Workshop on Transportation Network and Management

Data-driven fundamental models for pedestrian movements

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Congestion

Research challenges

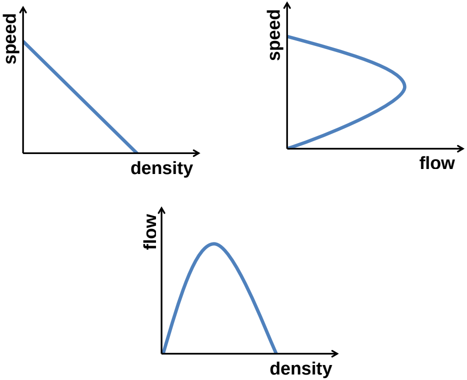
- Understand, describe and predict
- Optimization of current infrastructure and operations
- Efficient planning and management of future pedestrian facilities

Fundamentals

Quantities

- Density **k** (ped/m^2)
- Speed **v** (m/s)
- Flow **q** (ped/m·s)

Relationships



Daamen (2004), Duives et al. (2015)

Limitations

Fundamental quantities

- Highly inspired by vehicular traffic
- Arbitrary spatial and temporal discretization

Fundamental relationships

- Deterministic models: equilibrium assumption
- Empirical observations: scattered pattern

Pedestrian flow characterization

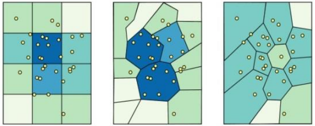
Pedestrian flow characterization

Quantities

- Density **k** (ped/m^2)
- Speed **v** (m/s)
- Flow **q** (ped/m·s)

Challenges

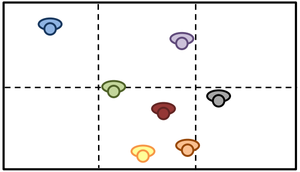
- Discretization method
- Complex pedestrian movements
  - Heterogeneous population
  - Multi-directional flows



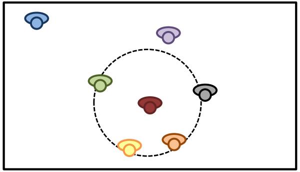
Daamen (2004), Duives et al. (2015)

Spatial discretization

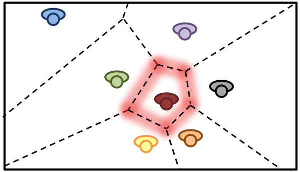
Grid-based



Range-based



Voronoi-based



Steffen and Seyfried (2010), Saberi and Mahmassani (2014), Duives et al. (2015)

Data-driven approach: 3DVoro

Nikolić, M. and Bierlaire, M. (to appear). **Data-driven spatio-temporal discretization for pedestrian flow characterization**, accepted for the *22nd International Symposium on Transportation and Traffic Theory*.

Context

Model

- Space-time representation: $\Omega \subset \mathbb{R}^3$
- Units: meters and seconds
- $p = (x, y, t) \in \Omega$: physical position (x, y) in space at a specific time t
- Assumption: Ω is convex (obstacle-free and bounded)

Data: trajectories

- Continuous: $\Gamma_i : \{p_i(t) | p_i(t) = (x_i(t), y_i(t), t)\}$
- Discrete (sample): $\Gamma_i : \{p_{is} | p_{is} = (x_{is}, y_{is}, t_s)\}, t_s = [t_0, t_1, ..., t_f]$

3D Voronoi diagram

Definition

- Associate $p \in \Omega$ with the closest Γ_i:

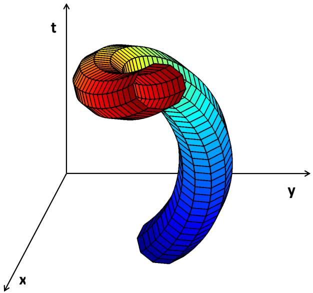
$$\delta_\Gamma(p,\Gamma_i) = \begin{cases} 1, & D(p,\Gamma_i) \leq D(p,\Gamma_j), \forall j \\ 0, & \text{otherwise} \end{cases}$$

$$D(p,\Gamma_i) = \min_{p_i}\{d(p,p_i)\}$$

- Various definitions of $d(\cdot,\cdot)$ are possible

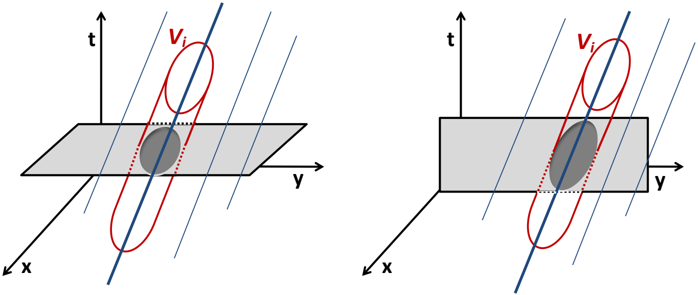
- Voronoi cell for Γ_i:

$$V_i = p \in |\delta_\Gamma(p,\Gamma_i) = 1$$



Intersection with a plane

$\mathcal{P}_{(a,b,c),p_0}$: plane through p_0 with normal vector (a, b, c)



$\mathcal{P}_{(0,0,1),p_0}$ $\mathcal{P}_{(0,1,0),p_0}$

Voronoi-based traffic quantities

Consider $(x, y, t) \in \Omega$, and i such that $(x, y, t) \in V_i$

Density: $k(x, y, t) = \frac{1}{|V_i \cap \mathcal{P}_{(0,0,1),(x,y,t)}|}$

Flow: $\vec{q}_{(a,b,0)}(x, y, t) = \frac{1}{|V_i \cap \mathcal{P}_{(a,b,0),(x,y,t)}|}$

Velocity: $\vec{v}_{(a,b,0)}(x, y, t) = \frac{|V_i \cap \mathcal{P}_{(0,0,1),(x,y,t)}|}{|V_i \cap \mathcal{P}_{(a,b,0),(x,y,t)}|}$

Properties

- Data-driven discretization
- General framework
- Microscopic characterization
- Applicable to continuous and discrete data

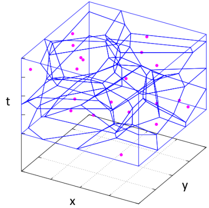
3DVoro: Application

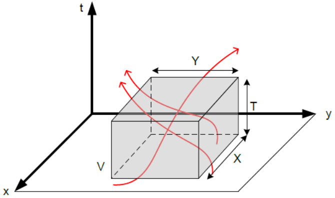
Synthetic data

- NOMAD simulation tool (Campanella et al.; 2014)
- Flow composition: uni-directional and bi-directional
- Scenarios: low/high demand, homogenous/heterogeneous population

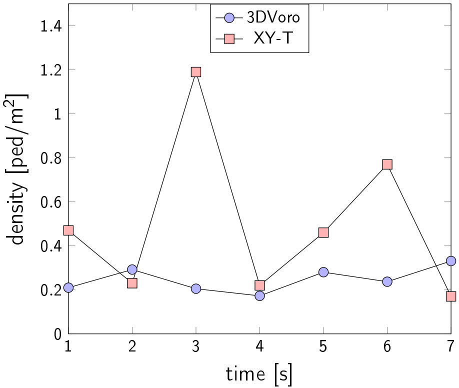
Analysis

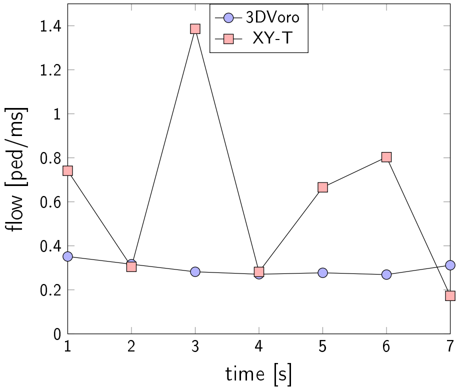
- 3DVoro and XY-T methods



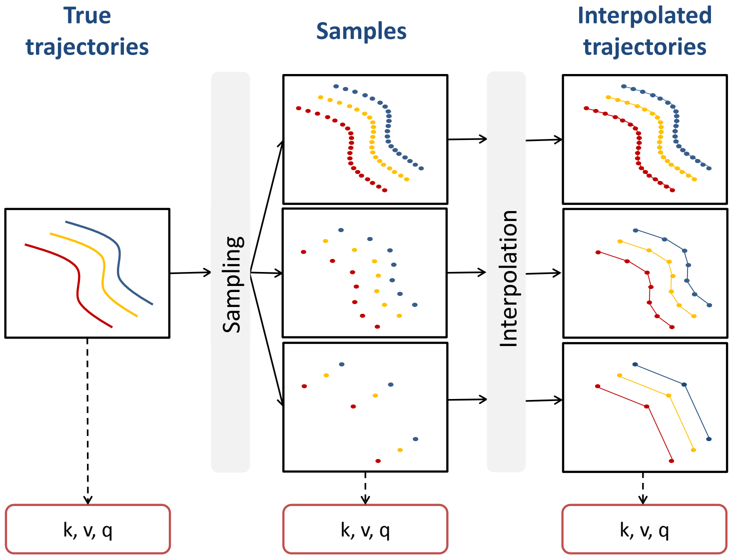


Nature of the results

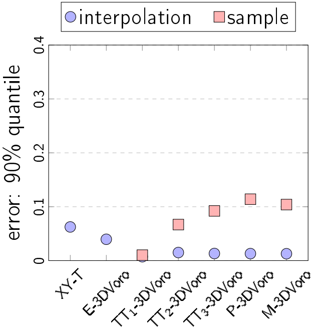




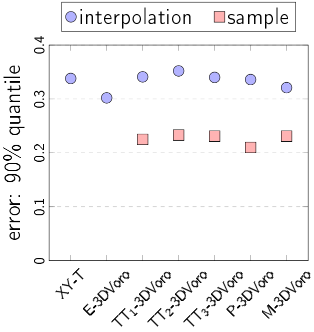
Robustness to sampling of trajectories



Robustness to sampling of trajectories



High sampling frequency



Low sampling frequency

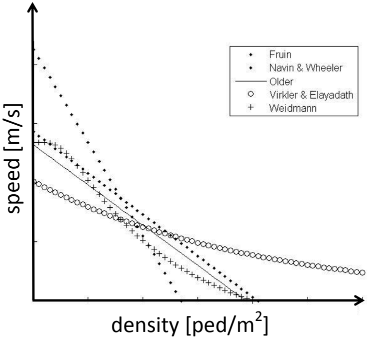
3DVoro: Main findings

- Data-driven and microscopic discretization
- Well defined, flexible and general
- Smooth transitions in measured characteristics
- Robust to noise in the data
- Robust to sampling of trajectories

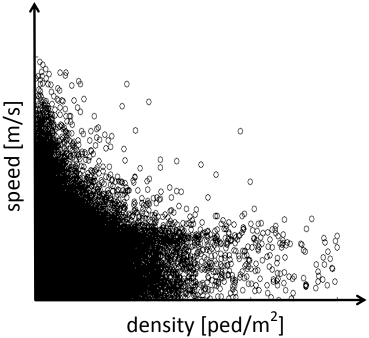
Pedestrian flow modeling

Speed-density relationship

Models

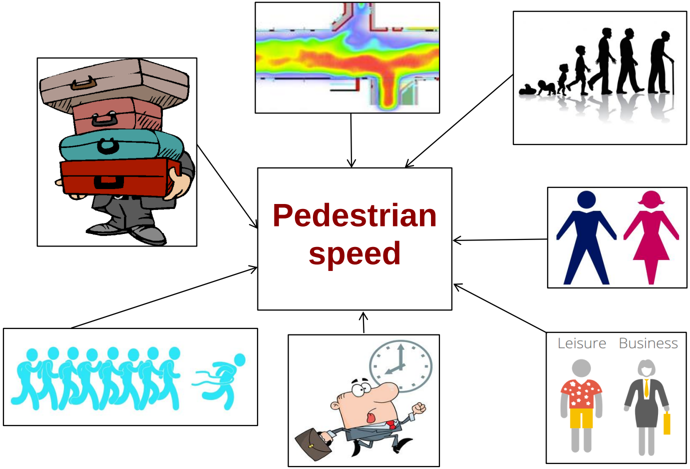


Empirical observations



Daamen (2004), Zhang (2012)

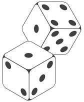
What affects the speed of pedestrians?



Weidmann (1993), Daamen (2004)

How to account for pedestrian heterogeneity?

- Relaxing the homogeneity assumption of the equilibrium
- **Probabilistic modeling approach**
  - Pedestrian probabilistic speed-density relationship: **PedProb-vk**
  - Multi-class speed-density relationship: **MC-vk**



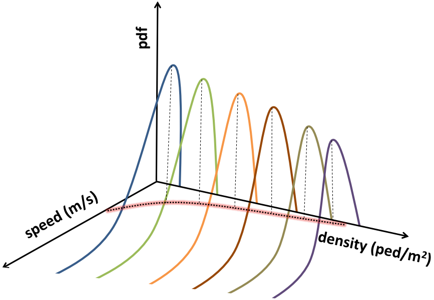
Multi-class speed-density relationship: MC-vk

Nikolić, M., Bierlaire, M., Lapparent, M. and Scarinci, R. (to appear). **Multi-class speed-density relationship for pedestrian traffic**, submitted to *Transportation Research Part B: Methodological*.

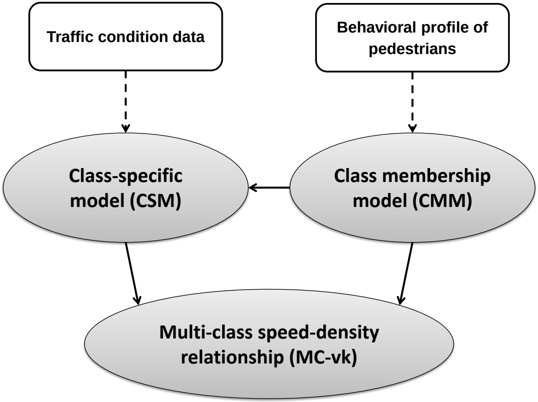
Modeling framework

Assumptions

- The speed of pedestrians is a random variable
- Population is partitioned into classes
- The speed-density relationship varies across classes



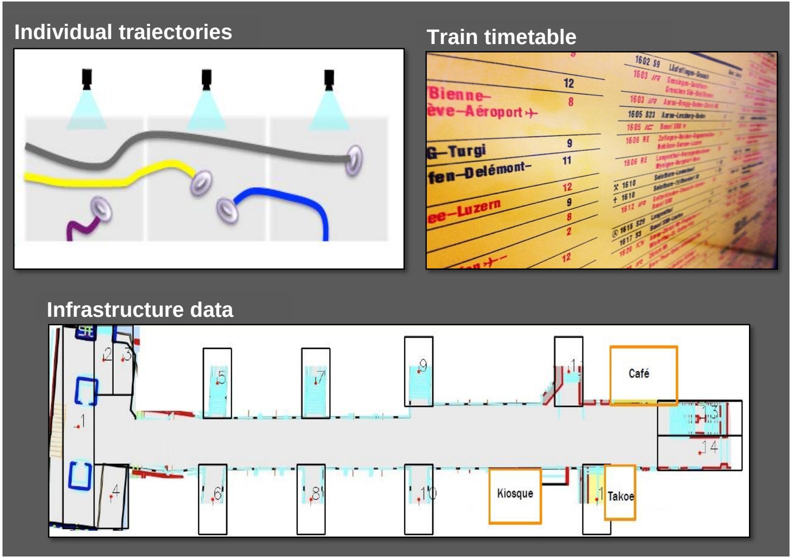
Modeling framework



$$f_{MC-vk}(v_i|k_i, X_i; \theta_j(k_i), \beta_j) = \sum_{j=1}^{J} \underbrace{f_j(v_i|k_i, j; \theta_j(k_i))}_{\text{CSM}} \underbrace{\Pr(j|X_i; \beta_j)}_{\text{CMM}}$$

Lausanne railway station

Lausanne railway station: Data



Model specification: Lausanne railway station

Classes: C_1 and C_2

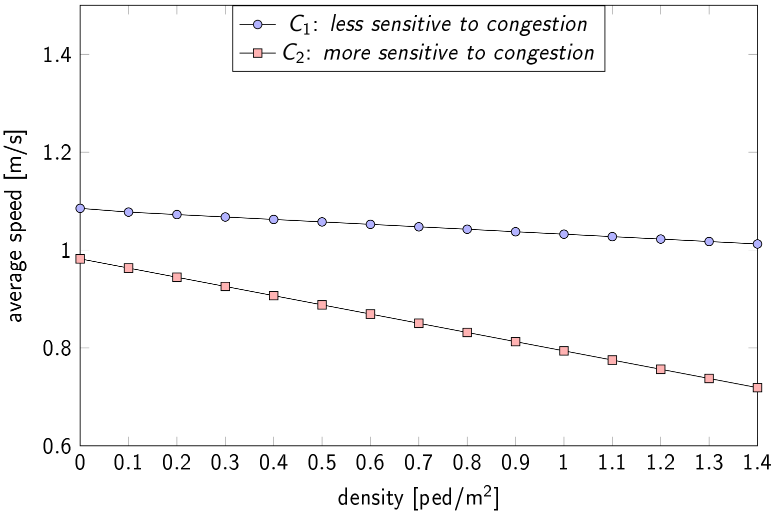
Class-specific model (CSM)

- Rayleigh model:
  $f_j(v_i|k_i, j; \mu_j(k_i)) = \frac{v_i}{2\mu_j^2(k_i)/\pi} \exp(-\frac{v_i^2}{4\mu_j^2(k_i)/\pi})$
- Mean: $\mu_j(k_i) = v_{f,j} - \gamma_j k_i$

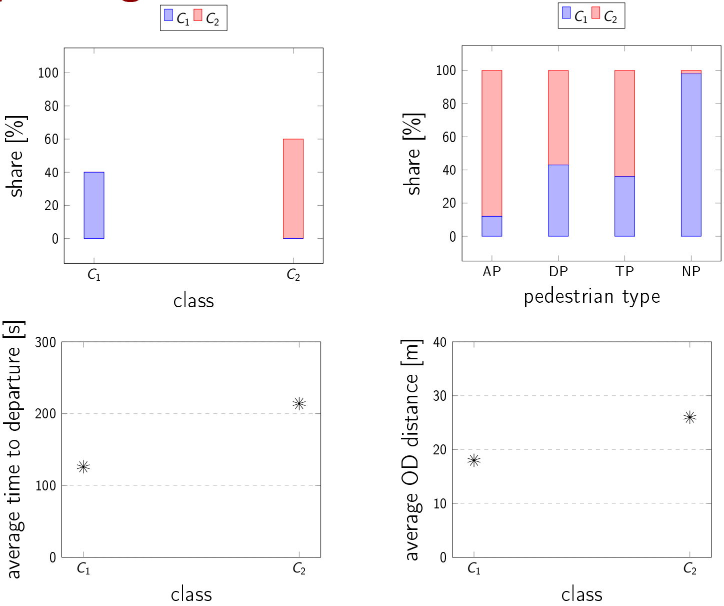
Class membership model (CMM)

- Fitness function:
  $U_{i,j} = V_{i,j} + \varepsilon_{i,j} = CSC_j + \beta_j X_i + \varepsilon_{i,j}$
- Logit model:
  $\Pr(j|X_i; \beta_j) = \frac{e^{V_{i,j}}}{\sum_{j=1}^{2} e^{V_{i,j}}}$
- Explanatory variables
  - Pedestrian type
  - Time period
  - OD distance
  - Time to departure

Class-specific behavior



Class profiling



Introduction

Characterization

3DVoro

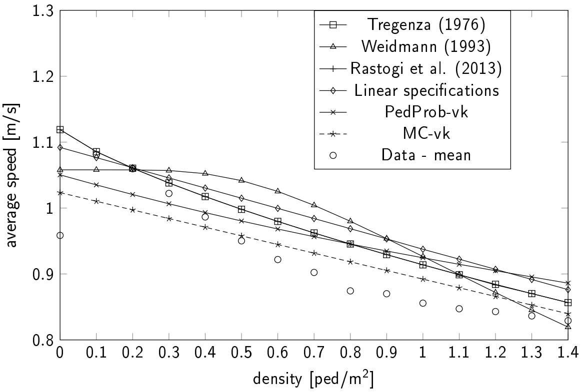
Modeling

MC-vk

Conclusion

References

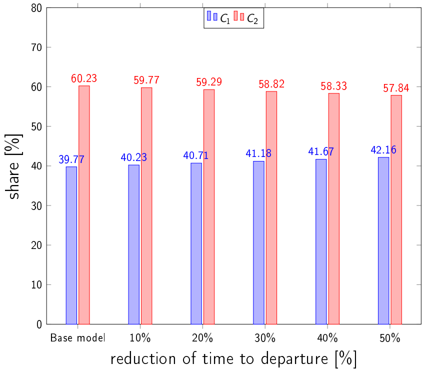
Comparison with deterministic models



Model	Weidmann (1993)	Tregenza (1976)	Rastogi et al. (2013)	Linear	*PedProb-vk*	*MC-vk*
MSE	$4.81e^{-03}$	$3.63e^{-03}$	$3.95e^{-03}$	$4.99e^{-03}$	$3.17e^{-03}$	$1.51e^{-03}$
$\bar{R}^2$	$2.64e^{-01}$	$4.45e^{-01}$	$3.96e^{-01}$	$2.37e^{-01}$	$5.16e^{-01}$	$7.69e^{-01}$

Scenario analysis: train timetable modification

- Instrument for policy making and daily operations
- Impact of different scenarios on the movement behavior and LoS
- Augmentation by posterior analysis



MC-vk: Main findings

- Probabilistic approach to account for heterogeneity
- Conceptually insightful
- Parsimonious, flexible and fairly general
- Superior compared to the deterministic approaches
- Suitable for forecasting analysis

Conclusion

Main contributions

- Utilization of data potential
- Data-driven discretization and characterization
- Probabilistic models for speed-density relationship
- Application on different case studies and practical guidelines

Future directions

Models

- Characterization: anisotropy and presence of obstacles
- Speed-density relationships: anisotropy and dynamics

Applications

- Level-of-service analysis
- Planning, design and optimization
- Simulation and management of pedestrian traffic

Data

- Different behavioral situations and types of infrastructure
- Real sites, new collection technologies

Thank you

Workshop on Transportation Network and Management:
Data-driven fundamental models for pedestrian movements
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