The Hong Kong Polytechnic University
香港理工大學

École Polytechnique Fédérale de Lausanne

hEART 2015

A dynamic network loading model for anisotropic and congested pedestrian flows

Flurin S. Hänseler, William H.K. Lam, Michel Bierlaire, Gael Lederrey, Marija Nikolić

September 9, 2015

Unsteady, anisotropic and congested flow

Figure: Passageway in Central Station (MTR), Hong Kong

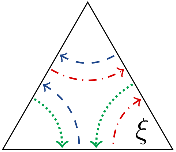
Aggregate pedestrian flow models

- graph-based models [CS94, Løv94]
  - interaction between streams entirely neglected
- cell transmission models [ASKT07, GHW11, HBFM14]
  - inherent assumption of isotropy
- continuum models [Hug02, HWZ^{+}09, HvWKDD14]
  - expensive, particularly for multi-class applications

Scope: ‘cheap’ anisotropic macroscopic loading model

Decomposition of pedestrian flow into streams

- contiguous area ξ of size A_ξ
- each stream $\lambda \in \Lambda_\xi$ characterized by
  - exogenous direction
  - accumulation M_λ
  - uni-directional speed V_λ



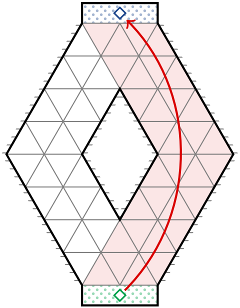
e.g. triangular area

stream-based fundamental diagram $\boldsymbol{f}(\boldsymbol{M})$ [WLC+10, XW15, FL15]

- accumulation and speed vectors: $\boldsymbol{M}_\xi = [M_\lambda]$, $\boldsymbol{V}_\xi = [V_\lambda]$
- bounded velocity: $0 \leq V_\lambda \leq V_f, \forall \lambda \in \Lambda_\xi$
- monotonic density-speed relation: $\partial V_\lambda / \partial M_{\lambda'} \leq 0, \forall \lambda, \lambda' \in \Lambda_\xi$

$$\boldsymbol{V}_\xi = V_f \boldsymbol{f}_\xi(\boldsymbol{M}_\xi; A_\xi)$$

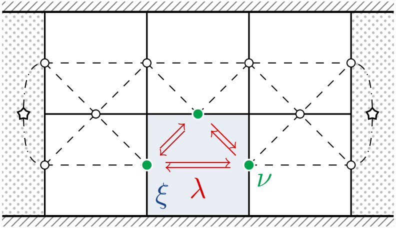
Time, space and demand



- time interval $\tau \in \mathcal{T}$
  - choice of $\Delta T = |\tau|$ crucial
- area $\xi \in \mathcal{X}$
  - no assumption regarding shape and size
- route $\rho \in \mathcal{R}$
  - origin/destination area: ξ_ρ^o, ξ_ρ^d
  - accessible network: $\mathcal{X}_\rho \subset \mathcal{X}$
- pedestrian group $\ell \in \mathcal{L}$
  - departure time interval τ_ℓ
  - group size x_ℓ
  - route ρ_ℓ

Pedestrian walking network

- $\mathcal{X}$: set of areas $\xi \in \mathcal{X}$
- $\mathcal{N}$: set of nodes $\nu \in \mathcal{N}$
- Λ: set of streams $\lambda \in \Lambda$, $\lambda : \nu_\lambda^o \to \nu_\lambda^d$
  - $L_\lambda > 0$: length of stream λ, $L_{\min} = \min_{\lambda \in \Lambda} L_\lambda$
  - Λ_ξ: set of streams associated with area ξ



- area: range of interaction
- node: flow valve/splitter
- stream: uni-directional flow

State variables and hydrodynamic flow

- fragment size
  - $M^{\ell}_{\lambda,\tau}$: accumulation of group ℓ on stream λ during interval τ
- aggregated variables
  - stream accumulation: $M_{\lambda,\tau} = \sum_{\ell\in\mathcal{L}} M^{\ell}_{\lambda,\tau}$
  - area accumulation: $M_{\xi,\tau} = \sum_{\lambda\in\Lambda_{\xi}} M_{\lambda,\tau}$
- 'hydrodynamic flow' on stream $\lambda \in \Lambda$ during interval τ
  - for uni-directional flow: flux = density $\times$ velocity
  - $\Delta Q_{\lambda,\tau} = L_{\mathsf{min}}/L_{\lambda} M_{\lambda,\tau} f_{\lambda}(\boldsymbol{M}_{\xi,\tau})$ if $\Delta T = \Delta L_{\mathsf{min}}/V_f$ (CFL)
  - reaches maximum $\Delta Q^{\mathsf{opt}}_{\lambda,\tau}$ at $M^{\mathsf{opt}}_{\lambda,\tau}$

Hydrodynamic flow capacities

- hydrodynamic inflow capacity

$$\Delta Q^{\mathsf{in}}_{\lambda,\tau} = \begin{cases} \Delta Q^{\mathsf{opt}}_{\lambda,\tau} & \text{if } M_{\lambda,\tau} \leq M^{\mathsf{opt}}_{\lambda,\tau} \\ \Delta Q_{\lambda,\tau} & \text{otherwise} \end{cases}$$

- hydrodynamic outflow capacity

$$\Delta Q^{\mathsf{out}}_{\lambda,\tau} = \begin{cases} \Delta Q_{\lambda,\tau} & \text{if } M_{\lambda,\tau} \leq M^{\mathsf{opt}}_{\lambda,\tau} \\ \Delta Q^{\mathsf{opt}}_{\lambda,\tau} & \text{otherwise} \end{cases}$$

Sending capacity

- receiving capacity of stream λ during interval τ

$$R_{\lambda,\tau} = \Delta Q^{\text{in}}_{\lambda,\tau}$$

- sending capacity of group ℓ on stream λ during interval τ

$$S^{\ell}_{\lambda\to\lambda',\tau} = \delta^{\rho_\ell}_{\lambda\to\lambda',\tau} \min\left\{ M^{\ell}_{\lambda,\tau}, \frac{M^{\ell}_{\lambda,\tau}}{M_{\lambda,\tau}} \Delta Q^{\text{out}}_{\lambda,\tau} \right\}$$

  - $\delta^{\rho}_{\lambda\to\lambda',\tau}$: turning proportion
  - free-flow: full local group proceeds
  - congestion: demand-proportional supply distribution

Actual transition flow

- candidate inflow to stream λ during interval τ

$$S_{\lambda,\tau} = \sum_{\lambda' \in \Phi_\lambda^\rho} \sum_{\ell \in \mathcal{L}} S^\ell_{\lambda' \to \lambda,\tau}$$

  - Φ_λ^ρ, Θ_λ^ρ: set of up-/downstream adjacent streams on route ρ

- actual transition flow

$$G^\ell_{\lambda \to \lambda',\tau} = \begin{cases} S^\ell_{\lambda \to \lambda',\tau} & \text{if } S_{\lambda',\tau} \leq R_{\lambda',\tau} \\ \zeta^\ell_{\lambda \to \lambda',\tau} R_{\lambda',\tau} & \text{otherwise} \end{cases}$$

  - congestion: demand-proportional supply

$$\zeta^\ell_{\lambda \to \lambda',\tau} = \frac{S^\ell_{\lambda \to \lambda',\tau}}{S_{\lambda',\tau}}$$

Propagation model

- continuity equation $\forall\, \tau \in \mathcal{T}$, $\forall\, \lambda \in \Lambda$, $\forall\, \ell \in \mathcal{L}$

$$M^{\ell}_{\lambda,\tau+1} = M^{\ell}_{\lambda,\tau} + \sum_{\lambda' \in \Phi^{\rho_\ell}_{\lambda}} G^{\ell}_{\lambda' \to \lambda,\tau} - \sum_{\lambda'' \in \Theta^{\rho_\ell}_{\lambda}} G^{\ell}_{\lambda \to \lambda'',\tau} + W^{\ell}_{\lambda,\tau}$$

  - source/sink term

Specification: Pedestrian fundamental diagram

- specification inspired by research at HKU [WLC+10, XW15]
- stream-based fundamental diagram (SbFD)

$$V_\lambda = V_f \cdot \exp\left\{-\vartheta\left(\frac{M_\xi}{A_\xi}\right)^2\right\} \prod_{\lambda' \in \Lambda_\xi} \exp\left(-\beta\left(1-\cos\varphi_{\lambda,\lambda'}\right)\frac{\mathcal{M}_{\lambda'}}{\mathcal{A}_\xi}\right)$$

  - isotropic reduction (Drake, 1967)
  - reduction due to pair-wise interaction of streams
    $\varphi_{\lambda,\lambda'}$: intersection angle between streams λ, λ'

- state-of-the-practice: Weidmann, 1992 [Wei92]

$$V_\lambda = V_f\left\{1-\exp\left[-\gamma\left(\frac{A_\xi}{M_\xi}-\frac{1}{k_{\text{jam}}}\right)\right]\right\}$$

Specification: Turning proportions

Potential field-based model [GHW11, HBFM14]

- route-specific potential $P^{\rho}_{\nu,\tau}$
  - e.g. $P^{\rho}_{\nu,\tau} \sim$ shortest path distance from node ν to area ξ^{d}_{ρ} along route ρ for traffic conditions prevalent during interval τ
- turning proportions ($\lambda' \in \Theta^{\rho}_{\lambda}$)
  - logit-type model with weight μ

$$\delta^{\rho}_{\lambda \to \lambda', \tau} = \frac{\exp\{-\mu P^{\rho}_{\nu^{d}_{\lambda'}, \tau}\}}{\sum_{\lambda'' \in \Theta^{\rho}_{\lambda}} \exp\{-\mu P^{\rho}_{\nu^{d}_{\lambda''}, \tau}\}}$$

Calibration

- maximum likelihood estimation
  - $\boldsymbol{\theta}$: unknown parameter vector
  - pedestrian $i = \{1, \ldots, N\}$
    - tt_i^{obs}: observed travel time
    - $f_i^{\text{est}}(tt|\boldsymbol{X}, \boldsymbol{\theta})$: estimated travel time probability density

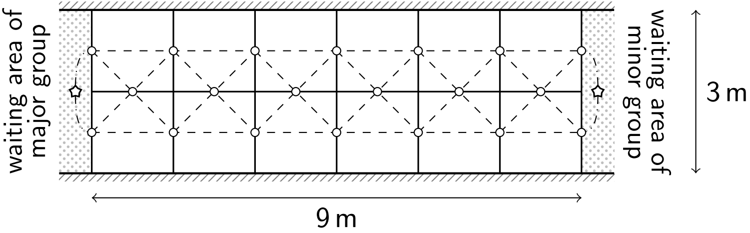
$$\hat{\boldsymbol{\theta}} = \arg\max \tilde{\mathcal{L}}(\boldsymbol{tt}_{\text{obs}}|\boldsymbol{X}, \boldsymbol{\theta})$$

with

$$\tilde{\mathcal{L}}(\boldsymbol{tt}_{\text{obs}}|\boldsymbol{X}, \boldsymbol{\theta}) = \sum_{i=1}^{N} \log\left(f_i^{\text{est}}(tt_i^{\text{obs}}|\boldsymbol{X}, \boldsymbol{\theta})\right)$$

- optimization algorithm: derivative-free trust-region method with random sampling of initial parameters [Pow09]

Counter-flow experiment (Wong et al., 2010)



Counter-flow experiment: Observed speeds

Exp.	major group		minor group	
#84	87 ped	1.08 ± 0.15 m/s	–	–
#85	79	1.19 ± 0.13	9 ped	0.80 ± 0.14 m/s
#86	68	0.90 ± 0.10	18	0.74 ± 0.15
#87	61	0.82 ± 0.06	26	0.67 ± 0.10
#88	53	0.83 ± 0.09	30	0.79 ± 0.15
#89	44	0.79 ± 0.10	44	0.79 ± 0.18

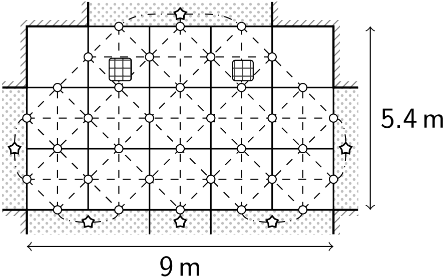
Extracted from Wong et al., 2010 [WLC+10]

Counter-flow experiment: Results

	Zero-Model	Drake	SbFD	Weidmann
$\tilde{\mathcal{L}}^{calib}_{85,87}$	–416.9	-374.0	-348.2	-360.7
V_f [m/s]	1.166	1.170	1.115	1.169
μ [-]	1.43	12.15	10.18	14.84
ϑ [m^4]		0.078	0.001	
β [m^2]			0.210	
γ [m^{-2}]				4.92
k_j [m^{-2}]				6.58
$\tilde{\mathcal{L}}^{valid}_{84}$	-175.6	-166.2	-151.7	-170.1
$\tilde{\mathcal{L}}^{valid}_{86}$	-188.9	-182.6	-173.7	-196.7
$\tilde{\mathcal{L}}^{valid}_{88}$	-198.1	-189.3	-178.0	-213.7
$\tilde{\mathcal{L}}^{valid}_{89}$	-227.1	-201.4	-194.4	-223.3

(SbFD also significantly better at aggregate level – not shown)

Cross-flow experiment (Plaue et al., 2014)

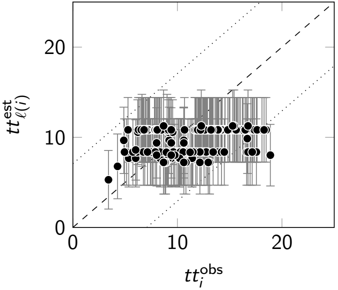


Cross-flow experiment: Results

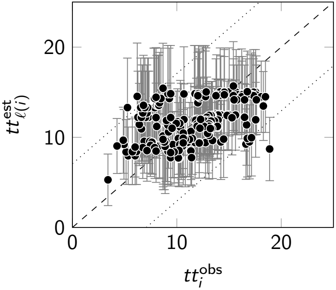
	Zero-Model	Drake	SbFD	Weidmann
$\tilde{\mathcal{L}}$	-578.0	-547.5	-527.3	-545.4
V_f [m/s]	1.307	1.308	1.308	1.332
μ [-]	1.16	1.39	2.64	2.05
ϑ [m^4]		0.139	0.143	
β [m^2]			0.300	
γ [m^{-2}]				1.76
k_j [m^{-2}]				5.99

Aggregate route travel times:

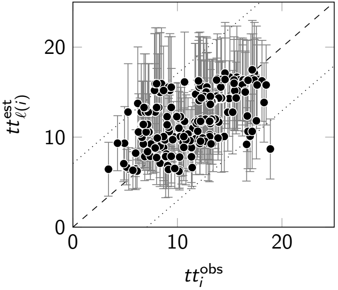
	N_{ped}	tt_{obs}	tt_{zero}	tt_{drake}	tt_{sbfd}	tt_{weid}
W $\rightarrow$ E	118	12.4	10.8	13.3	12.6	14.0
N $\rightarrow$ S	46	10.6	8.4	10.0	10.9	9.9



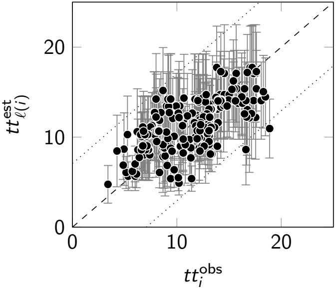
(a) Zero-Model (L^2-error: 53.3 s)



(b) Drake (L^2-error: 47.6 s)

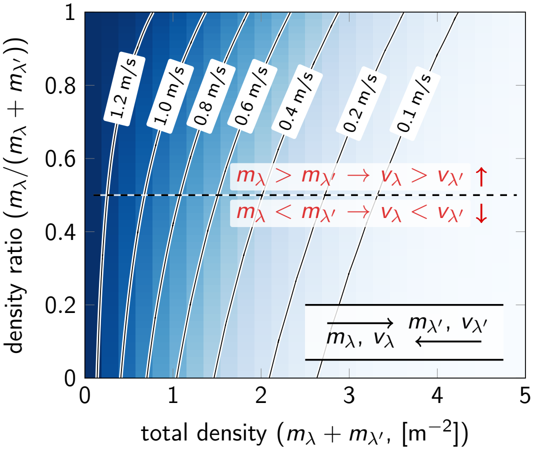


(c) Weidmann (L^2-error: 47.4 s)



(d) SbFD (L^2-error: 39.2 s)

Illustration: Walking speed in counter-flow



$\lambda \in \Lambda_\xi$:
$m_\lambda = M_\lambda / A_\xi$
$v_\lambda = V_\lambda / V_f$

Parameters:
$V_f = 1.308$ m/s
$\vartheta = 0.143$ m^4
$\beta = 0.300$ m^2
(Berlin data set)

Concluding remarks

- macroscopic model for congested, multi-directional flow
- explicit consideration of anisotropy
  - stream-based fundamental diagram
- calibration and validation using MLE
  - counter- and cross-flow experiments (Hong Kong and Berlin)
- future work
  - improvement in specification (e.g. fundamental diagram)
  - phenomena of self-organization
  - applications within DTA-framework, demand estimation

Thank you

hEART 2015:

A dynamic network loading model for anisotropic and congested pedestrian flows

Flurin S. Hänseler, William H.K. Lam, Michel Bierlaire,
Gael Lederrey, Marija Nikolić

Help by R. Scarinci, M. de Lapparent and J.-P. Lebacque is appreciated.
Financial support by SNSF, EPFL and PolyU is gratefully acknowledged.

– flurin.haenseler@epfl.ch

Bibliography I

M. Asano, A. Sumalee, M. Kuwahara, and S. Tanaka.
Dynamic cell transmission-based pedestrian model with multidirectional flows and strategic route choices.
Transportation Research Record: Journal of the Transportation Research Board, 2039(1):42–49, 2007.

J. Y. Cheah and J. M. G. Smith.
Generalized M/G/c/c state dependent queueing models and pedestrian traffic flows.
Queueing Systems, 15(1):365–386, 1994.

Bibliography II

G. Flötteröd and G. Lämmel.
Bidirectional pedestrian fundamental diagram.
Transportation Research Part B: Methodological, 71:194–212, 2015.

R. Y. Guo, H. J. Huang, and S. C. Wong.
Collection, spillback, and dissipation in pedestrian evacuation: A network-based method.
Transportation Research Part B: Methodological, 45(3):490–506, 2011.

Bibliography III

F. S. Hänseler, M. Bierlaire, B. Farooq, and T. Mühlematter.
A macroscopic loading model for time-varying pedestrian flows in public walking areas.
Transportation Research Part B: Methodological, 69:60–80, 2014.

R. L. Hughes.
A continuum theory for the flow of pedestrians.
Transportation Research Part B: Methodological, 36(6):507–535, 2002.

Bibliography IV

- S. P. Hoogendoorn, F. L. M. van Wageningen-Kessels, W. Daamen, and D. C. Duives.
  Continuum modelling of pedestrian flows: From microscopic principles to self-organised macroscopic phenomena.
  Physica A: Statistical Mechanics and its Applications, 416:684–694, 2014.

- L. Huang, S. C. Wong, M. Zhang, C. W. Shu, and W. H. K. Lam.
  Revisiting Hughes' dynamic continuum model for pedestrian flow and the development of an efficient solution algorithm.
  Transportation Research Part B: Methodological, 43(1):127–141, 2009.

Bibliography V

G. G. Løvås.
Modeling and simulation of pedestrian traffic flow.
Transportation Research Part B: Methodological, 28(6):429–443, 1994.

M. J. D. Powell.
The BOBYQA algorithm for bound constrained optimization without derivatives.
Report DAMTP 2009/NA06, Department of Applied Mathematics and Theoretical Physics, Cambridge University, 2009.

Bibliography VI

U. Weidmann.
Transporttechnik der Fussgänger.
Schriftenreihe des IVT Nr. 90. Institute for Transport Planning and Systems, ETH Zürich, Switzerland, 1992.

S. C. Wong, W. L. Leung, S. H. Chan, W. H. K. Lam, N. H. C. Yung, C. Y. Liu, and P. Zhang.
Bidirectional pedestrian stream model with oblique intersecting angle.
Journal of Transportation Engineering, 136(3):234–242, 2010.

Bibliography VII

S. Xie and S. C. Wong.
A Bayesian inference approach to the development of a multidirectional pedestrian stream model.
Transportmetrica A: Transport Science, 11(1):61–73, 2015.