HKSTS Post-Conference Workshop

A macroscopic loading model for dynamic, multi-directional and congested pedestrian flows

Flurin S. Hänseler, William H.K. Lam, Michel Bierlaire

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Modeling of pedestrian behavior

Levels of pedestrian behavior [HB04]

- **strategical:** choice of departure time and activity pattern
- **tactical:** choice of activity scheduling and route
- **operational:** en-route path choice, walking behavior

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This work:

- focus on operational level
- interaction across levels kept in mind

→ development of macroscopic network loading model

Unsteady, anisotropic and congested flow

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

Aggregate pedestrian flow models

- link transmission models/queuing networks [CS94, Løv94]
  - interaction between links neglected
- cell transmission models [ASKT07, GHW11, HBFM14]
  - inherent assumption of isotropy
- continuum models [Hug02, HWZ+09, HvWKDD14]
  - expensive, particularly for multi-class applications

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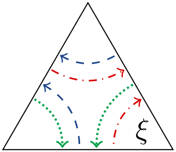
Idea: ‘cell-based link-transmission model’
$\rightarrow$ stream-based pedestrian fundamental diagram [WLC+10, XW14]

Decomposition of pedestrian flow into streams

- contiguous area ξ of size A_ξ
- each stream $\sigma \in \Sigma_\xi$ characterized by
  - direction (exogenous)
  - area occupation m_ξ^σ
  - uni-directional velocity V_ξ^σ



e.g. decomposition based on exit edge

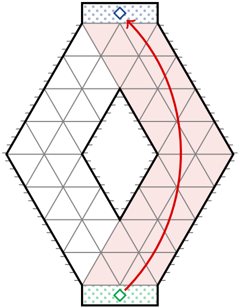
stream-based fundamental diagram $\boldsymbol{f}(\boldsymbol{m})$

- bounded velocity: $0 \leq V_\xi^\sigma \leq V_f,\ \forall\, \sigma \in \Sigma_\xi$
- concave density-speed relation: $\partial V_\xi^\sigma / \partial m_\xi^{\sigma'} \leq 0,\ \forall\, \sigma, \sigma' \in \Sigma_\xi$
- speed and density vectors: $\boldsymbol{v}_\xi^\Sigma = [V_\sigma / V_f]$, $\boldsymbol{m}_\xi^\Sigma = [m_\sigma]$

$$v_\xi^\sigma = f_\xi^\sigma(\boldsymbol{m}_\xi^\Sigma, \boldsymbol{v}_\xi^\Sigma; A_\xi)$$

- several specifications available [WLC+10, XW14, FL15]

Time, space and demand

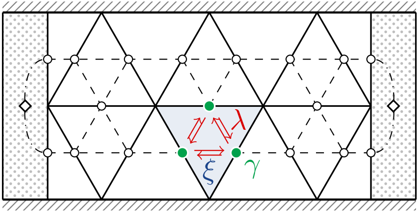


- time interval $\tau \in \mathcal{T}$
  - choice of $\Delta t = |\tau|$ crucial
- cell $\xi \in \mathcal{X}$
  - convex space partitioning
- route $\rho \in \mathcal{R}$
  - origin/destination cell: ξ_ρ^o, ξ_ρ^d
  - accessible network: $\mathcal{X}_\rho \subset \mathcal{X}$
- pedestrian group $\ell \in \mathcal{L}$
  - departure interval τ_ℓ
  - group size x_ℓ
  - route ρ_ℓ

Pedestrian walking network

Pedestrian network $\mathcal{G} = \{\mathcal{N}, \Lambda\}$

- $\mathcal{N}$: set of nodes $\nu \in \mathcal{N}$ connecting adjacent cells
- Λ: set of links $\lambda \in \Lambda$, $\lambda : \nu_\lambda^o \to \nu_\lambda^d$
  - Λ_ξ: set of links associated with cell ξ
  - Λ_ξ^σ: set of links associated with stream σ in cell ξ
  - Φ_λ^ρ, Θ_λ^ρ: set of up-/downstream adjacent links on route ρ
  - $L_\lambda > 0$: length of link λ, $L_{\min} = \min_{\lambda \in \Lambda} L_\lambda$



- links: uni-directional flow
- cells: range of interaction
- nodes: flow valves/splitters

State variables and hydrodynamic flow

- state variables
  - $m^{\ell}_{\lambda,\tau}$: size of group ℓ on link λ during interval τ
  - aggregation per link: $m_{\lambda,\tau} = \sum_{\ell \in \mathcal{L}} m^{\ell}_{\lambda,\tau}$
  - aggregation per stream: $m^{\sigma}_{\xi,\tau} = \sum_{\lambda \in \Lambda^{\sigma}_{\xi}} m_{\lambda,\tau}$
  - aggregation per cell: $m_{\xi,\tau} = \sum_{\lambda \in \Lambda_{\xi}} m_{\lambda,\tau}$

- 'hydrodynamic flow' on link $\lambda \in \Lambda^{\sigma}_{\xi}$ during interval τ
  - for uni-directional stream: flux = density × velocity
  - $\Delta Q_{\lambda,\tau} = L_{\min}/L_{\lambda} m_{\lambda,\tau} f_{\sigma}(\boldsymbol{m}^{\Sigma}_{\xi,\tau})$ if $\Delta t = \Delta L / v_f$ (CFL)
  - reaches maximum $\Delta Q^{\text{opt}}_{\lambda,\tau}$ at $m^{\text{opt}}_{\lambda,\tau}$

Hydrodynamic flow capacities

- hydrodynamic inflow capacity

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

- hydrodynamic outflow capacity

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

Link model

- receiving capacity on link λ during interval τ

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

- sending capacity of group ℓ on link 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 proportions
  - free-flow: full local group proceeds
  - congestion: demand-proportional supply distribution

Gate model

- candidate inflow to link λ during interval τ

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

- transition flow

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

  - congestion: demand-proportional supply

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

Propagation model

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

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

  - source/sink term

Specification: En-route path choice model

Potential field-based model (see e.g. [GHW11, HBFM14])

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

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

Specification: Pedestrian fundamental diagram

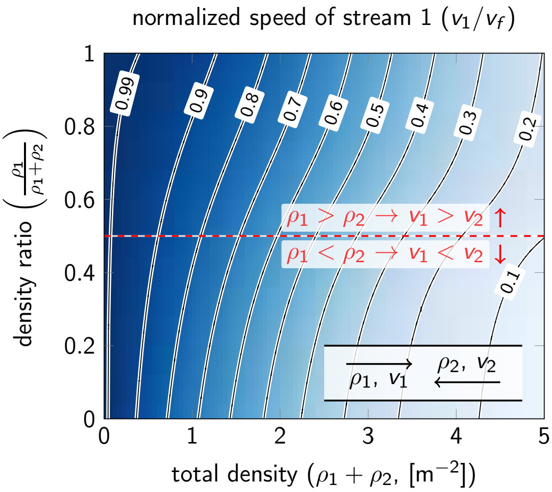
- model by Xie and Wong, 2014 [XW14]

$$v_\sigma = \exp\left\{-\vartheta\left(\frac{m_\xi}{A_\xi}\right)^2\right\} \prod_{\sigma' \in \Sigma_\xi} g(m_\sigma, m_{\sigma'}, v_\sigma, v_{\sigma'}, \varphi_{\sigma,\sigma'})$$

  - isotropic reduction in speed
  - reduction due to pair-wise interaction of streams

- next slide: illustration for counter-flow ($\alpha = 1.0$, $\beta = 0.132$, $\vartheta = 0.065$ m^2; see Xie and Wong, 2014, for details)

Specification: Pedestrian fundamental diagram



Final remarks

Conclusions:

- need for accurate yet affordable network loading model
- pedestrian flow often unsteady, anisotropic and congested
- idea: 'cell-based link-transmission model'
  - key: stream-based pedestrian fundamental diagram

Next steps:

- implementation (almost complete)
- consideration of test cases/case study
- calibration

Thank you

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