Challenges in Pedestrian Flow Modelling

Macroscopic Modeling of Crowds capturing Self-Organisation

Serge Hoogendoorn, *Winnie Daamen, Femke van Wageningen-Kessels, and others…*

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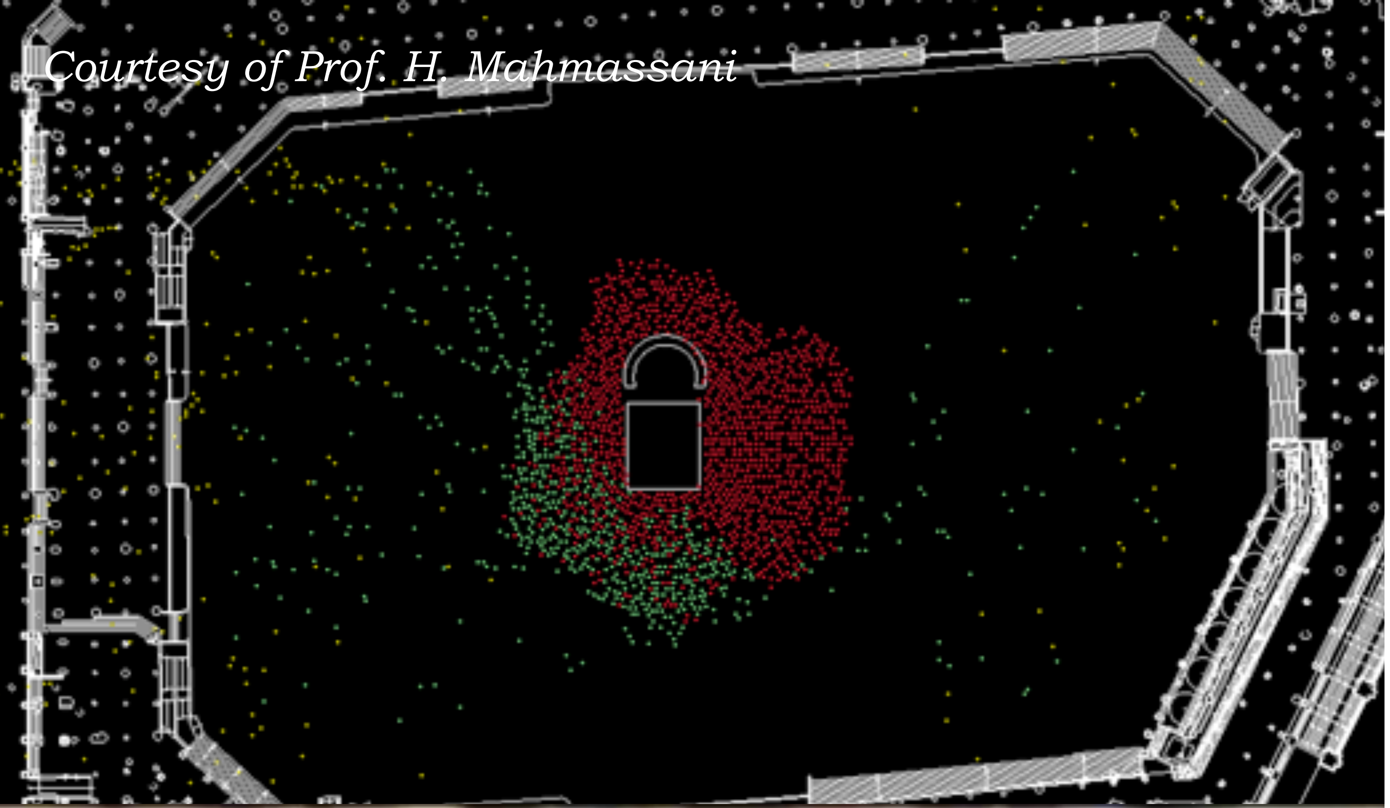
Societal Urgency

Examples showing increasing importance of crowd modeling & management

Religious or social gathersings, events, (re-)urbanisaiton, increase use of transit and rail…

- Situations where large crowds gather are frequent (sports events, religious events, festivals, etc.); occurrence of 'spontaneous events' due to social media
- Transit (in particular train) is becoming more important leading to overcrowding of train stations under normal and exceptional situations (e.g. renovation of Utrecht Central Station)
- Walking (and cycling) are becoming more important due to (re-)urbanisation (strong reduction car-mobility in Dutch cities)
- When things go wrong, societal impacts are huge!



How can models be used to support planning, organisation, design, and control?

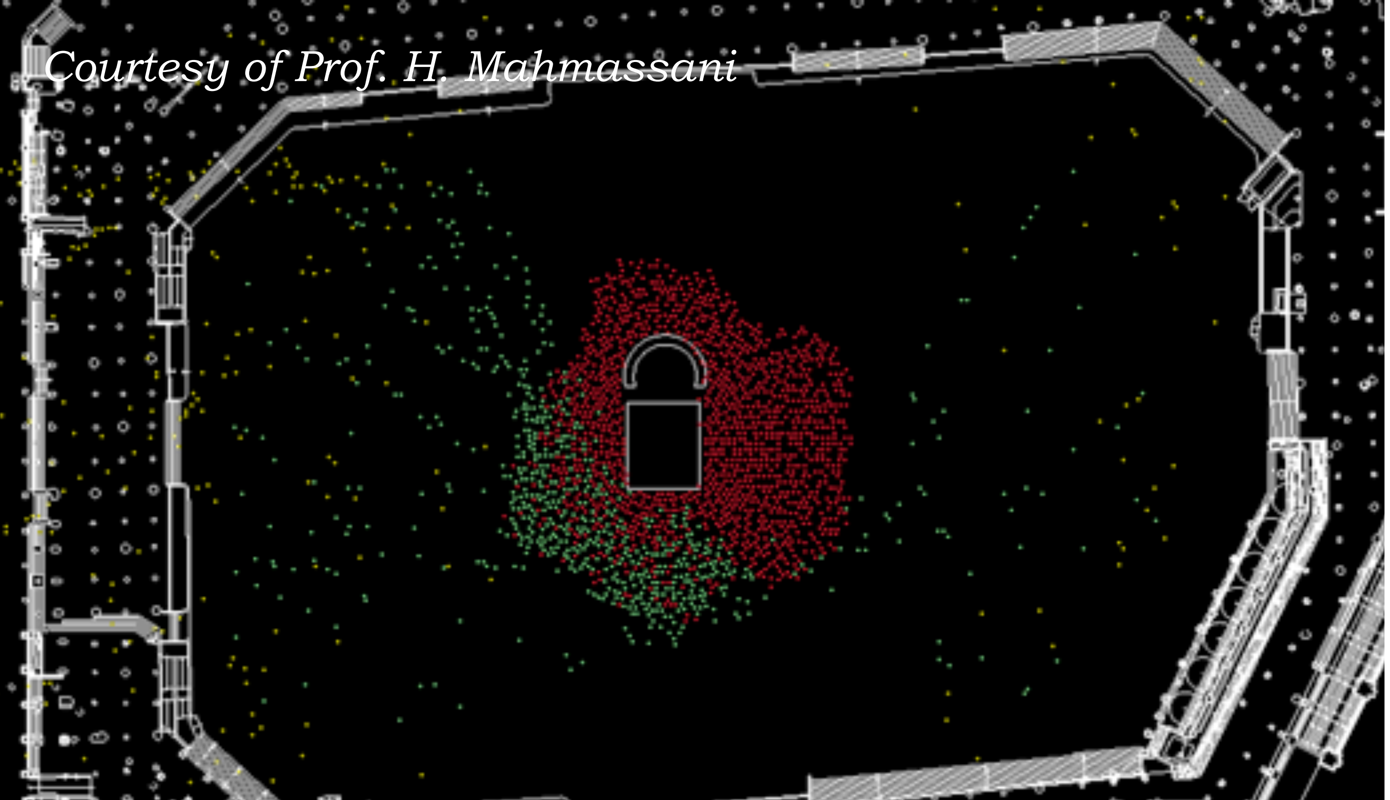
- Testing (new) designs of stations, buildings, stadions, etc.
- Testing evacuation plans for buildings
- Testing crowd management and control measures and strategies
- Training of crowd managers
- On-line crowd management systems as part of state estimation and prediction

Development of valid models requires good data!!!

Engineering challenges

Societal urgencies leads to demand for engineering solutions

Importance of Theory and Models for Pedestrian and Crowd Dynamics



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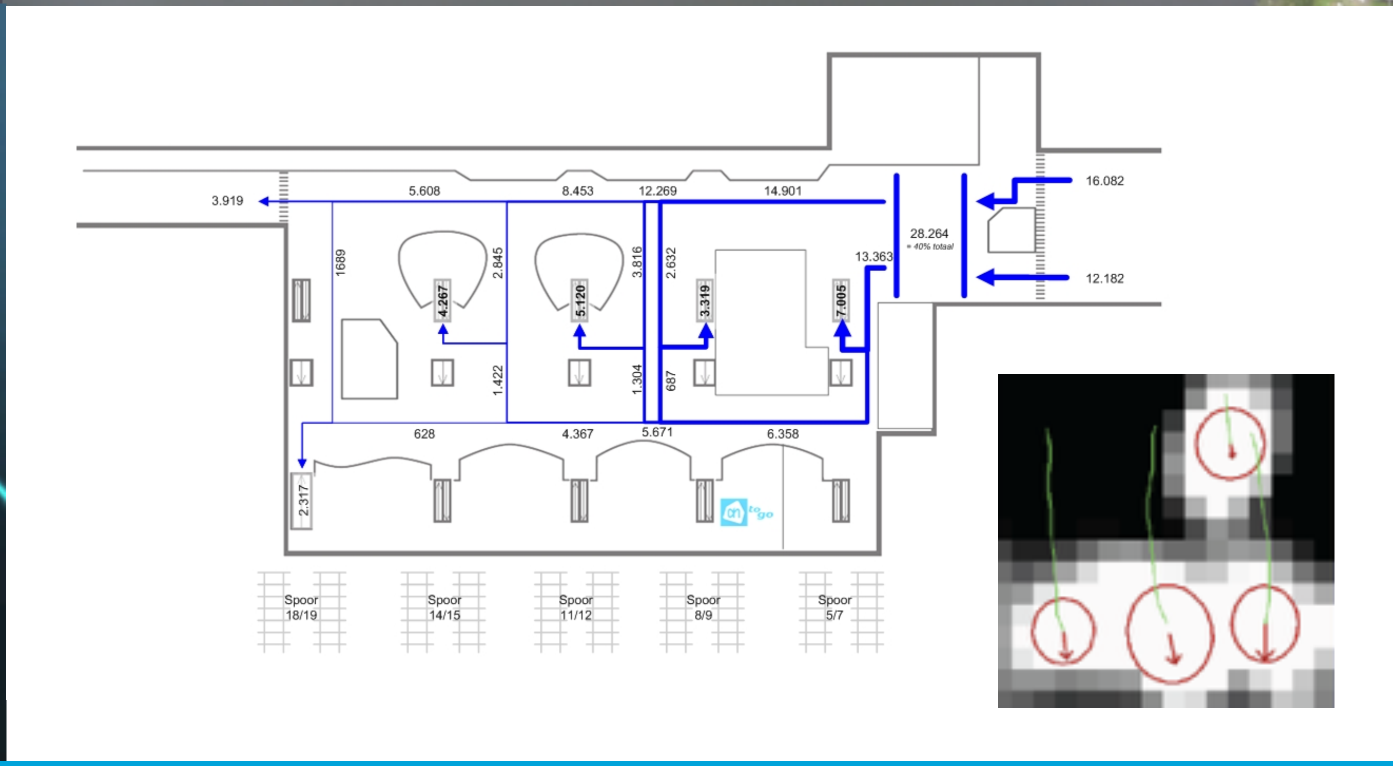
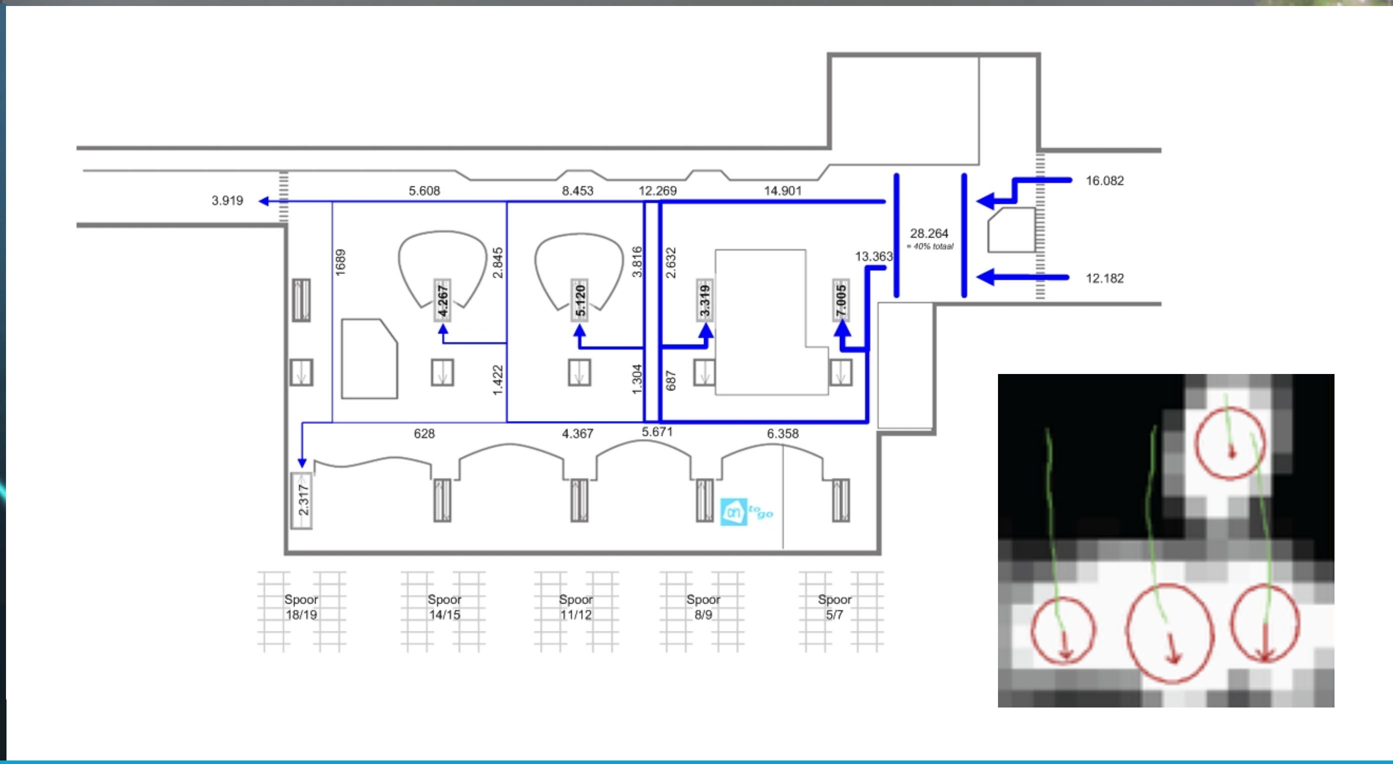


Understanding Pedestrian Flows

Field observations, controlled experiments, virtual laboratories

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



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Empirical characteristics and relations

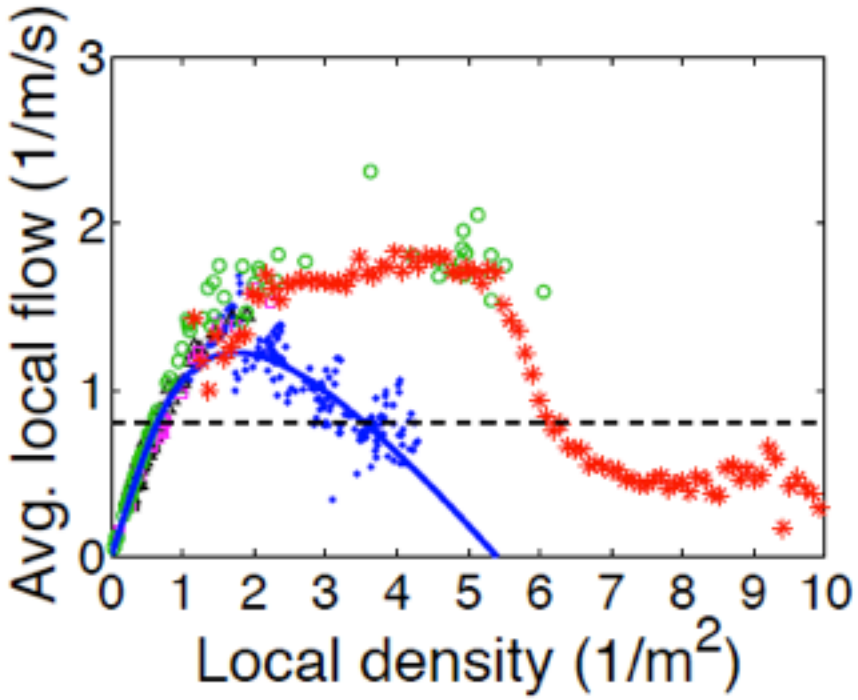
- Experimental research capacity values:

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

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

Fundamental diagram pedestrian flows

- Relation between density and flow / speed
- Big influence of context!
- Example shows regular FD and FD determined from Jamarat Bridge



Traffic flow characteristics for pedestrians...

Capacity, fundamental diagram, and influence of context

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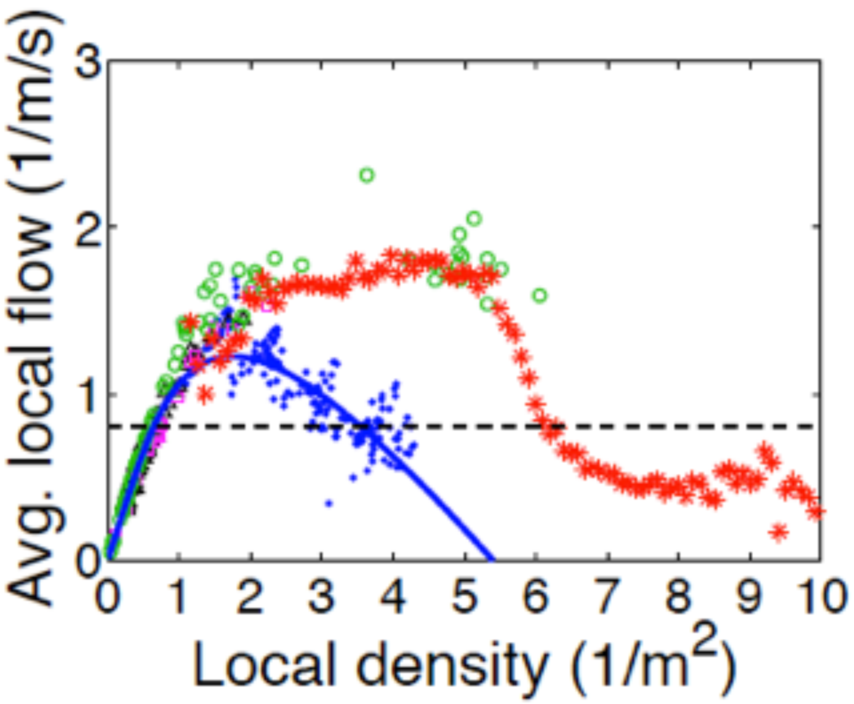
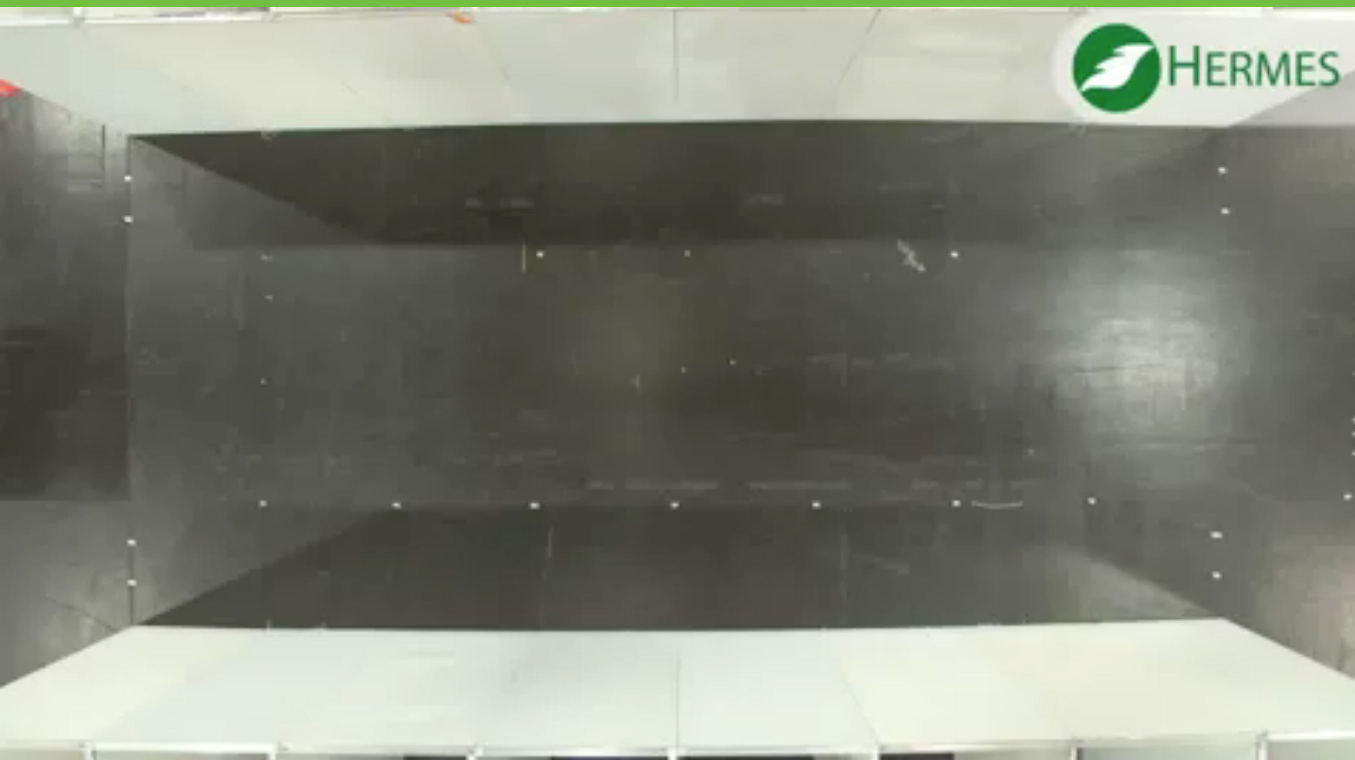


Traffic flow characteristics for pedestrians…

Capacity, fundamental diagram, and influence of context

Phenomena in pedestrian flow operations

Fascinating world of pedestrian flow dynamics!



Examples self-organisation

- Self-organisation of dynamic lanes in bi-directional flow
- Formation of diagonal stripes in crossing flows
- Viscous fingering in multi-directional flows

Characteristics:

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

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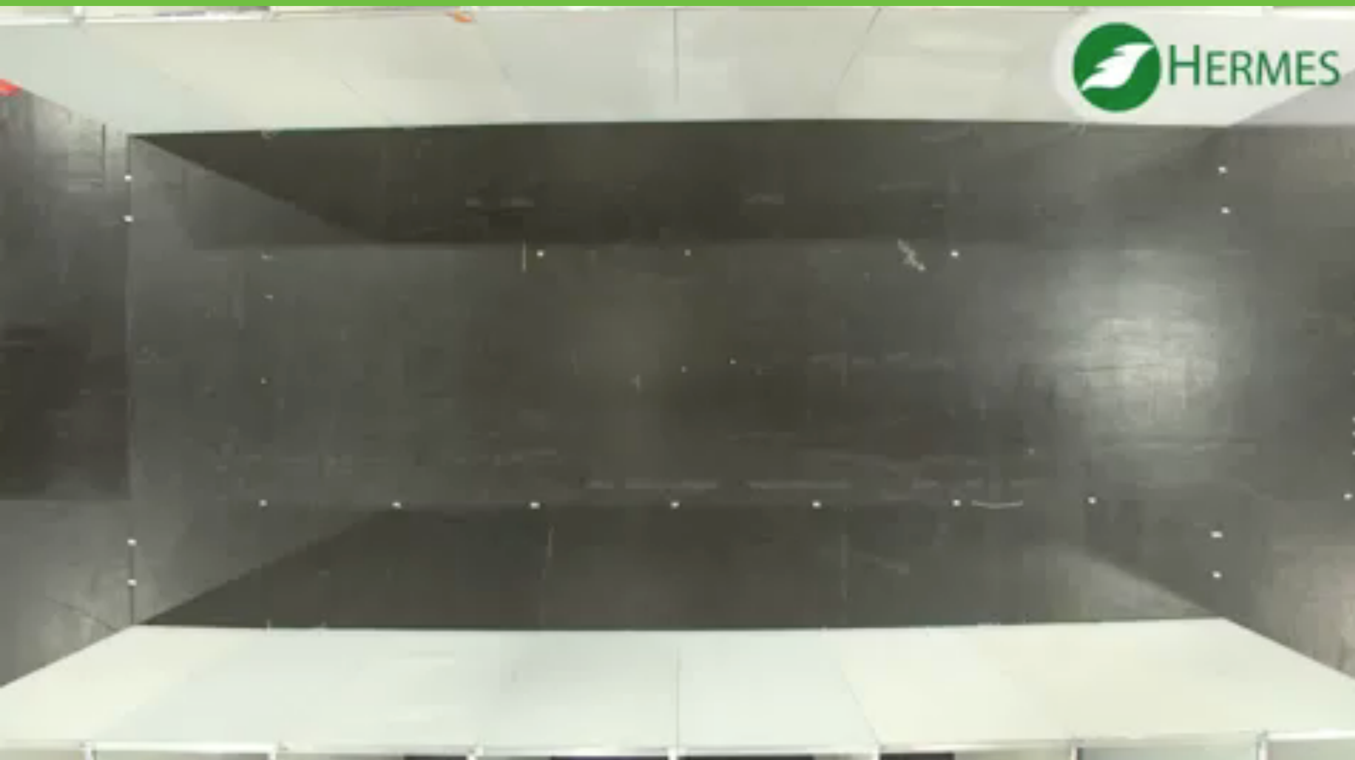

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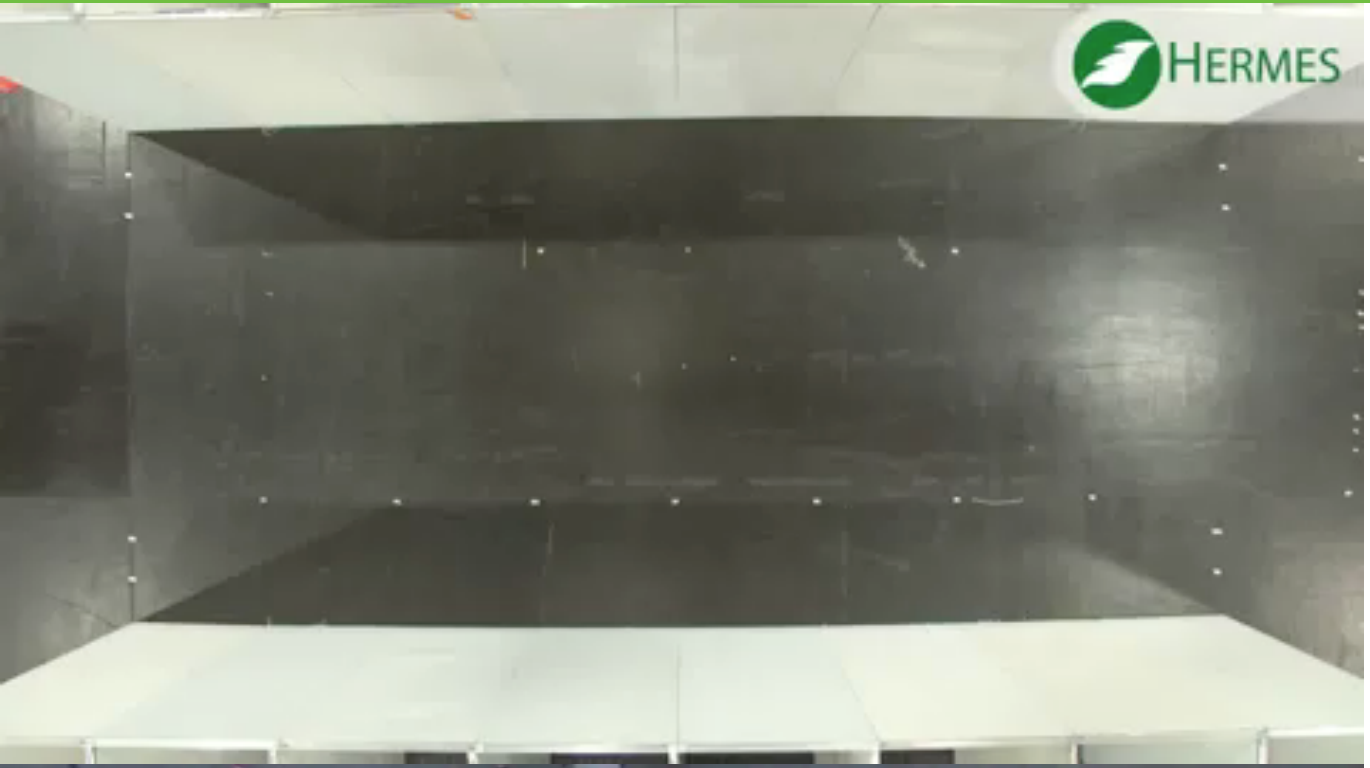

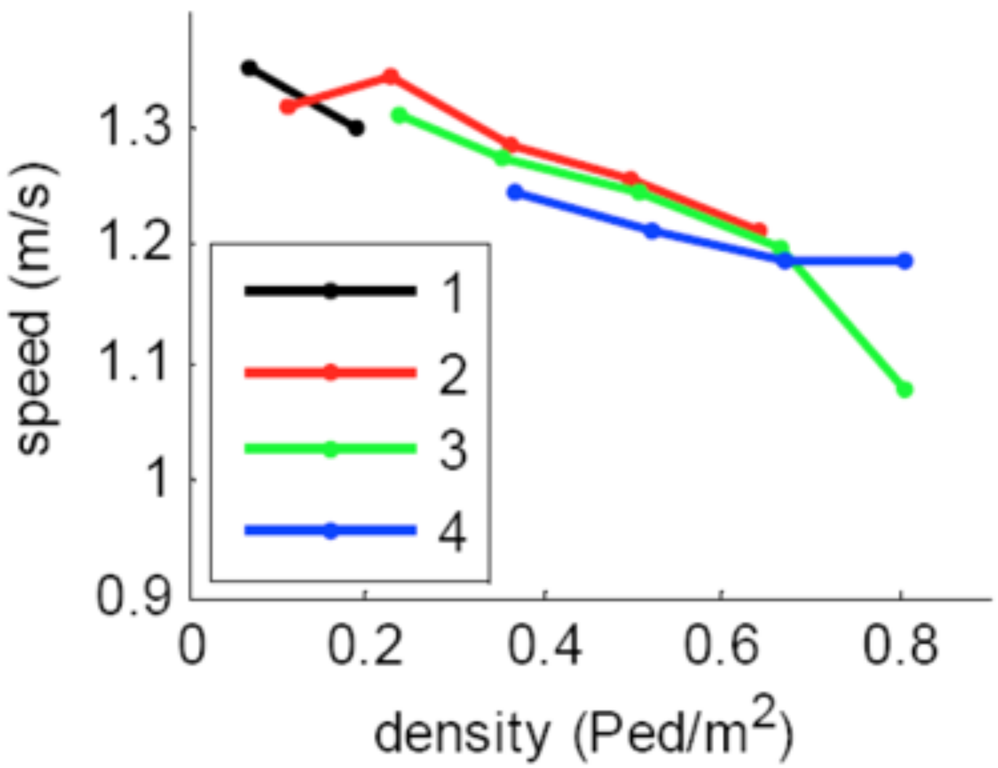

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Limits to efficient self-organisation

Overloading causes phase transitions

Examples failing 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

- Generalised network fundamental diagram can be sensibly defined for pedestrian flows!

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The Modelling Challenge

Reproducing key phenomena in pedestrian dynamics

Towards useful pedestrian flow models…

Challenge is to come up with a model that can reproduce or 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?

The Modelling Challenge

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Pedestrian modelling approaches

Representation and behaviour roles

Examples of micro, meso, and macroscopic pedestrian modelling approaches

Representation: / Behavioural rules:	Individual particles	Continuum
Individual behaviour (predictive)	Microscopic simulation models (social forces, CA, NOMAD, etc.)	Gas-kinetic models (Hoogendoorn, Helbing)
Aggregate behaviour (descriptive)	Particle discretisation models (SimPed)	Macroscopic continuum models (Hughes, Columbo, Hoogendoorn)

Research emphasis on **microscopic simulation models** and on **walking behaviour**

Example: NOMAD Game Theoretical Model

Interaction modelling by using differential game theory

Or: Pedestrian Economicus as main theoretical assumption…

Application of differential game theory:

Level of anisotropy reflected by this parameter

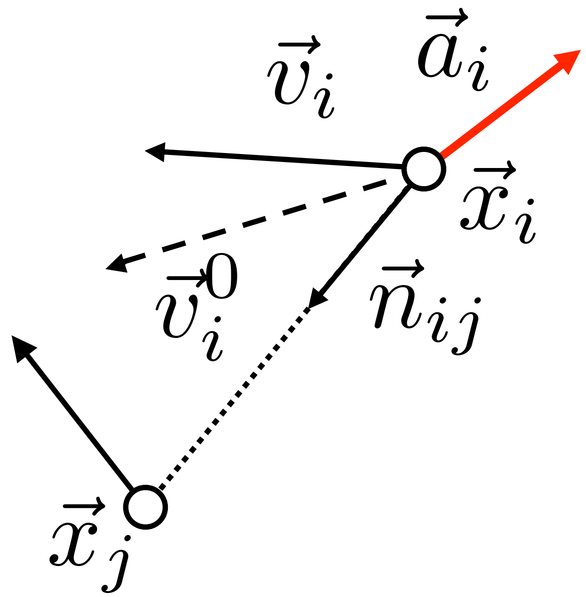
- Pedestrians minimise predicted walking cost, due to straying from intended path, being too close to others / obstacles and effort, yielding $\mathbf{a}_i(t)$:

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

- Simplified model is similar to **Social Forces model** of Helbing

Face validity?

- Model results in reasonable fundamental diagrams
- What about self-organisation?



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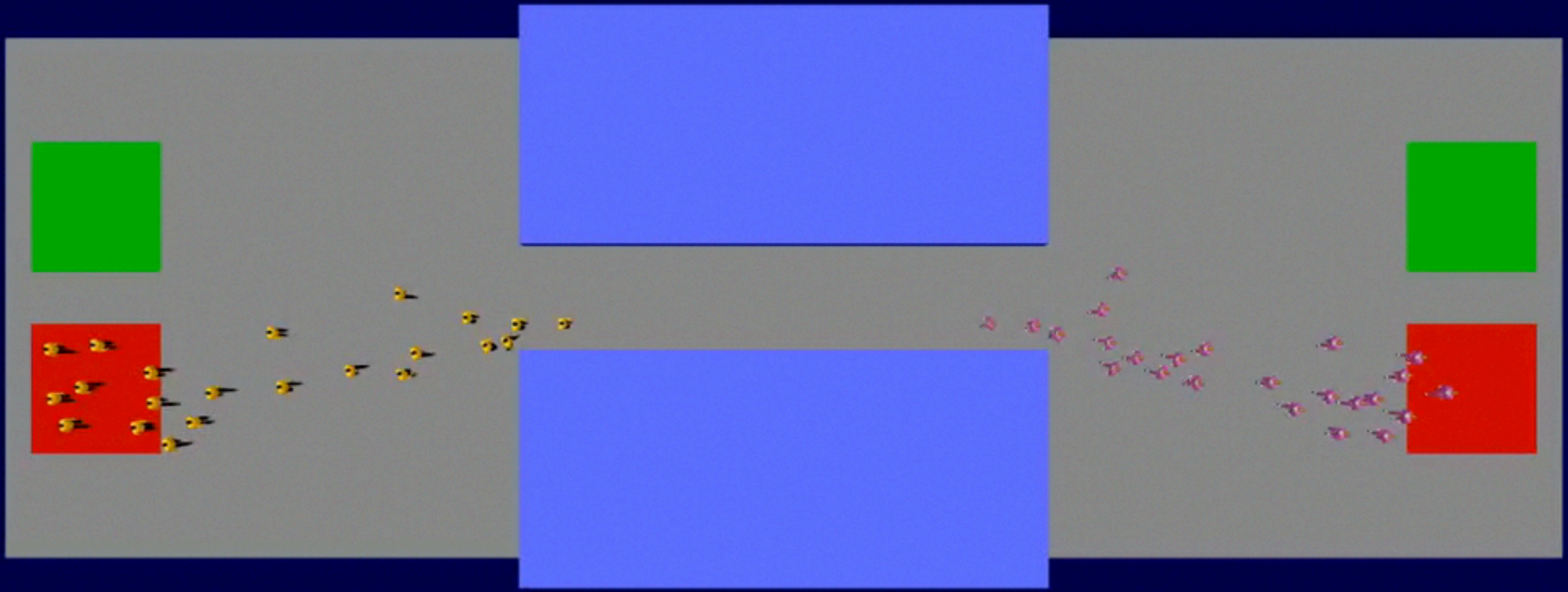
Example shows lane formation process for homogeneous groups…



Heterogeneity yields less efficient lane formation (freezing by heating)

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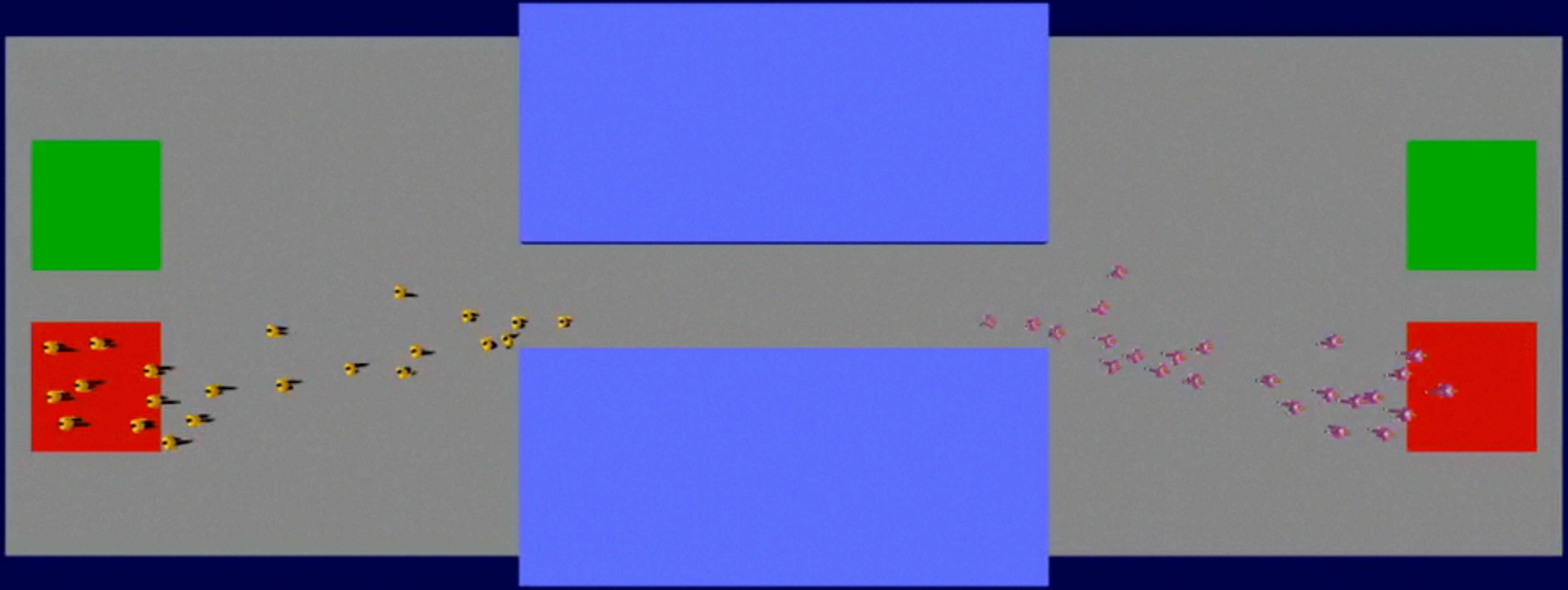

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Example: NOMAD Game Theoretical Model

Interaction modelling by using differential game theory

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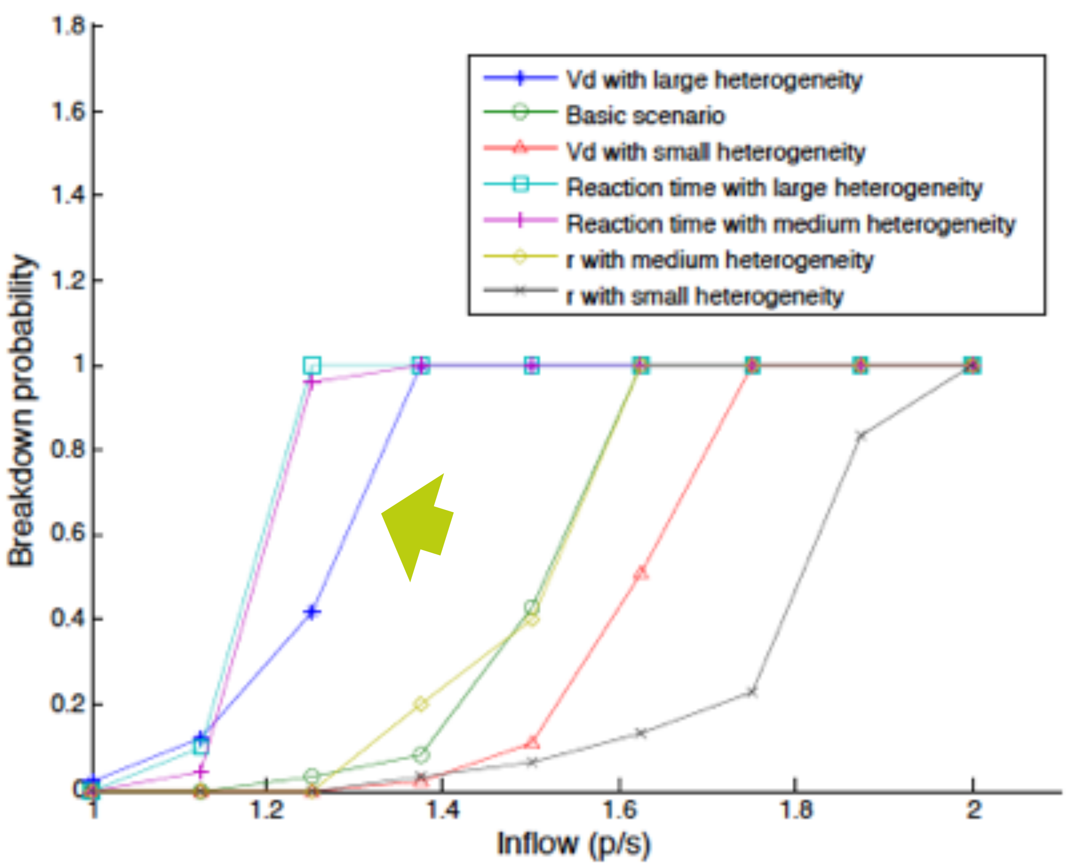
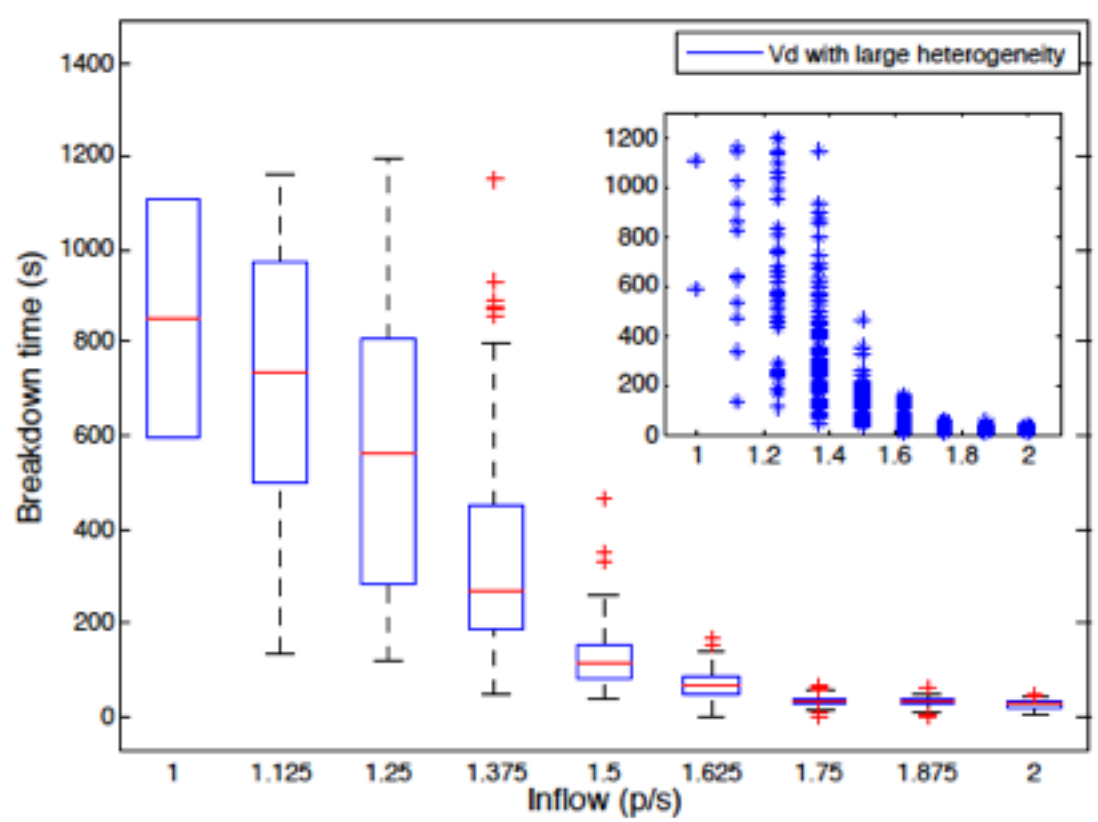
Is NOMAD able to reproduce breakdown in case of oversaturation?

- Testing NOMAD / Social Forces model using different demand patterns to investigate if and under which conditions breakdown occurs
- Large impact of population heterogeneity ('freezing by heating') + reaction time





*) **Work by Xiaoxia Yang, Winnie Daamen, Serge Paul Hoogendoorn, Yao Chen, Hairong Dong**

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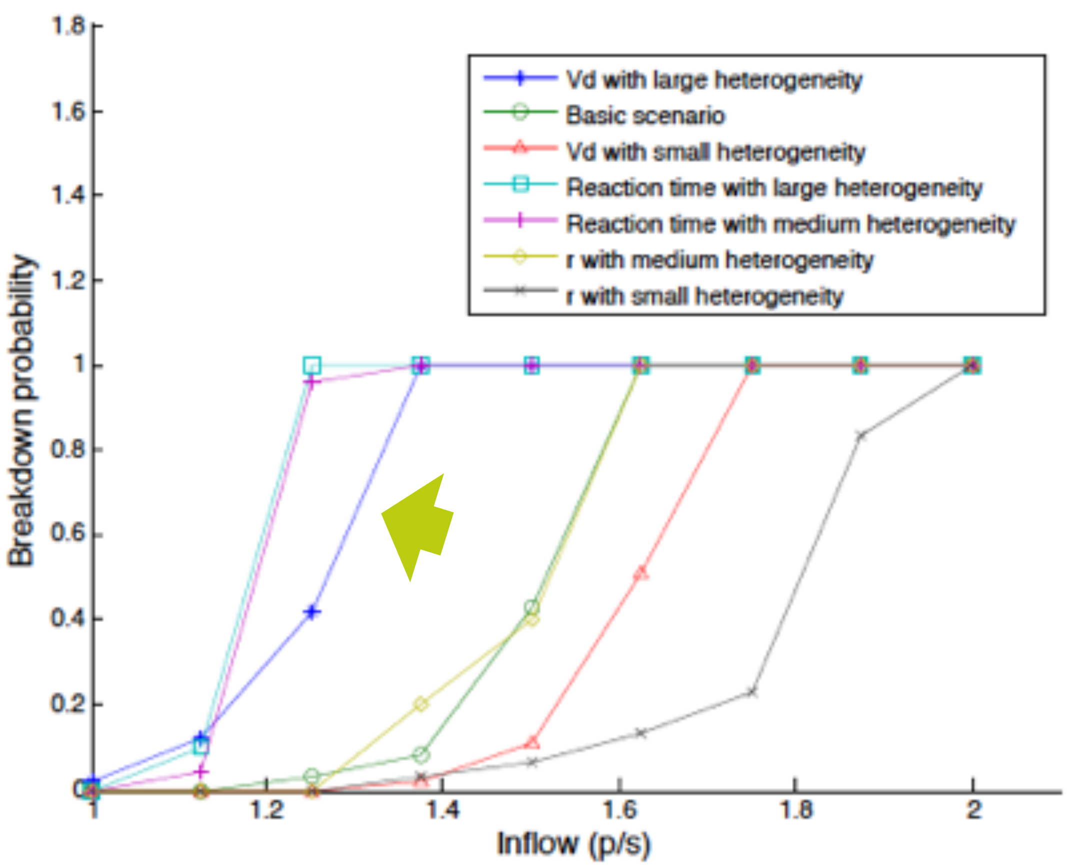

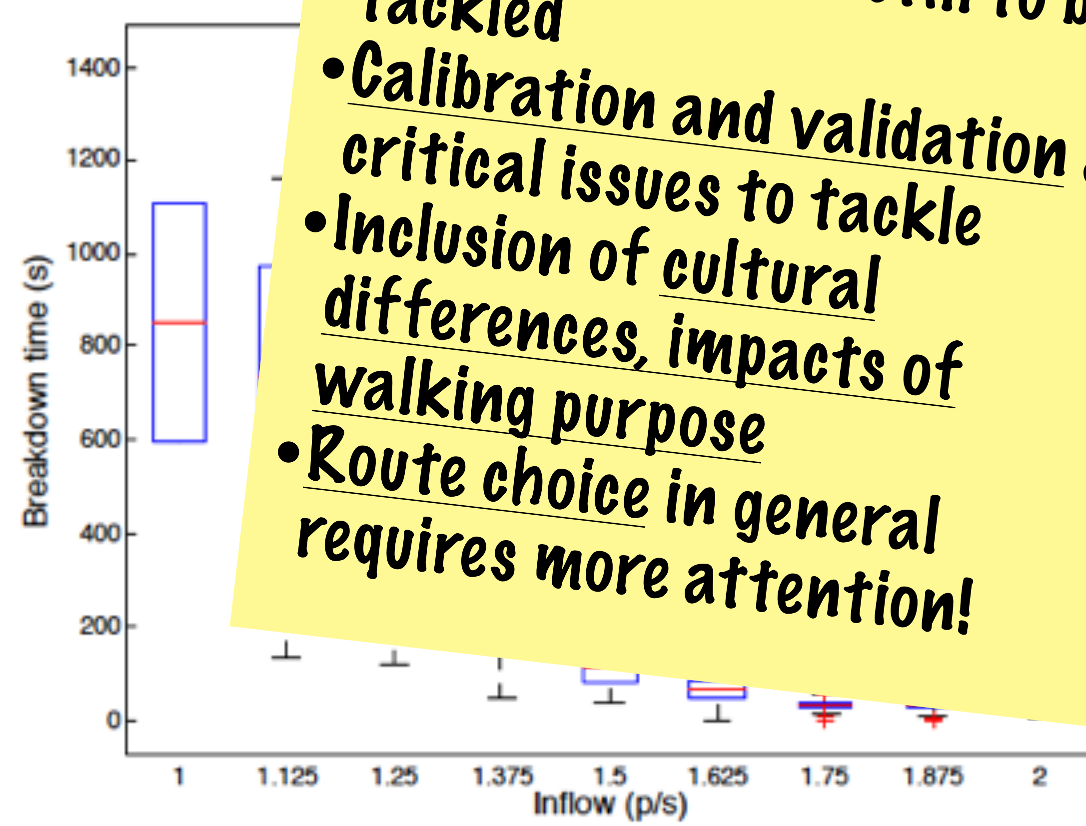

- Microscopic models have been relatively successful, although several issues are still to be tackled
- Calibration and validation are critical issues to tackle
- Inclusion of cultural differences, impacts of walking purpose
- Route choice in general requires more attention!

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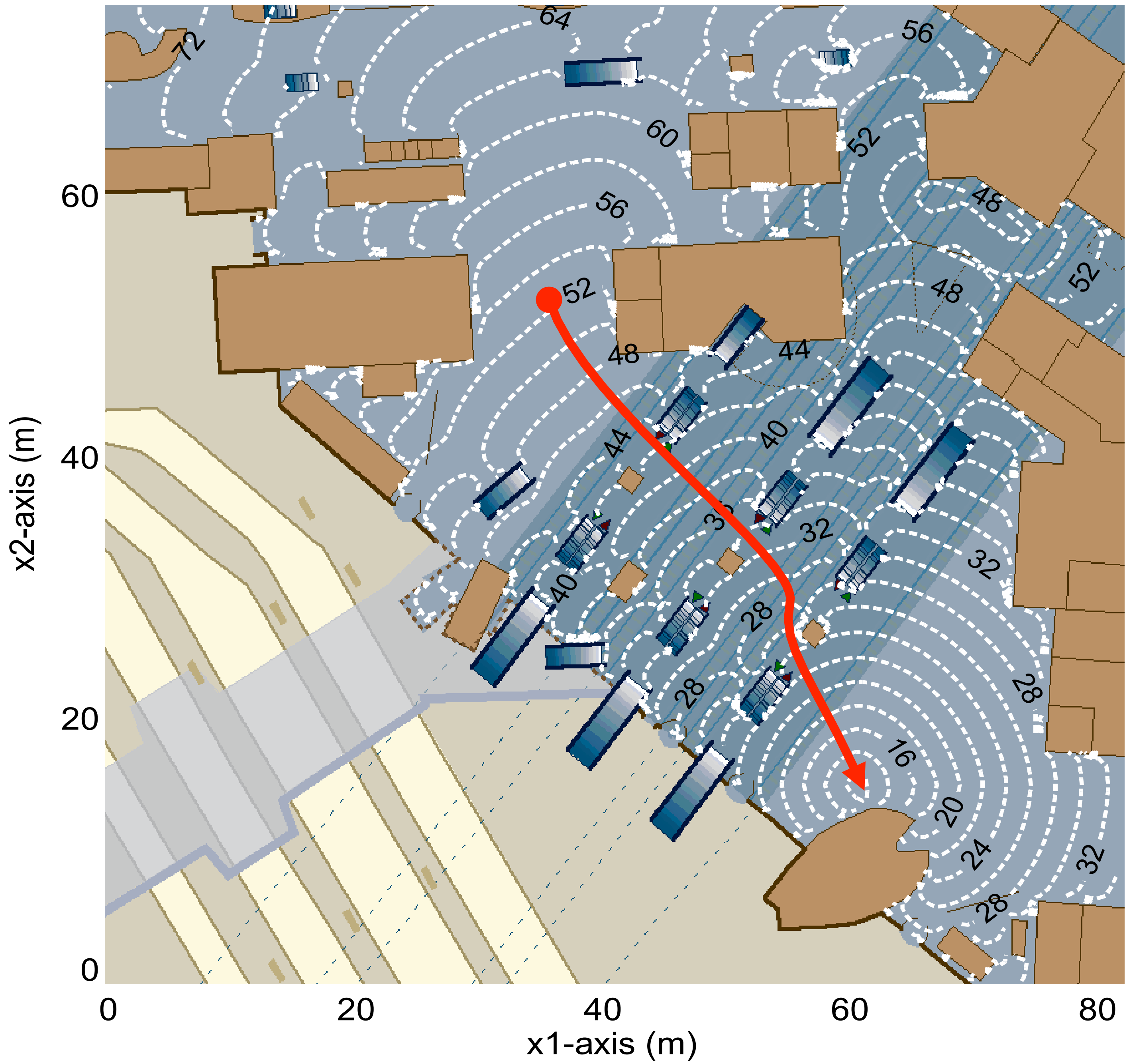
Dynamic programming

- NOMAD route choice: $\vec{v}_i^{\,0} = \vec{\gamma}^{\,0} \cdot V^0$
- Let W(t,**x**) denote minimum expected cost (travel time) from (t,**x**) to destination(s)
- W(t,**x**) satisfies HJB equation:

$$-\frac{\partial W}{\partial t} = L(t, \vec{x}, \vec{v}^{\,0}) + \vec{v}^{\,0} \nabla W + \frac{\sigma^2}{2} \Delta W$$

where $\vec{\gamma}^{\,0} = -\nabla W / \| \nabla W \|$

- Optimal direction $\vec{\gamma}^{\,0}$ perpendicular to iso-cost curves
- Efficient numerical solution approaches available...



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)

- Kinematic wave model for pedestrian flow for each destination d

$$\frac{\partial \rho_d}{\partial t} + \nabla \cdot \vec{q}_d = r - s \quad \text{with} \quad \vec{q}_d = \vec{\gamma}_d \cdot \rho_d \cdot V(\rho_1, \ldots, \rho_D)$$

- Here V is the (multi-class) equilibrium speed; the optimal direction:

$$\vec{\gamma}_d(t, \vec{x}) = -\frac{\nabla W_d(t, \vec{x})}{\| \nabla W_d(t, \vec{x}) \|}$$

- Stems from minimum cost $W_d(t,\mathbf{x})$ for each (set of) destination(s) d
- Is this a reasonable model?

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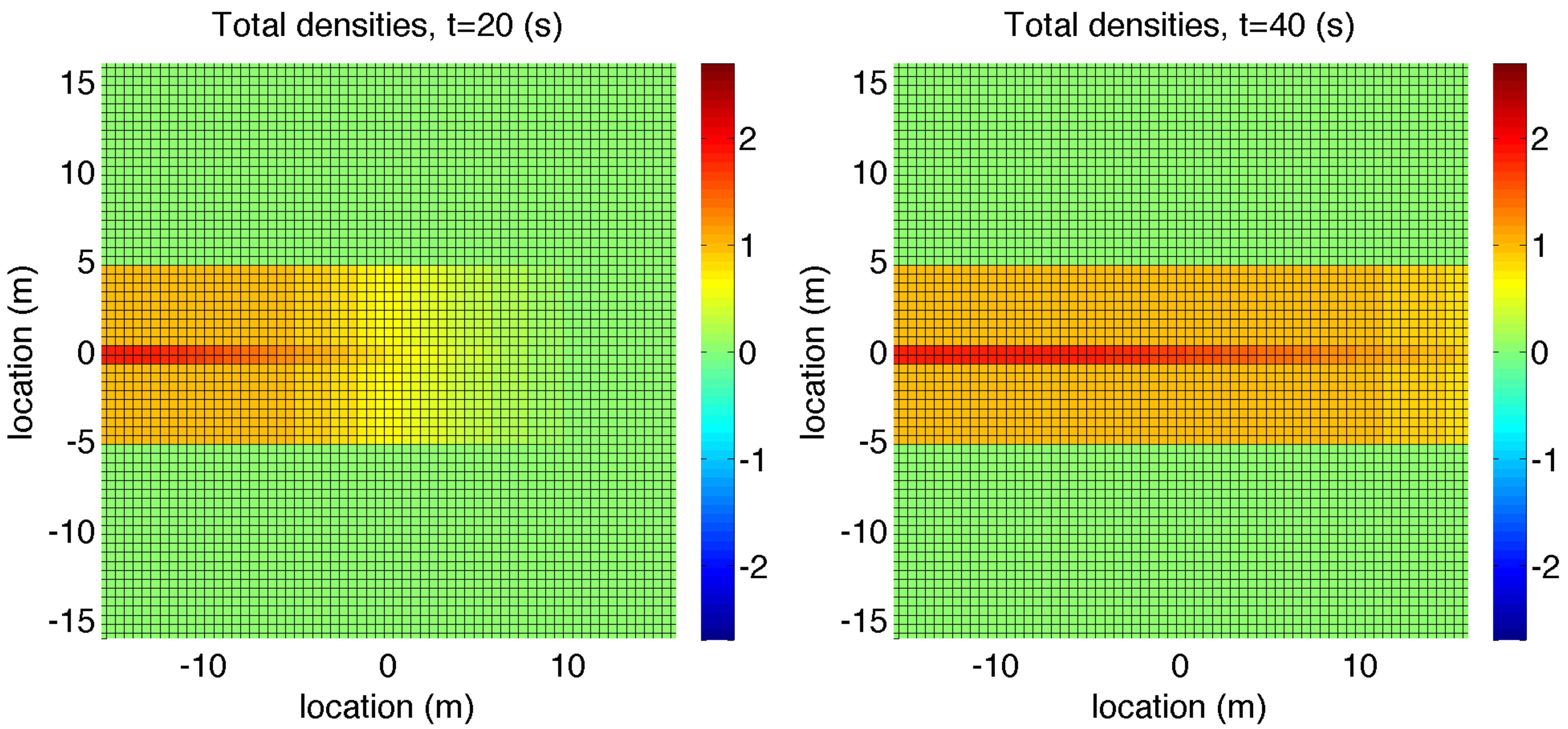
- Is this a reasonable model?
- No, since there is only pre-determined (global) route choice, the model will have unrealistic features

Continuum modelling

Dynamic assignment in continuous time and space

Macroscopic traffic flow modelling…



Solution? Include a term describing local route / direction choice…

Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models…

- 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 density as the 'probability' of a pedestrian being present, which 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:

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

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

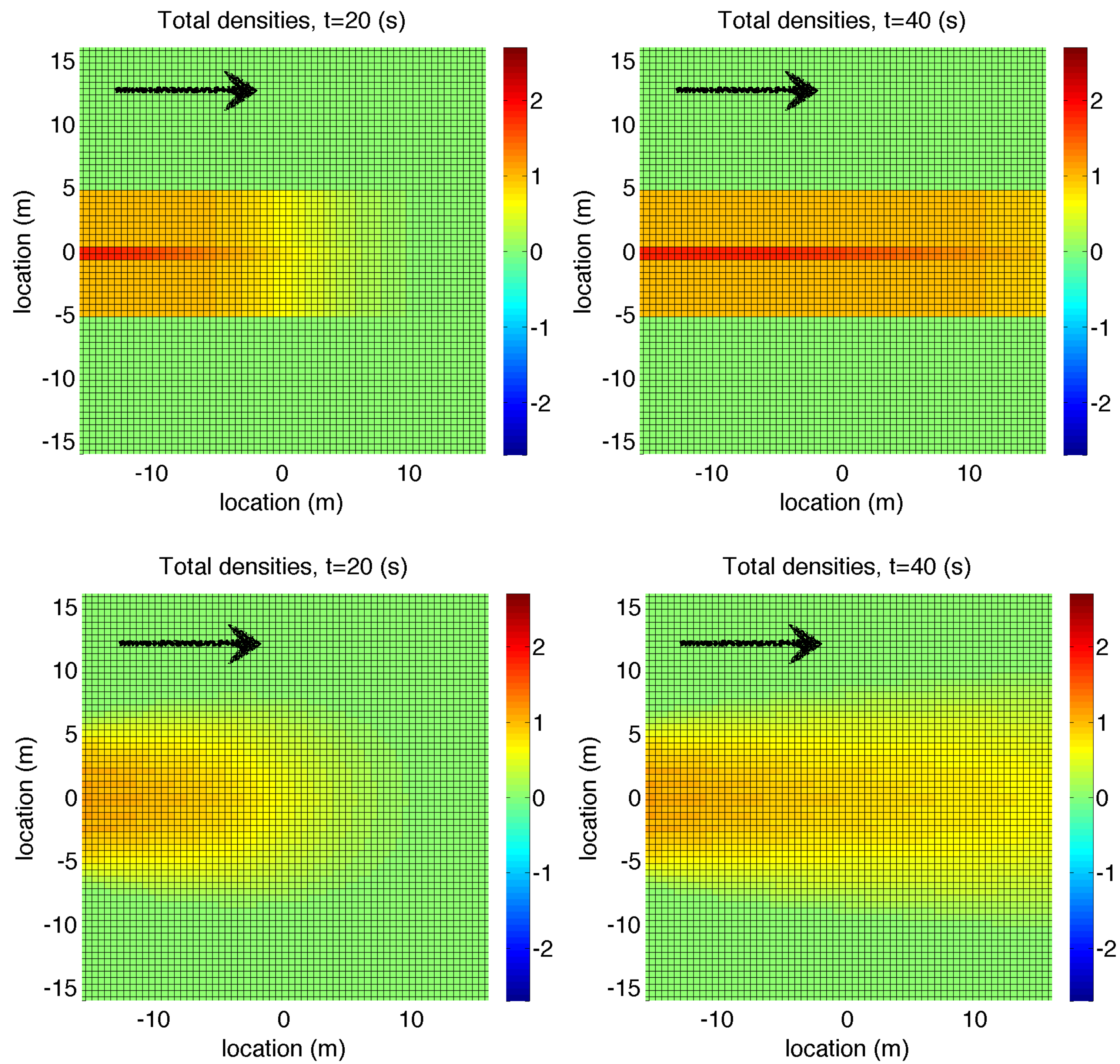
- with: $\alpha_0 = \pi\tau AB^2(1-\lambda)$ and $\beta_0 = 2\pi\tau AB^3(1+\lambda)$
- Check behaviour of model by looking at isotropic flow ($\lambda = 1$) and homogeneous flow conditions ($\nabla\rho = \vec{0}$)
- Multi-class generalisation + Godunov scheme numerical approximation

Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models…

- Uni-directional flow situation
- Picture shows differences between situation without and with local route choice for two time instances
- Model introduces 'lateral diffusion' since pedestrians will look for lower density areas actively
- Diffusion can be controlled by choosing parameters differently
- Model shows plausible behaviour

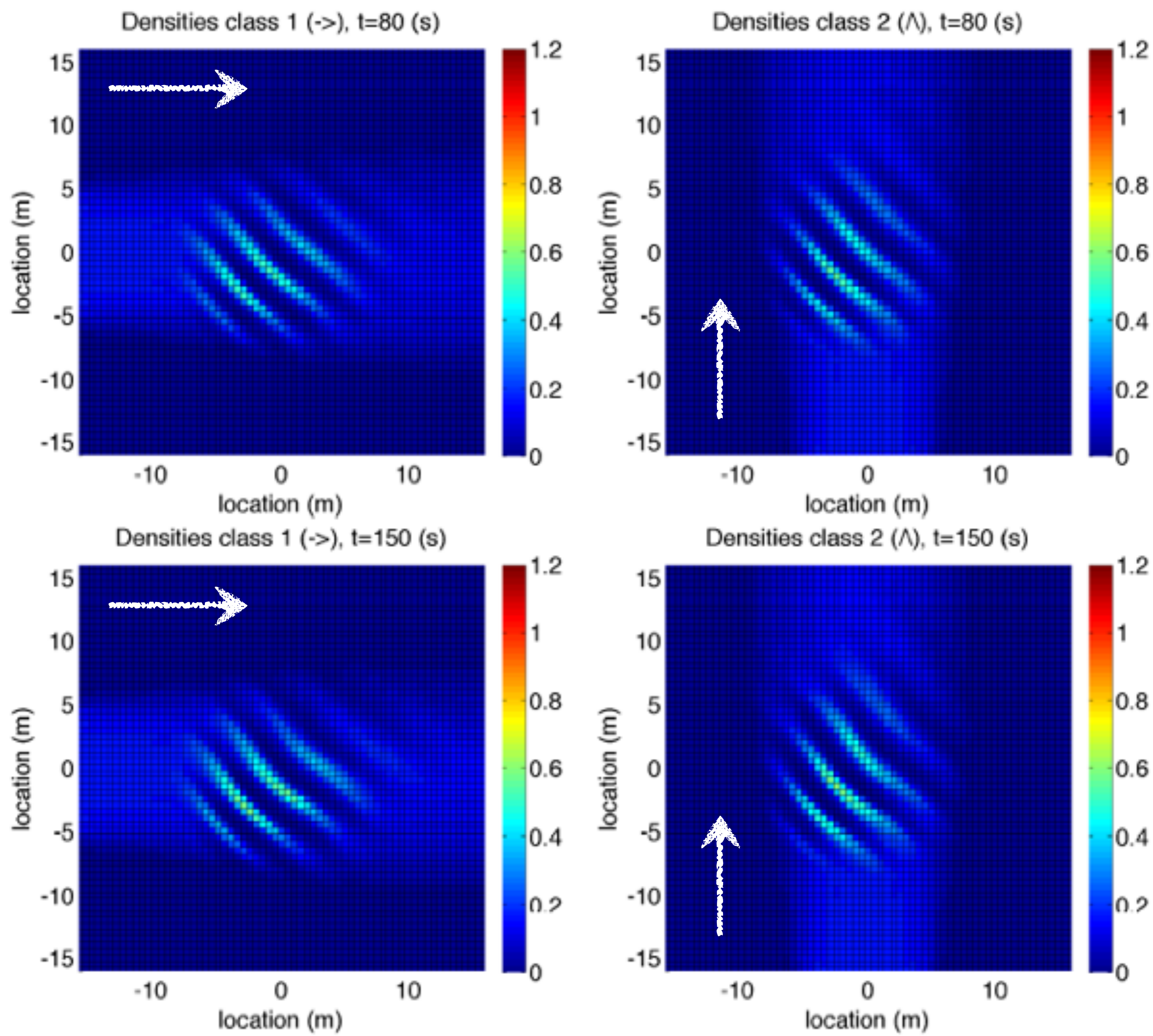


Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models…

- Simulation results also show formation of diagonal stripes…
- Patterns which are formed depend on parameters of models
- In particular, non-equal impact of own class and other classes on diversion behaviour appears important

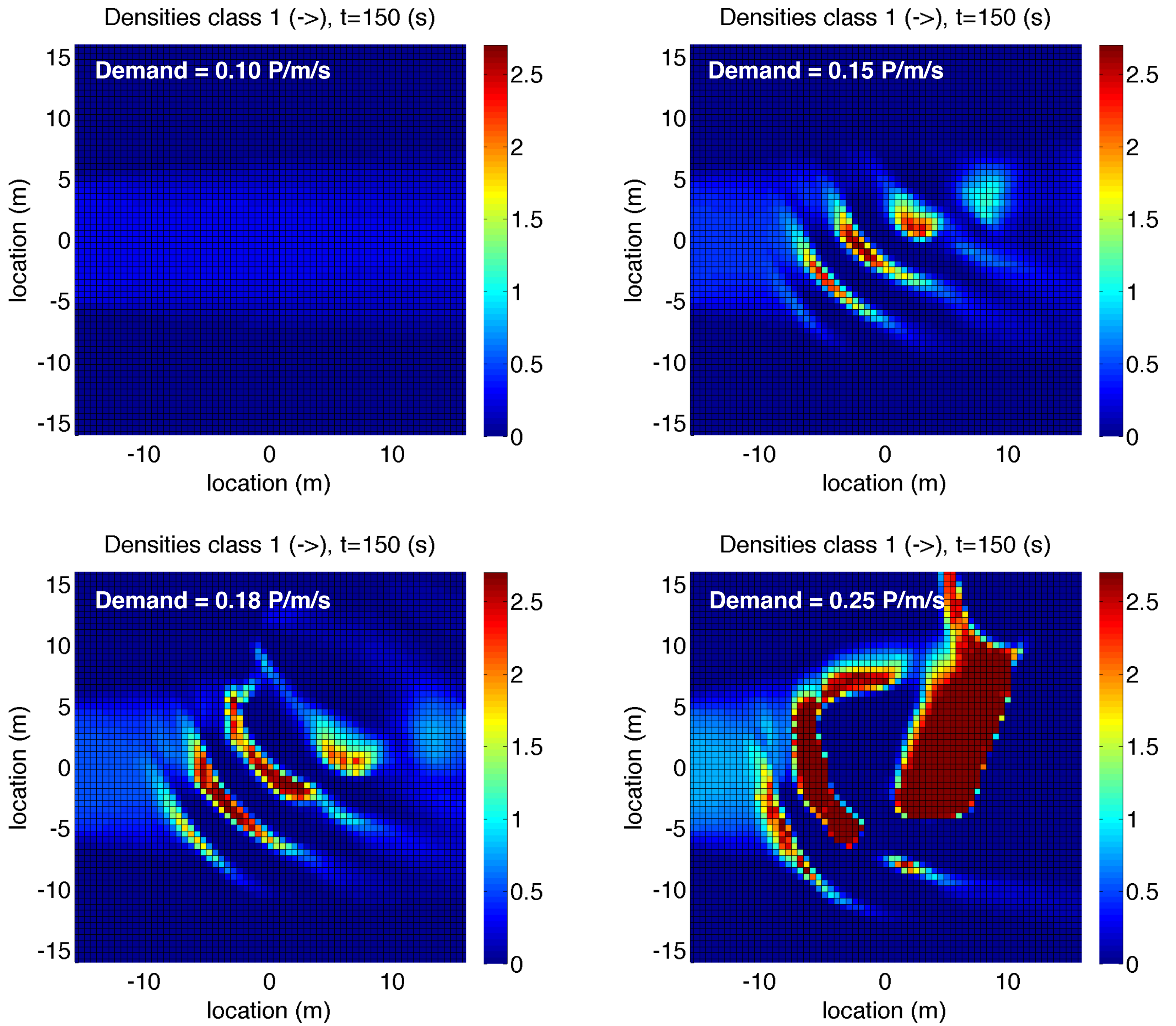


Continuum modelling - part 2

Computationally efficient modelling

Connecting microscopic to macroscopic models...

- Whether self-organisation occurs depends on demand level
- Low demand levels, no self-organisation
- Self-organisation fails for high demands and results in complete grid-lock (no outflow)
- Macroscopic model appears able to qualitatively reproduce crowd characteristics!



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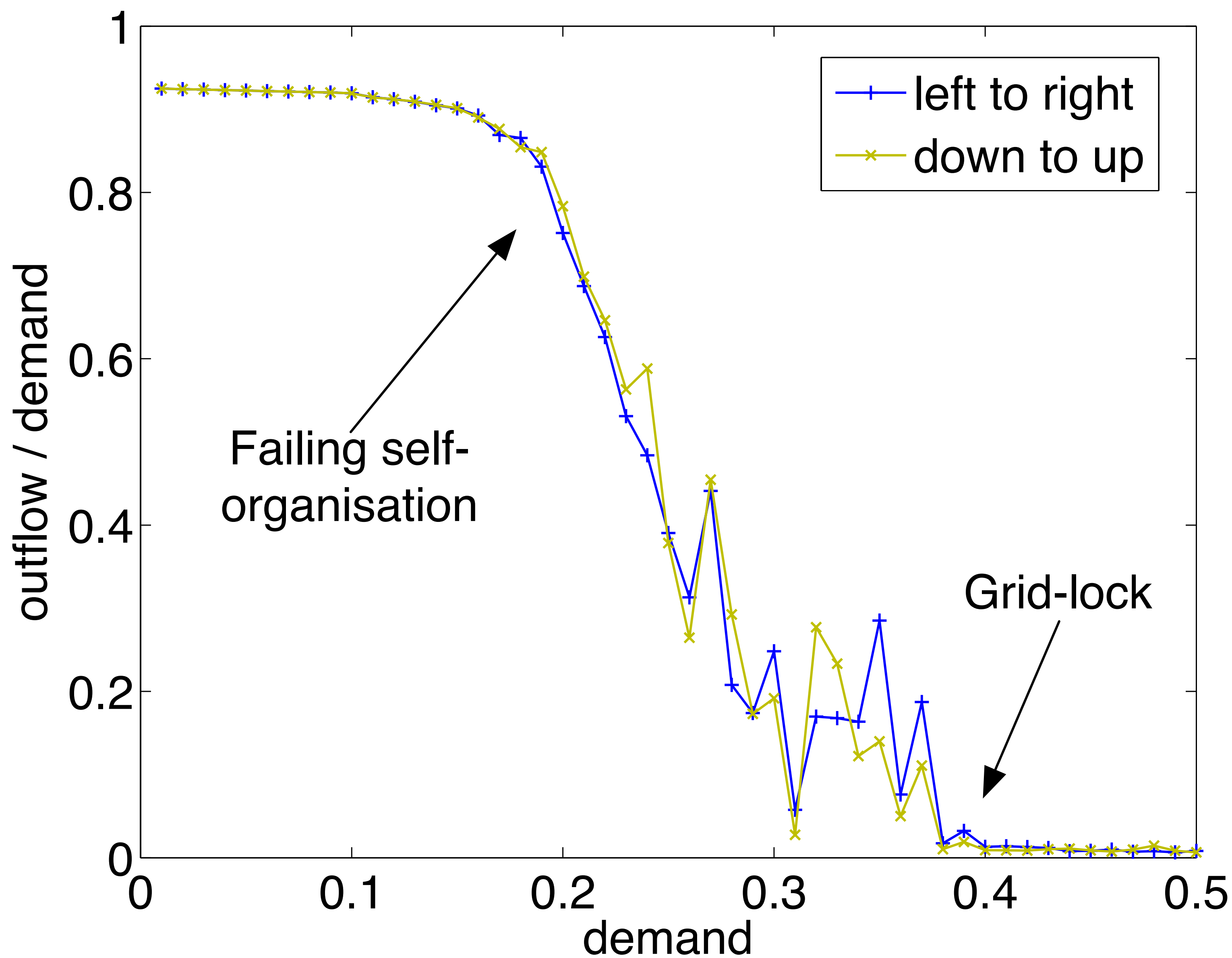

Continuum modelling - part 2

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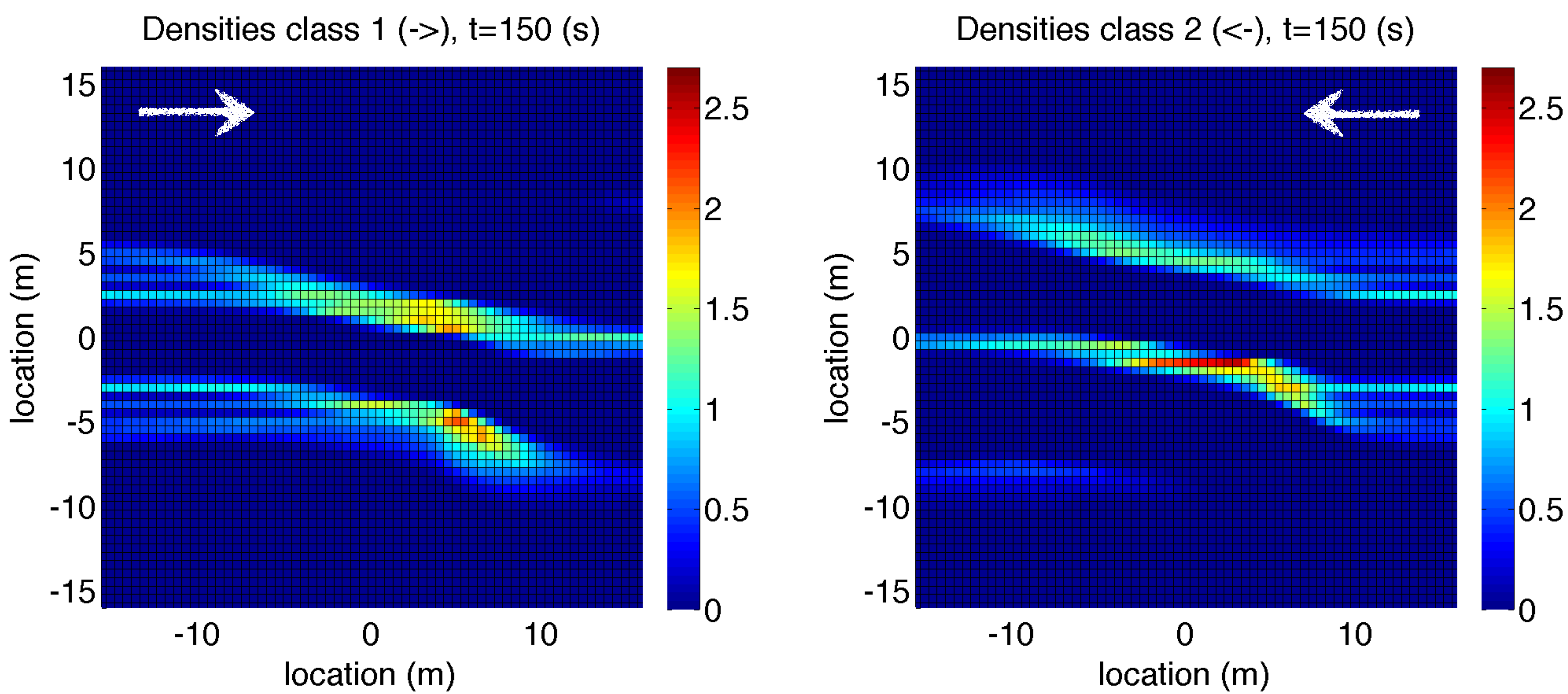
Connecting microscopic to macroscopic models…

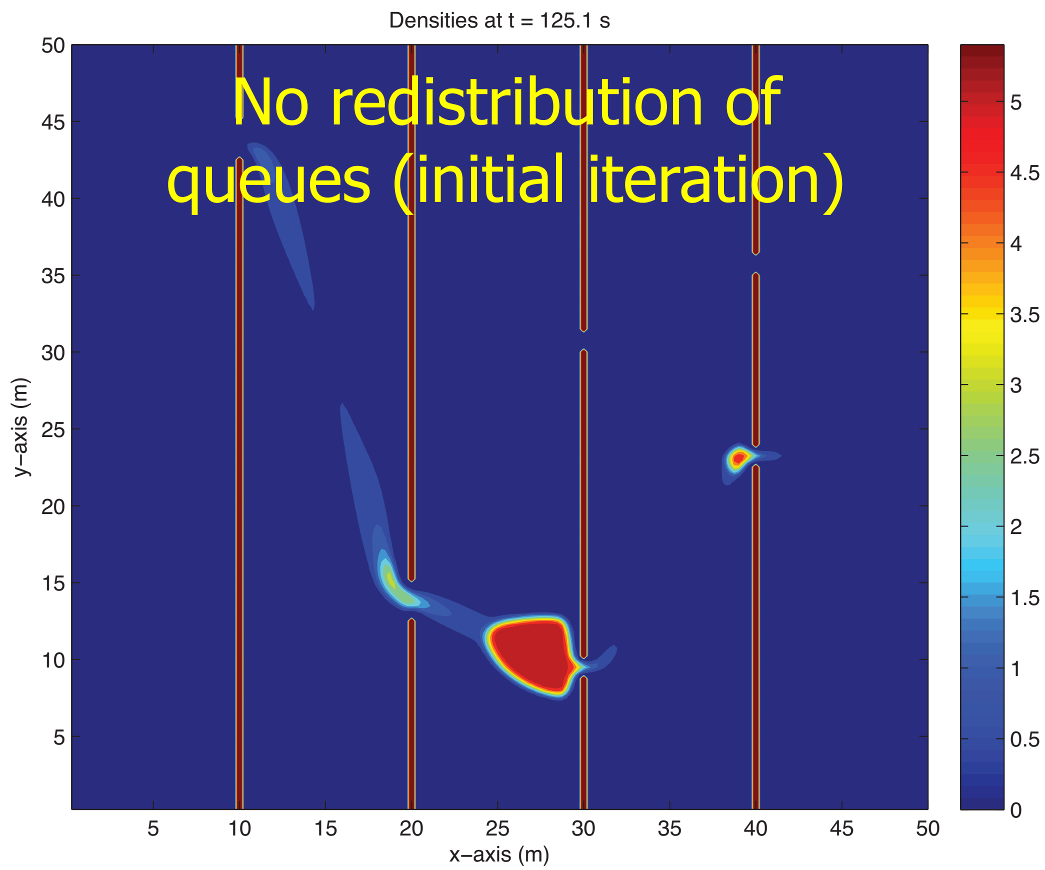
- Model seems to reproduce self-organised patterns (e.g. example below shows lane formation for bi-directional flows)

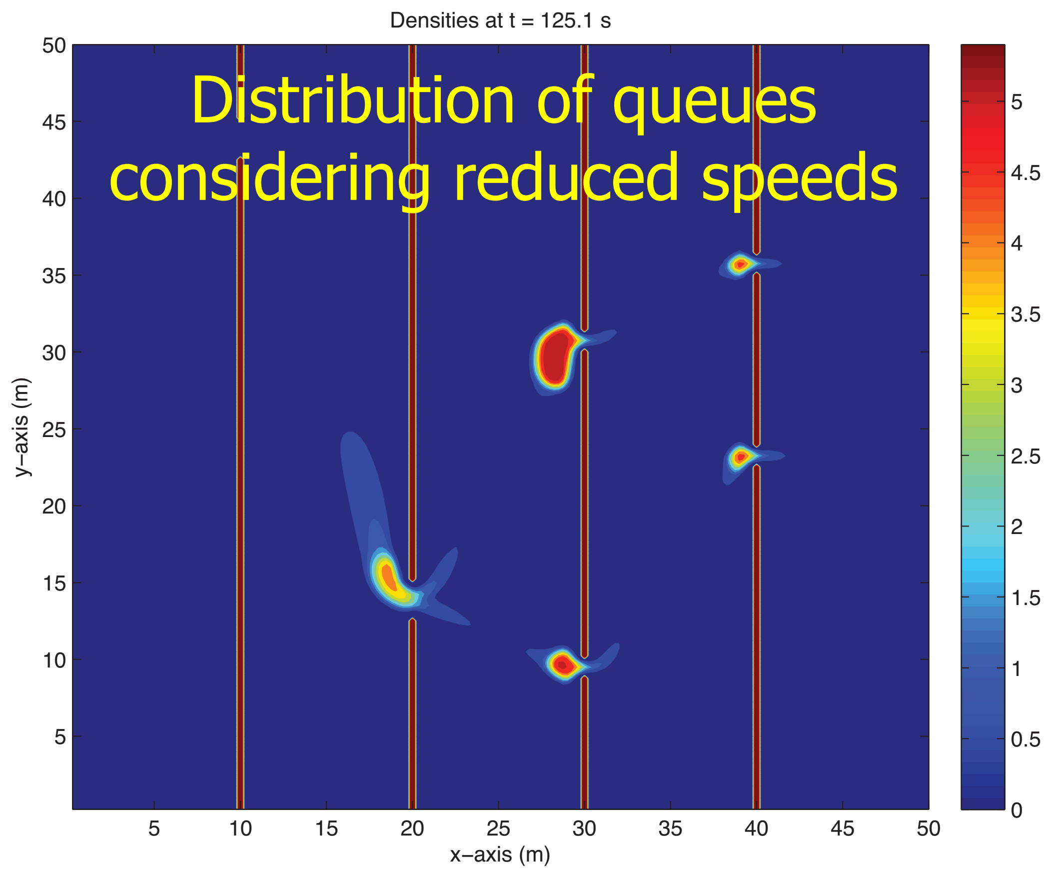


Applications?

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





Want to know more? Stay in touch!