hEART 2013

A mesoscopic dynamic flow model for pedestrian movement in railway stations

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Pedestrian flows in train stations (Lucerne, CH)
Framework for pedestrian flow estimation

Train timetable
Spatio-temporal observations
Travel surveys

Demand estimation
Traffic assignment

Dynamic trip table
Travel time, occupation

Demand
supply
Network-based pedestrian propagation models

- graph-based representation of space
- **cell-transmission models (CTM)** [AM90, Dag94, ASKT07]
  - mesoscopic: aggregate group of pedestrians
  - deterministic: 1st order flow theory
  - system dynamics: macroscopic fundamental diagram
- **queueing network based models** [CS94, Løv94, Daa04]
  - disaggregate: individual agents
  - stochastic: random queues
Representation of pedestrian facilities

- walkable area
- entry/exit points
- route $R = (r_0, r_1, \ldots)$
  - topological area $r$
  - ‘classical’ route choice
- path $\Gamma = (\xi_1, \xi_2, \ldots)$
  - discretization cell $\xi$
  - local path choice
Framework of pedestrian propagation model

- pedestrian fundamental diagram [Wei93]

\[ v = \min(\frac{k}{k_{\text{opt}}} - \frac{1}{k_{\text{jam}}}, \frac{q}{q_{\text{opt}}}) \]

\[ k_{\text{opt}} = 1.75 \]

\[ k_{\text{jam}} = 5.4 \]

\[ q_{\text{opt}} = 1.22 \]

\[ v_f = 1.34 \]
Framework of pedestrian propagation model

- pedestrian fundamental diagram [Wei93]
  - deterministic, isotropic density-velocity relation
  - hydrodynamic flow \( q(k) = kv(k) \)

- space: network of cells \( G = (V, E) \)
  - cells \( \xi \in V \), edges \( e \in E \)
  - in- and outflow edges of cell \( \xi \): \( I(\xi) \), \( O(\xi) \)

- time: discrete intervals \( \tau \in \mathcal{T} \)
  - uniform length \( \Delta t = \Delta L/v_f \), \( \Delta L^2 \): cell size

- pedestrians: groups \( \ell \in \mathcal{L} \)
  - route \( R \), departure interval \( \tau_0 \), size \( m_0 \)
  - \( m_\ell(\xi, \tau) \): size of group \( \ell \) in cell \( \xi \) during interval \( \tau \)
Advancement of group $\ell$ along path $\Gamma$

- ‘sending capacity’ of gate $g : i \rightarrow j$, $g \in \Gamma$ during interval $\tau$

\[
S^\ell_g(\tau) = \min \left\{ \frac{m^{\ell}(i, \tau)}{\sum_{\ell \in \mathcal{L}} m^{\ell}(i, \tau)} \cdot \tilde{Q}_i(\tau) \right\}
\]

- free flow: all agents proceed
- congestion: demand-proportional supply
- hydrodynamic outflow capacity

\[
\tilde{Q}_\xi(\tau) = \begin{cases} 
Q_\xi(\tau) & \text{if } \sum_{\ell \in \mathcal{L}} m_\ell(\xi, \tau) \leq k_{\text{opt}}\Delta L^2 \\
Q_{\xi, \text{opt}} & \text{otherwise}
\end{cases}
\]

$\sim Q_\xi(\tau)$: cumulated hydrodynamic cell flow

Ref: [ASKT07]
Advancement of group $\ell$ along path $\Gamma$

- ‘sending capacity’ of gate $g : i \rightarrow j$, $g \in \Gamma$ during interval $\tau$

\[
S_{g}^\ell(\tau) = \min \left\{ m_{\ell}(i, \tau), \frac{m_{\ell}(i, \tau)}{\sum_{\ell \in \mathcal{L}} m_{\ell}(i, \tau)} \cdot \bar{Q}_{i}(\tau) \right\}
\]

- ‘receiving capacity’ of cell $j$ during interval $\tau$

\[
R_{j}(\tau) = \min \left\{ N - \sum_{\ell \in \mathcal{L}} m_{\ell}(i, \tau), \hat{Q}_{j}(\tau) \right\}
\]

- cellular capacity ($N = k_{jam}\Delta L^2$)
- hydrodynamic inflow capacity

\[
\hat{Q}_{\xi}(\tau) = \begin{cases} 
Q_{\xi, opt} & \text{if } \sum_{\ell \in \mathcal{L}} m_{\ell}(\xi, \tau) \leq k_{opt}\Delta L^2 \\
Q_{\xi}(\tau) & \text{otherwise}
\end{cases}
\]

Ref: [ASKT07]
Advancement of group $\ell$ along path $\Gamma$

- actual flow along gate $g : i \rightarrow j$, $g \in \Gamma$ during interval $\tau$

\[
y_g^\ell(\tau) = \begin{cases} 
S_g^\ell(\tau) & \text{if } \sum_{h \in \mathcal{I}(j)} \sum_{\ell \in \mathcal{L}} S_h^\ell(\tau) \leq R_j(\tau) \\
X_g^\ell(\tau) R_j(\tau) & \text{otherwise}
\end{cases}
\]

- cell congestion: demand proportional supply distribution

\[
X_g^\ell(\tau) = \frac{S_g^\ell(\tau)}{\sum_{k \in \mathcal{I}(j)} \sum_{\ell \in \mathcal{L}} S_k^\ell(\tau)}
\]

- recursion for group $\ell$ in cell $i$

\[
m_\ell(i, \tau + 1) = m_\ell(i, \tau) + y_f^\ell(\tau) - y_g^\ell(\tau)
\]

- $\Gamma = (\ldots, f, g, \ldots)$, where $f : h \rightarrow i$, $g : i \rightarrow j$

Ref: [ASKT07]
Cell potentials for **en-route path choice**

- **route** \( R = (r_0, r_1, \ldots) \)
- **path** \( \Gamma = (\xi_1, \ldots, \xi_*) \)
- **route-specific floor field** \( F^R \)
  - distance to **destination** \( \star \)
  - \( F^R_{\xi} = \min \) if \( \xi = \xi_{\star}^R \)
- **traffic-dependent floor field**
  - prevailing speed \( v_{\xi}(\tau)/v_f \)
- **potential of cell** \( \xi \)
  - \( P^R_{\xi}(\tau) = F^R_{\xi} - \alpha \frac{v_{\xi}(\tau)}{v_f} \)
  - lower is ‘closer’ to destination
  - route \( R \), interval \( \tau \)

Ref: [HG08, GHW11]
Advancement of group $\ell$ along route $R$

- turning proportion: edge $g : i \rightarrow j$, $g \in \mathcal{E}_R$, interval $\tau$
  \[
  D^R_g(\tau) = \begin{cases} 
    \frac{P^R_j(\tau) - P^R_i(\tau)}{\sum_{k \in \Theta^R_i(\tau)}\{P^R_k(\tau) - P^R_i(\tau)\}}, & g \in \Theta^R_i(\tau) \\
    0, & \text{otherwise}
  \end{cases}
  \]

- sending capacity: edge $g : i \rightarrow j$, interval $\tau$
  \[
  S^\ell_g(\tau) = D^R_g(\tau) \min \left\{ m^\ell(i, \tau), \frac{m^\ell(i, \tau)}{\sum_{l \in \mathcal{L}} m^\ell(i, \tau)} \tilde{Q}_i(\tau) \right\}
  \]

- recursion for group $\ell$ in cell $\xi \in \mathcal{V}_R$
  \[
  m^\ell(\xi, \tau + 1) = m^\ell(\xi, \tau) + \sum_{h \in \Phi^R_\xi(\tau)} y^\ell_h(\tau) - \sum_{g \in \Theta^R_\xi(\tau)} y^\ell_g(\tau)
  \]
  \[
  - \Phi^R_\xi(\tau), \Theta^R_\xi(\tau): \text{set of up- and downstream neighbors of cell } \xi
  \]
Bi-directional flow in orthogonal crossing

Simulation parameters:
\[ \gamma = 1.913 \text{ #/m}^2, \]
\[ k_{jam} = 5.4 \text{ #/m}^2, \]
\[ n_0/N = 1, \alpha = 1 \]

<table>
<thead>
<tr>
<th>LOS</th>
<th>[#/m^2]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&lt; 0.179</td>
</tr>
<tr>
<td>B</td>
<td>&lt; 0.270</td>
</tr>
<tr>
<td>C</td>
<td>&lt; 0.455</td>
</tr>
<tr>
<td>D</td>
<td>&lt; 0.714</td>
</tr>
<tr>
<td>E</td>
<td>&lt; 1.333</td>
</tr>
<tr>
<td>F</td>
<td>≥ 1.333</td>
</tr>
</tbody>
</table>
Sensitivity towards congestion in counter-flow

normalized Kladek diagram: decreasing sensitivity w.r.t. congestion

\[ \gamma = \{0.1, 0.25, 0.5, 1.0, 1.913^*, 4, 10\} \]

* Default value according to [Wei93]
Sensitivity towards congestion in counter-flow

\[ k_{\text{jam}} = 5.4 \ \#/m^2, \ \frac{n_0}{N} = 0.5 \]

<table>
<thead>
<tr>
<th>( \gamma )</th>
<th>( \gamma = 0.1 )</th>
<th>( \gamma = 0.25 )</th>
<th>( \gamma = 0.5 )</th>
<th>( \gamma = 1 )</th>
<th>( \gamma = 1.913 )</th>
<th>( \gamma = 4 )</th>
<th>( \gamma = 10 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
<td>2.7 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 2.7</td>
</tr>
</tbody>
</table>
En-route path choice in bottleneck

\[ P^R_\xi(\tau) = F^R_\xi - \alpha \frac{v_\xi(\tau)}{v_f} \]

\[ \gamma = 1.913 \text{#/m}^2, \ k_{jam} = 5.4 \text{#/m}^2, \ n_0/N = 1.5 \]

\( \alpha = 0 \):

\( \alpha = 5 \):
Calibration using pedestrian tracking data

- data: pedestrian trajectories from multi-directional walkway (2 days, 7:37 – 7:52, Lausanne train station, Switzerland)
- objective function: \( \min \| \tau_{sim} - \tau_{obs} \|^2 \)
- calibration technique: simulated annealing [Ros06]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \mu_{cal} \pm \sigma_{cal} )</th>
<th>[Wei93]</th>
</tr>
</thead>
<tbody>
<tr>
<td>free-flow speed ( (v_f) )</td>
<td>1.069 ± 0.006</td>
<td>1.34</td>
</tr>
<tr>
<td>congestion sensitivity ( (\gamma) )</td>
<td>1.963 ± 0.069</td>
<td>1.913</td>
</tr>
<tr>
<td>jam density ( (k_{jam}) )</td>
<td>6.227 ± 0.424</td>
<td>5.4</td>
</tr>
<tr>
<td>path choice parameter ( (\alpha) )</td>
<td>0.555 ± 0.278</td>
<td>-</td>
</tr>
</tbody>
</table>

Table: Preliminary results of calibration
Calibration using pedestrian tracking data

- stochasticity of density-speed relation
- small density range

![Graph showing the relationship between average density and average speed, with data points and lines indicating calibrated values using PedCTM by Weidmann [Wei93]].

Lausanne (75 m², 60 s)

- calibrated using PedCTM
- Weidmann [Wei93]
Computational performance: Case study

Peak hour in pedestrian underpass of Lausanne train station: 07:00 – 08:30 (90 min), $N_{ped} = 9132$, $A_{tot} = 685.27 \text{ m}^2$

$t_{run} = 8 \text{ min 37 s}$ (MacBook Pro 2011)

Animation : Lausanne train station, 07:40 – 07:46, January 22, 2013

Simulation parameters: $v_f = 1.096 \text{ m/s}$, $\gamma = 1.913 \#/\text{m}^2$, $k_{jam} = 5.4 \#/\text{m}^2$, $\alpha = 0.5$, $N_{cell} = 94$, $\Delta L = 2.7 \text{ m}$, $\Delta \tau = 2.464 \text{ s}$, $N_\tau = 2192$
Conclusions

- congestion in pedestrian facilities of railway stations
- demand estimation ⇔ traffic assignment
  - space: route, path ⇔ areas, cells
  - pedestrians: groups with same route & departure time
- cell-based pedestrian propagation model
  - 1st-order pedestrian flow theory
  - multi-directionalinity
  - en-route path choice
- sensitivity analysis, preliminary calibration, case study
hEART 2013:

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