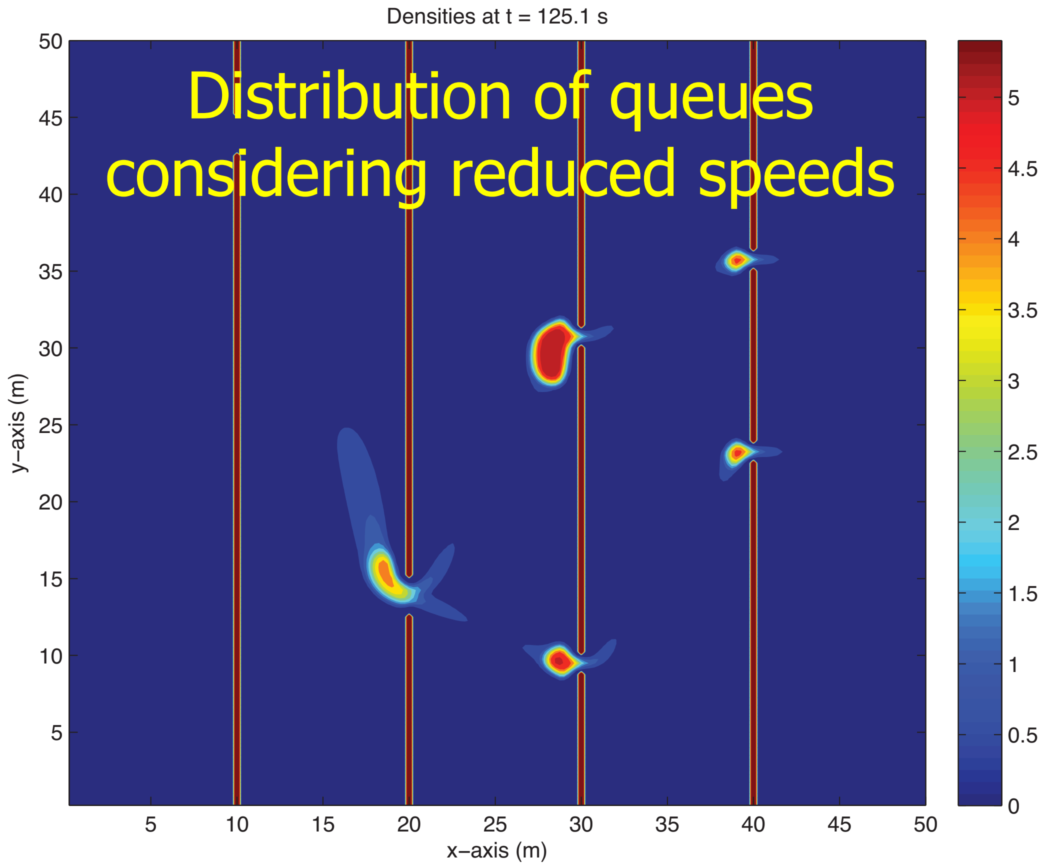


Applications?

Use of macroscopic flow model in optimisation

- Work presented at TRB 2013 proposes **optimisation technique to minimise evacuation times**
- Bi-level approach combining optimal routing (HJB equation) and continuum flow model (presented here)
- Preliminary results are very promising





Final remarks...

Challenges in modelling

Results for the first TRB subcommittee workshop

- Validation and calibration is a major challenge: need methodologies, data and information extraction methods
- Specialised models may be needed e.g. for train stations, for evacuations and for areas where pedestrians interact with vehicles
- Differences between cultures, genders, ages, climates should be considered
- Route choice models are even less developed than flow models and therefore also need more attention
- Operations are strongly context dependent as so should the models! No ‘one size fits all’!
- Professionals should also be considered in our efforts and be educated n how to use our tools and models and what they can expect from them and what not

Want to know more? Stay in touch!