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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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!

Examples showing increasing importance of crowd modeling & management

Religious or social gatherings, events, (re-)urbanisation, increase use of transit and rail…
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!!!
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Engineering challenges

Societal urgencies leads to demand for engineering solutions

*Importance of Theory and Models for Pedestrian and Crowd Dynamics*
Understanding Pedestrian Flows

Field observations, controlled experiments, virtual laboratories

_Data collection remains a challenge, but many new opportunities arise!_
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Data collection remains a challenge, but many new opportunities arise!
**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
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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Phenomena in pedestrian flow operations
Fascinating world of pedestrian flow dynamics!
Examples of self-organisation:

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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?
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Pedestrian modelling approaches
Representation and behaviour roles

Examples of micro, meso, and macroscopic pedestrian modelling approaches

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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:
• Pedestrians minimise predicted walking cost, due to straying from intended path, being too close to others / obstacles and effort, yielding $a_i(t)$:

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

• Simplified model is similar to Social Forces model of Helbing

Face validity?
• Model results in reasonable fundamental diagrams
• What about self-organisation?
Example: NOMAD Game Theoretical Model

Interaction modelling by using differential game theory

Or: Pedestrian Economicus as main theoretical assumption...

Example shows lane formation process for homogeneous groups...

Heterogeneity yields less efficient lane formation (freezing by heating)
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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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Dynamic programming

- NOMAD route choice: $\vec{v}_i^0 = \vec{y}^0 \cdot V^0$
- 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 $\vec{y}^0 = -\nabla W / \| \nabla W \|$
- Optimal direction $\vec{y}^0$ 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 $W_d(t, \vec{x})$ for each (set of) destination(s) $d$

- Is this a reasonable model?
Multi-class macroscopic model of Hoogendoorn and Bovy (2004)

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- Stems from minimum cost $W_d(t, \bar{x})$ for each (set of) destination(s) $d$

- 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...
• NOMAD / Social-forces model as starting point:

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

• Equilibrium relation stemming from model (\( a_i = 0 \)):

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

• Interpret density as the ‘probability’ of a pedestrian being present, which gives a macroscopic equilibrium relation (expected velocity), which equals:

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

• 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
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
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!
Whether self-organisation occurs depends on demand level

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- Self-organisation fails for high demands and results in complete grid-lock (no outflow)

- Macroscopic model appears able to qualitatively reproduce crowd characteristics!

For low densities, pedestrians will have very little incentive to adapt their path; while for high densities, they will be forced to adapt to maintain movement. The influence of the density gradients will be smaller for lower densities than for higher densities. This means that the delay factor yields a non-linear, effective density dependent weight factor.

We will investigate the impact of the delay factor. Examining Eqn. (9) shows that on the contrary to the crowdedness factor, the delay factor provides just the opposite result: the formation of diagonal stripes occurs by showing the normalised outflow.

Examples clearly illustrate the impact of the weights earlier (at a demand of 0.1 \( P/m/s \)) onward, the outflow completely stagnates and a grid-lock situation occurs. Also note that between 0.22 \( P/m/s \) and 0.28 \( P/m/s \), the demand - outflow relation appears more erratic, showing that efficiency is substantially reduced. Again, the results seem realistic compared to empirical knowledge about self-organised phenomena in pedestrian flows, at least from a qualitative perspective.

For a linear perceived speed-density function, we have shown that for low densities and small demand levels, self-organisation does not occur; if demand is too high, self-organisation stagnates and flow efficiency is substantially reduced. Again, the results seem realistic compared to empirical knowledge about self-organised phenomena in pedestrian flows, at least from a qualitative perspective.

Considering larger values for the effective density dependent weight factor, the results seem realistic compared to empirical knowledge about self-organised phenomena in pedestrian flows, at least from a qualitative perspective.

Based on these simulation results, we may conclude that the self-organisation that the model reproduces depends on the demand levels considered: if demand is too low, self-organisation does not occur; if demand is sufficiently low implying that there is sufficient interaction.

Connecting microscopic to macroscopic models...

To illustrate this process further, we have determined the average outflow of the area for both considered directions (again, scaled to demand to ensure that we can compare the different scenarios). Fig. 7 shows the results of this experiment: note that the average flow for the considered 400 s simulation period is never equal to 1, even if the demand - outflow ratio decreases strongly with increasing demand.

Fig. 8 (right) shows this result by showing the normalised outflow. For a linear perceived speed-density function, we have shown that for low densities and small demand levels, self-organisation does not occur; if demand is too high, self-organisation stagnates and flow efficiency is substantially reduced. Again, the results seem realistic compared to empirical knowledge about self-organised phenomena in pedestrian flows, at least from a qualitative perspective.

Fig. 7. Density contour plot (left) and scaled outflow rate (right).

Fig. 6. Density contour plot (left) and scaled outflow rate (right).

Fig. 5. Density contour plot (left) and scaled outflow rate (right).

The figure shows clearly how self-organisation and the failing thereof impacts the efficiency of the process: from the start-up period where the outflow is still zero.

\[ \text{demand} / \text{outflow} \]

\[ \text{outflow} / \text{demand} \]

\[ \text{demand} \]

\[ \text{outflow} \]

\[ \text{grid-lock} \]

\[ \text{failing self-organisation} \]

\[ \text{self-organisation} \]
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)

![Densities class 1 (->), t=150 (s)](image1)

![Densities class 2 (<=), t=150 (s)](image2)
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
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 on how to use our tools and models and what they can expect from them and what not.

Want to know more? Stay in touch!