ÉCOLE POLYTECHNIQUE
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A mesoscopic dynamic flow model for pedestrian movement in railway stations

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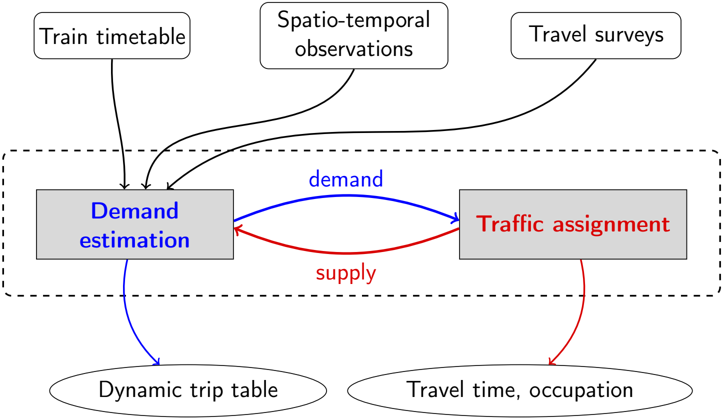
Pedestrian flows in train stations (Lucerne, CH)

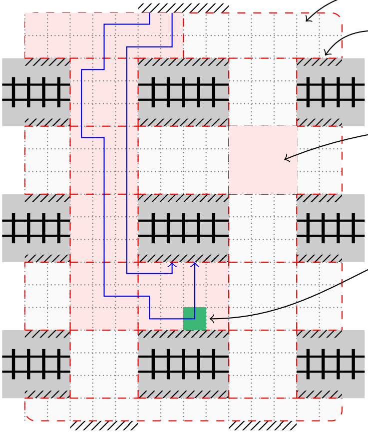
Framework for pedestrian flow estimation



Network-based pedestrian propagation models

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

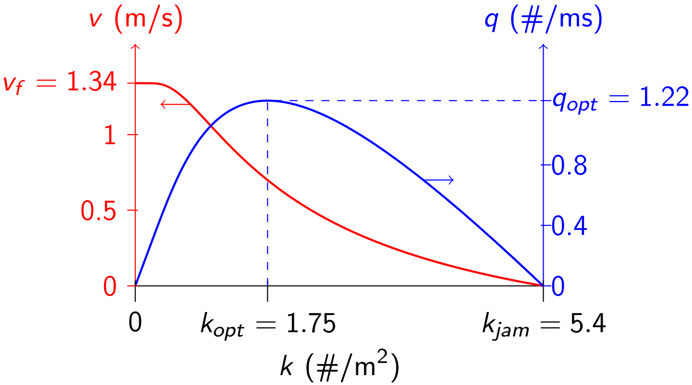
Representation of pedestrian facilities



- 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 ξ
  - local path choice

Framework of pedestrian propagation model

- pedestrian fundamental diagram [Wei93]



Framework of pedestrian propagation model

- pedestrian fundamental diagram [Wei93]
  - deterministic, isotropic density-velocity relation
  - hydrodynamic flow $q(k) = kv(k)$
- space: network of cells $\mathcal{G} = (\mathcal{V}, \mathcal{E})$
  - cells $\xi \in \mathcal{V}$, edges $g \in \mathcal{E}$
  - in- and outflow edges of cell ξ: $\mathcal{I}(\xi)$, $\mathcal{O}(\xi)$
- time: discrete intervals $\tau \in \mathcal{T}$
  - uniform length $\Delta t = \Delta L / v_f$, ΔL^2: cell size
- pedestrians: groups $\ell \in \mathcal{L}$
  - route R, departure interval τ_0, size m_0
  - $m_\ell(\xi, \tau)$: size of group ℓ in cell ξ during interval τ

Advancement of group ℓ along path Γ

- 'sending capacity' of gate $g : i \to j$, $g \in \Gamma$ during interval τ

$$S_g^\ell(\tau) = \min \left\{ m_\ell(i,\tau), \frac{m_\ell(i,\tau)}{\sum_{\ell \in \mathcal{L}} m_\ell(i,\tau)} \cdot \tilde{Q}_i(\tau) \right\}$$

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

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

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

Advancement of group ℓ along path Γ

- 'sending capacity' of gate $g : i \to j$, $g \in \Gamma$ during interval τ

$$S_g^\ell(\tau) = \min\left\{ m_\ell(i,\tau),\ \frac{m_\ell(i,\tau)}{\sum_{\ell\in\mathcal{L}} m_\ell(i,\tau)} \cdot \tilde{Q}_i(\tau) \right\}$$

- 'receiving capacity' of cell j during interval τ

$$R_j(\tau) = \min\left\{ N - \textstyle\sum_{\ell\in\mathcal{L}} m_\ell(i,\tau),\ \hat{Q}_j(\tau) \right\}$$

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

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

Advancement of group ℓ along path Γ

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

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

  - cell congestion: demand proportional supply distribution

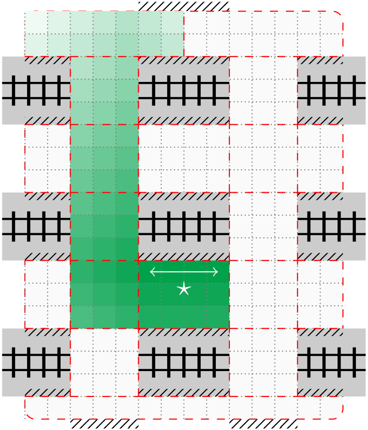
$$X_g^\ell(\tau) = \frac{S_g^\ell(\tau)}{\sum_{k\in\mathcal{I}(j)} \sum_{\ell\in\mathcal{L}} S_k^\ell(\tau)}$$

- recursion for group ℓ in cell i

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

  - $\Gamma = (\dots, f, g, \dots)$, where $f : h \to i$, $g : i \to j$

Cell potentials for en-route path choice



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

Ref: [HG08, GHW11]

Advancement of group ℓ along route R

- turning proportion: edge $g : i \to j$, $g \in \mathcal{E}_R$, interval τ

$$D_g^R(\tau) = \begin{cases} \frac{P_j^R(\tau) - P_i^R(\tau)}{\sum_{k \in \Theta_i^R(\tau)} \{P_k^R(\tau) - P_i^R(\tau)\}}, & g \in \Theta_i^R(\tau) \\ 0, & \text{otherwise} \end{cases}$$

- sending capacity: edge $g : i \to j$, interval τ

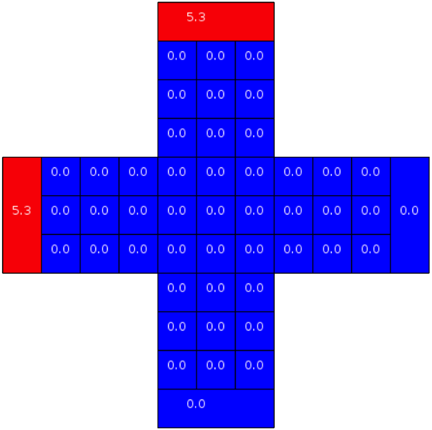
$$S_g^\ell(\tau) = D_g^R(\tau) \min \left\{ m_\ell(i,\tau), \frac{m_\ell(i,\tau)}{\sum_{l \in \mathcal{L}} m_\ell(i,\tau)} \tilde{Q}_i(\tau) \right\}$$

- recursion for group ℓ in cell $\xi \in \mathcal{V}_R$

$$m_\ell(\xi, \tau+1) = m_\ell(\xi, \tau) + \sum_{h \in \Phi_\xi^R(\tau)} y_h^\ell(\tau) - \sum_{g \in \Theta_\xi^R(\tau)} y_g^\ell(\tau)$$

  - $\Phi_\xi^R(\tau)$, $\Theta_\xi^R(\tau)$: set of up- and downstream neighbors of cell ξ

Bi-directional flow in orthogonal crossing

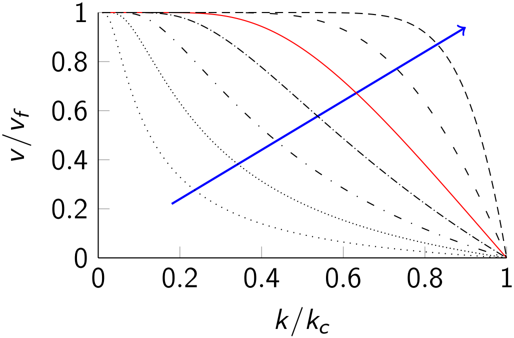


	LOS	[#/m^2]
Blue	A	< 0.179
Cyan	B	< 0.270
Green	C	< 0.455
Yellow	D	< 0.714
Orange	E	< 1.333
Red	F	≥ 1.333

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

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

$k_{jam} = 5.4\ \#/\mathrm{m}^2,\ n_0/N = 0.5$

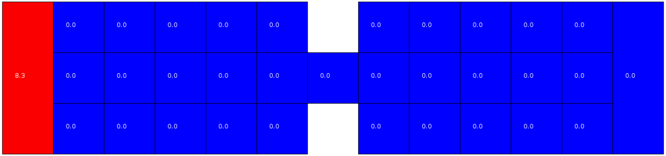
$\gamma = 0.1$	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7
$= 0.25$	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7
$= 0.5$	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7
$= 1$	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7
$= 1.913$	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.7
$= 4$	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
$= 10$	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

En-route path choice in bottleneck

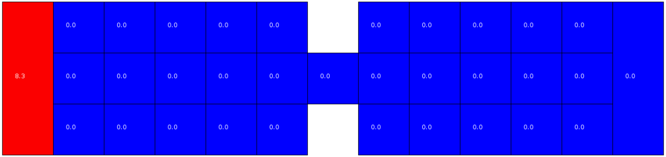
$$P_{\xi}^{R}(\tau) = F_{\xi}^{R} - \alpha \frac{v_{\xi}(\tau)}{v_f}$$

$$\gamma = 1.913 \ \#/\mathrm{m}^2, \ k_{jam} = 5.4 \ \#/\mathrm{m}^2, \ n_0/N = 1.5$$

$\alpha = 0$:



$\alpha = 5$:



Calibration using pedestrian tracking data

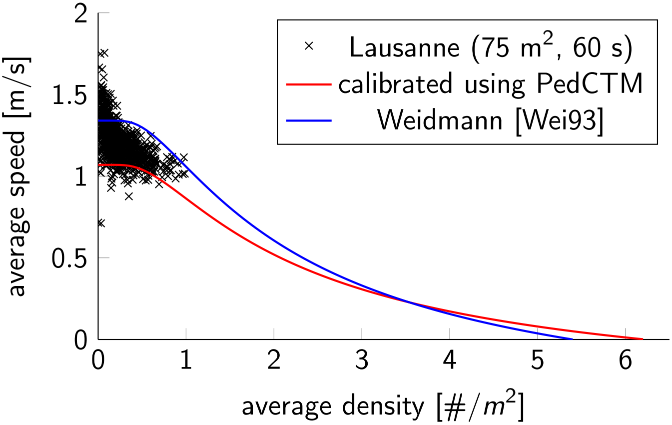
- data: pedestrian trajectories from multi-directional walkway (2 days, 7:37 – 7:52, Lausanne train station, Switzerland)
- objective function: $\min ||\tau_{sim} - \tau_{obs}||_2^2$
- calibration technique: simulated annealing [Ros06]

	$\mu_{cal} \pm \sigma_{cal}$	[Wei93]	
free-flow speed (v_f)	**1.069** $\pm$ 0.006	1.34	[m/s]
congestion sensitivity (γ)	1.963 $\pm$ 0.069	**1.913**	[#/m^2]
jam density (k_{jam})	6.227 $\pm$ 0.424	**5.4**	[#/m^2]
path choice parameter (α)	**0.555** $\pm$ 0.278	–	[-]

Table : Preliminary results of calibration

Calibration using pedestrian tracking data

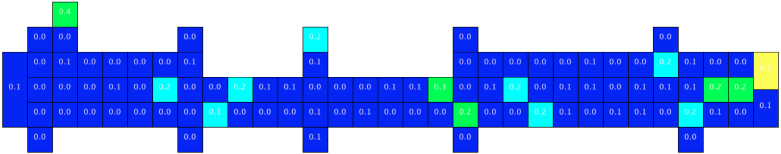
- stochasticity of density-speed relation
- small density range



Computational performance: Case study

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

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



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

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

Conclusions

- congestion in pedestrian facilities of railway stations
- demand estimation $\rightleftarrows$ traffic assignment
  - space: route, path $\leftrightarrow$ areas, cells
  - pedestrians: groups with same route & departure time
- cell-based pedestrian propagation model
  - 1^{st}-order pedestrian flow theory
  - multi-directionality
  - en-route path choice
- sensitivity analysis, preliminary calibration, case study

Thank you

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