Probabilistic speed-density relationship for pedestrians based on data driven space and time representation

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Introduction

Objective

- Detailed characterization of the pedestrian flow
- Utilization of data potential

Motivation

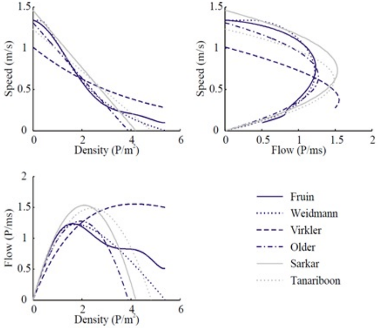
- Still not well explained
- Importance

  Specification and estimation of fundamental diagram
  Definition of a continuum pedestrian flow model

Fundamental flow indicators

- Density (k)
- Speed (v)
- Flow (q)
- Fundamental diagram

$$q = v \cdot k$$



source: (Daamen et al., 2005)

Data

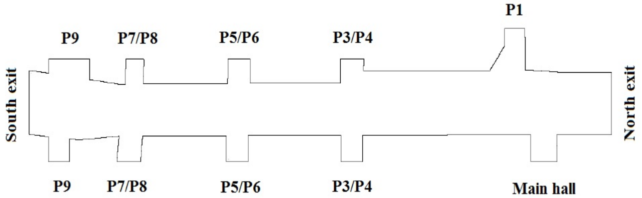
Visiosafe technology

- Spin-off of EPFL
- Gare de Lausanne
- Anonymous sensor based pedestrian tracking
  - Thermal sensors
  - Range sensors
- Vision processing outcome $(t, x(t), y(t), pedestrian_{id})$

Alahi, A., Jacques, L., Boursier, Y. and Vandergheynst, P. (2011). Sparsity driven people localization with a heterogeneous network of cameras, *Journal of Mathematical Imaging and Vision* 41(1-2): 39-58.

Gare de Lausanne

Pedestrian underpass West



- The busiest walking area in the station
- Area $\approx 685m^2$
- Area covered by 32 sensors

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Pedestrian flow characterization

Spatio-temporal discretization

Results may be highly sensitive

Loss of heterogeneity

Data driven approach

- Detailed pedestrian tracking input
- Adjusted to the reality of flow

Pedestrian flow characterization

Density

- Number of pedestrians per unit of space at a given time

Spatial discretization

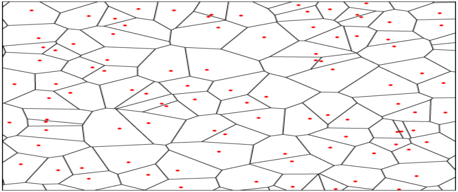
- Discretization units are too small - many remain empty
- Discretization units are too large - loss of information

Spatial discretization

Voronoi tessellations

- $p_1, p_2, \ldots, p_N$ is a finite set of points
- Voronoi space decomposition assigns a region to each point

$$V(p_i) = \{p \mid \|p - p_i\| \leq \|p - p_j\|, i \neq j\}$$



Steffen, B., and Seyfried, A., Methods for measuring pedestrian density, flow, speed and direction with minimal scatter, *Physica A: Statistical mechanics and its applications, 389(9), 1902-1910.*

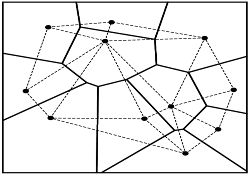
Spatial discretization

Numerical stability

- Small polygons allocated to pedestrians in very dense areas

Delaunay triangulation

- Merging of critical cells
- ξ, threshold distance
  $d(p_i, p_j) < \xi, \forall i, j$



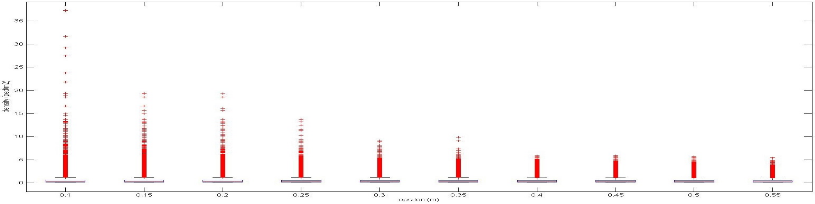
Spatial discretization

Numerical stability

- Small polygons allocated to pedestrians

Sensitivity analyses

- $\xi = 0.4m$
- ω_i, weight associated to the corresponding space



Spatial discretization

Probabilistic approach

- Voronoi diagram with overlapping cells
- Impose a minimum distance between the border of a cell and a pedestrian
- Conflicting regions

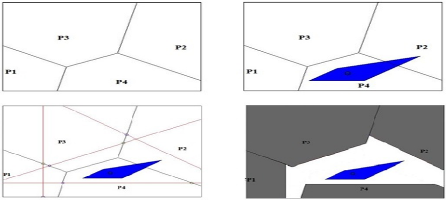
  A point p belongs to a pedestrian p_i with a probability w_i
- Delaunay triangulation

Spatial discretization

Presence of obstacles

- Assumption: two points can be connected by a straight line
- Voronoi diagram for points and Voronoi diagram areas

$$d(p_i, O) = min_{o_j} \{\|p_i - o_j\| \, | o_j \in O\}$$



Okabe, A., Boots, B., Sugihara, K. and Chiu, S. N. (2009). *Spatial tessellations: concepts and applications of Voronoi diagrams*, Vol. 501, John Wiley & Sons.

Pedestrian flow characterization

Density

- Set of points: pedestrians

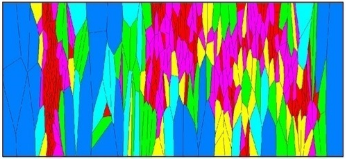
$$p_i = (x_i, y_i, t_i)$$

- Pedestrian-oriented density indicator

$$k_i = \frac{\omega_i}{|V(p_i)|}$$

Pedestrian flow characterization

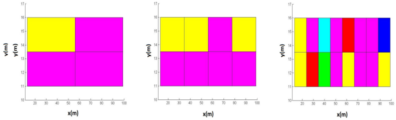
Voronoi density map



Pedestrian density
< 0.179 [ped/m²]
< 0.270
< 0.455
< 0.714
< 1.333
≥ 1.333

Table: Pedestrian walkway LoS density treshold values according to NCHRP (in SI units)

Cell-based density map



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Pedestrian flow characterization

Speed

$$p = (x(t), y(t), t)$$

$$v = v_p \cdot d \in \Re^2$$

$$v_p = \frac{\|p(t+\Delta t) - p(t-\Delta t)\|}{2\Delta t}$$

Time discretization

- Discretization interval is too small - noisy observations
- Discretization interval is too large - lower precision

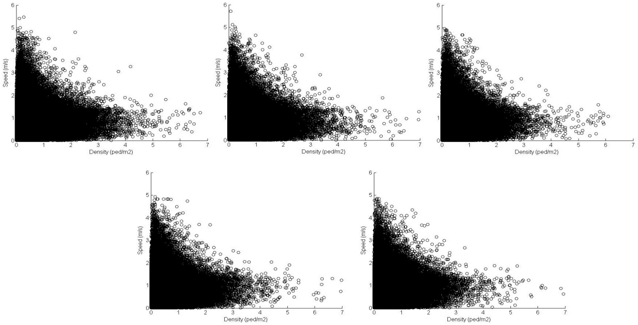
Time discretization

Moment	$v_{\Delta t=0.1s}$	$v_{\Delta t=0.2}$	$v_{\Delta t=0.3s}$	$v_{\Delta t=0.4s}$	$v_{\Delta t=0.5s}$	$v_{\Delta t=0.6s}$	$v_{\Delta t=0.7s}$	$v_{\Delta t=0.8s}$	$v_{\Delta t=0.9s}$	$v_{\Delta t=1s}$
1	1.1161	1.1158	1.1156	1.1155	1.1153	1.1152	1.1150	1.1149	1.1148	1.1147
2	0.4175	0.3296	0.2956	0.2747	0.2591	0.2465	0.2358	0.2263	0.2179	0.2104
3	5.7853	2.5957	1.7703	1.4310	1.2544	1.1476	1.0740	1.0188	0.9744	0.9363
4	134.4926	31.2621	15.5319	10.9042	9.0167	8.0657	7.4917	7.0994	6.8045	6.5660

- Kruskal-Wallis test ($H=4.61$, $df=9$, $p=0.87$)
  The moments represent the same population at 95% confidence level

Empirical speed-density relationship

Speed-density profiles



February 11.-15., 2013.: morning peak hour

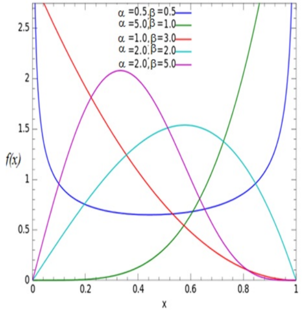
Probabilistic approach

Kumaraswamy distribution

- Defined on the bounded region $[\ell, u]$
- Two non-negative shape parameters α and β
- The simple closed form of pdf $f(x)$ and cdf $F(x)$

$$f(x) = \frac{\alpha \cdot \beta \cdot (x-\ell)^{\alpha - \mathbf{1}} \cdot ((u-\ell)^{\alpha} - (x-\ell)^{\alpha})^{(\beta - \mathbf{1})}}{(u-\ell)^{\alpha \cdot \beta}}$$

$$F(x) = 1 - (1 - (\frac{x-\ell}{u-\ell})^{\alpha})^{\beta}$$



Kumaraswamy, P. (1980). A generalized probability density function for double-bounded random processes, *Journal of Hydrology* 46(1): 79-88.

Probabilistic approach

Speed-density relationship

$$V \sim f\left(\alpha\left(k\right),\beta\left(k\right),\ell\left(k\right),u\left(k\right)\right)$$

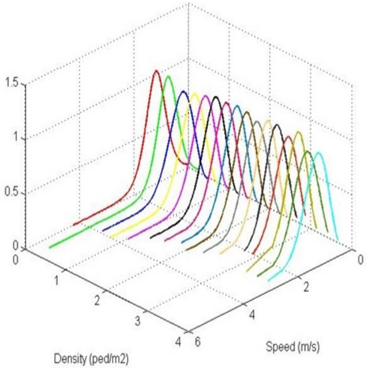
f - Kumaraswamy pdf

V - speed

k - density level

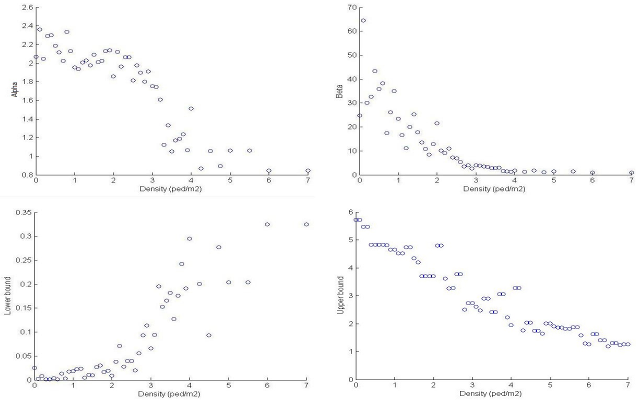
α, β - shape parameters

u,ℓ - boundary parameters



Probabilistic approach

Kumaraswamy parameters



Probabilistic approach

Specification of speed-density relationship

$$V \sim f\left(\alpha(k), \beta(k), \ell(k), u(k)\right)$$

Parameter	Specification#1	Specification#2
$\alpha(k)$	$a_\alpha k^3 + b_\alpha k^2 + c_\alpha k + d_\alpha$	$a_\alpha k^3 + b_\alpha k^2 + c_\alpha k + d_\alpha$
$\beta(k)$	$a_\beta exp(b_\beta k)$	$a_\beta exp(b_\beta k)$
$u(k)$	$a_u exp(b_u k)$	$a_u k^3 + b_u k^2 + c_u k + d_u$
$\ell(k)$	0	0

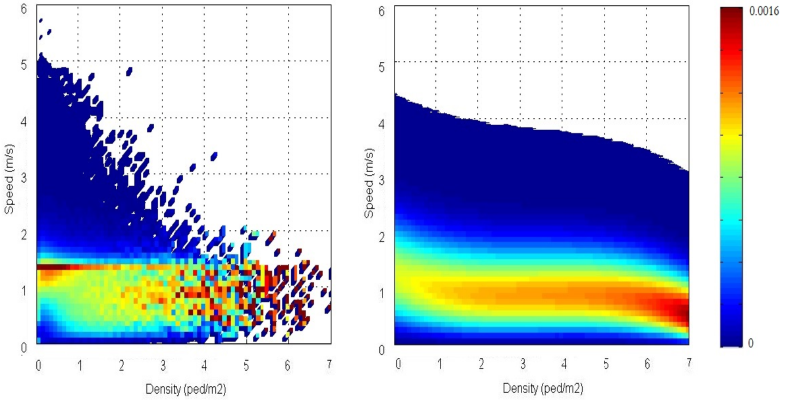
Maximum likelihood estimation

$$\log \mathcal{L} = \sum_{i=1}^{n} \log(\alpha(k_i)) + \sum_{i=1}^{n} \log(\beta(k_i)) + \sum_{i=1}^{n} (\alpha(k_i) - 1)\log(v_i - \ell(k_i)) + \sum_{i=1}^{n} (\beta(k_i) - 1)\log((u(k_i) - \ell(k_i))^{\alpha(k_i)} - (v_i - \ell(k_i))^{\alpha(k_i)}) - \sum_{i=1}^{n} \alpha(k_i)\beta(k_i)\log(u(k_i) - \ell(k_i))$$

Parameter	Specification#1	Specification#2
a_α	-0.0076	0.0498
b_α	0.0961	-0.2823
c_α	-0.3781	-0.0207
d_α	2.2185	2.0089
a_β	44.8191	45.362
b_β	-0.1057	-0.5945
a_u	7	0.0002
b_u	0	-0.0002
c_u		-0.0010
d_u		8.0017
$\log \mathcal{L}$	-891880	-932990

Probabilistic approach

Validation



Probabilistic approach

- Validation - observations outside the bounds
- Solutions to be investigated

Theoretical distributions that are not bounded from above (e.g.Weibull)

Postulated model

$$v = f(k) + \epsilon, \; f \text{ - Weidmann model}$$

Conclusion and next steps

- Pedestrian-oriented flow characterization
- Data-driven space and time discretization
- Probabilistic methodology to describe observed heterogeneity
- The framework is insufficient to explain the multidirectional nature of pedestrian flows

  Stream-based approach
- Case study: Gare de Lausanne

Thank you

References

Alahi, A., Jacques, L., Boursier, Y. and Vandergheynst, P. (2011). Sparsity driven people localization with a heterogeneous network of cameras, *Journal of Mathematical Imaging and Vision* 41(1-2): 39-58.

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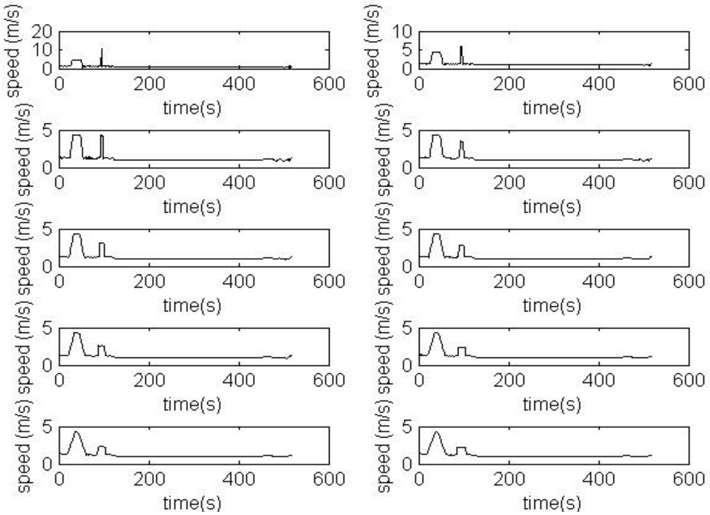
Effect of time discretization

Δt	min	mean	max	median	mode	$Q_{0.9}$	$Q_{0.95}$	$Q_{0.99}$
0.1	0.0050	1.1155	34.1162	1.1173	1.1000	1.7022	2.0096	3.0419
0.2	0.0025	1.1154	17.7847	1.1269	1.1000	1.6626	1.9470	2.9679
0.3	0.0017	1.1153	12.3805	1.1296	1.1000	1.6478	1.9231	2.9361
0.4	0.0013	1.1153	9.7226	1.1298	1.1000	1.6385	1.9087	2.8915
0.5	0.0010	1.1152	8.1288	1.1293	1.1000	1.6321	1.8992	2.8301
0.6	0.0008	1.1151	7.1808	1.1285	1.1000	1.6276	1.8910	2.7515
0.7	0.0017	1.1150	6.5927	1.1273	1.1000	1.6245	1.8848	2.6874
0.8	0.0036	1.1149	6.2454	1.1262	1.1000	1.6206	1.8785	2.6295
0.9	0.0039	1.1149	5.8898	1.1253	1.1000	1.6175	1.8700	2.5827
1	0.0052	1.1148	5.6450	1.1245	1.1000	1.6135	1.8615	2.5395


speed (m/s)
20
10
0
200
400
600
time(s)
5