Pedestrian flow characterization based on spatio-temporal Voronoi tessellations

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Motivation

Congestion

Optimization of pedestrian facilities and their operations

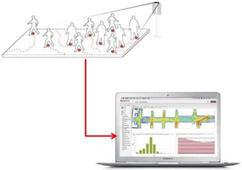
- Models for prediction of pedestrian flows
- Data for model specification, calibration and validation

Pedestrian data

Traditional collection

- Manual counting methods
- Surveys distributed to randomly selected individuals

Pedestrian tracking



- Controlled experiments [Daamen and Hoogendoorn, 2003]
- VisioSafe technology [Alahi et al., 2014]

Traffic characteristics

- Density (ped/m^2)
- Speed (m/s)
- Flow (ped/ms)

- LOS indicators
- Fundamental diagram specification
- Models of pedestrian dynamics

Related research

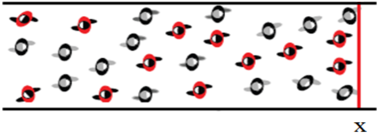
Method A [Zhang et al., 2012]

- A reference location in space (x) is considered
- Flow and (time-mean) speed are specified as the average over time (Δt)

$$q = \frac{n}{\Delta t}, \; v = \frac{1}{n}\sum_i v_i(t)$$

n - number of pedestrians passing the location x during Δt

$v_i(t)$ - instantaneous speed of pedestrian i



Related research

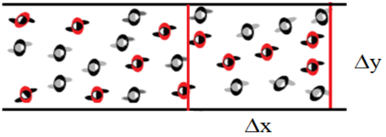
Method B [Zhang et al., 2012]

- Defines density and (space-mean) speed per unit of space ($\Delta x \times \Delta y$)

$$k = \frac{n}{\Delta x \Delta y}, \quad v = \frac{\sum_i v_i}{n}$$

$\Delta x, \Delta y$ - width and length of the measurement area

$v_i = \frac{\Delta x}{\Delta t_i}$ - individual space-mean speed



Related research

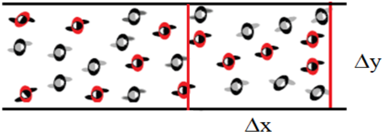
Method C [Zhang et al., 2012]

- Density and (space-mean) speed are specified as the average over time (Δt) and space ($\Delta x \times \Delta y$)

$$k = \frac{1}{\Delta t} \int\limits_t \frac{n}{\Delta x \Delta y} dt, \; v = \frac{\sum\limits_i v_i}{n}$$

$\Delta x, \Delta y$ - width and length of the measurement area

$v_i = \frac{\Delta x}{\Delta t_i}$ - individual space-mean speed



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Related research

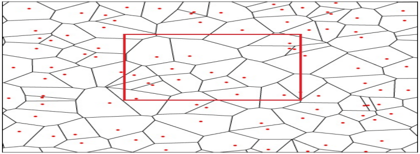
Method D [Zhang et al., 2012]

- Density and speed are defined per unit of space via Voronoi diagrams

$$k = \frac{\int\int \rho_{xy} dxdy}{\Delta x \Delta y}, \; v = \frac{\int\int v_{xy} dxdy}{\Delta x \Delta y}$$

$\rho_{xy} = \frac{1}{A_i}$, ρ_{xy} - density distribution, A_i - area of Voronoi cell associated to pedestrian i

v_{xy} - instantaneous speed of pedestrian i



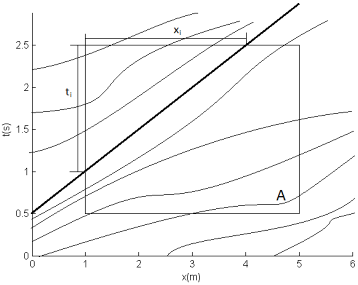
Related research

[Edie, 1963]

Density: $k(A) = \frac{\sum_i t_i}{|A|}$

Flow: $q(A) = \frac{\sum_i x_i}{|A|}$

Speed: $v(A) = \frac{\sum_i x_i}{\sum_i t_i}$



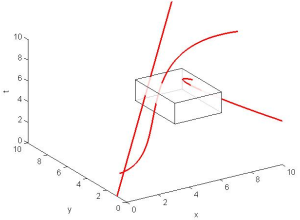
Related research

[van Wageningen-Kessels et al., 2014]

Density: $k(V) = \frac{\sum_i t_i}{Vol(V)}$

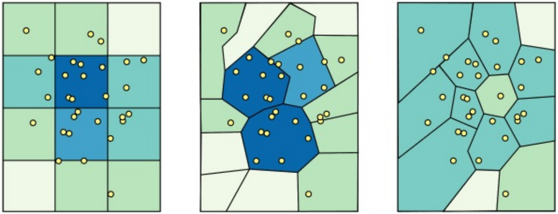
Flow: $q(V) = \frac{\sum_i d_i}{Vol(V)}$

Speed: $v(V) = \frac{\sum_i d_i}{\sum_i t_i}$



Pedestrian flow characterization - Issues

- Arbitrary chosen discretization, at least in one dimension
- It may generate noise in the data
- Results may be highly sensitive to minor changes of discretization

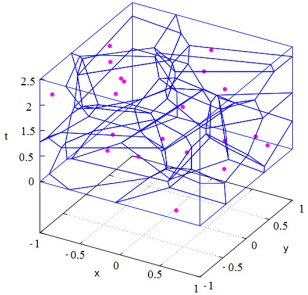


Pedestrian flow characterization - Issues

- Averaging over different degrees of freedom may lead to incomparable results
- Edie's definitions lead to consistent results in observations and modeling [van Wageningen-Kessels et al., 2014]

Pedestrian flow characterization - Data driven discretization

- New definitions of traffic variables
  - Rely on the approach proposed by [Edie, 1963]
  - Data driven discretization framework



Data-driven discretization framework

Space-time representation

- Triplet (x, y, t) represents a physical position (x, y) in space at a specific time t

- Space-time distance between points $p_1 = (x_1, y_1, t_1)$ and $p_2 = (x_2, y_2, t_2)$

$$d_\alpha = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2 + \alpha^2 (t_1 - t_2)^2}$$

α - 1 second of time is equivalent to α meters of distance

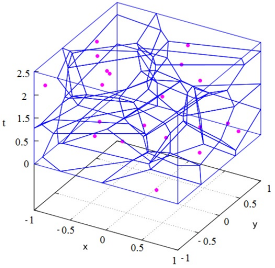
- Pedestrian trajectory: $p_i = (x_i(t), y_i(t), t)$
  - Pedestrian i positioned at $(x_i(t), y_i(t))$ at time t
- Sample of points: $p_{is} = (x_{is}, y_{is}, t_s)$, $t_s = (t_0, t_1, ..., t_f)$

Three-dimensional Voronoi diagram

- Sample of points: $p_{is} = (x_{is}, y_{is}, t_s)$, $t_s = (t_0, t_1, ..., t_f)$
- Three-dimensional Voronoi diagram

$$V_{is} = \{p | d_\alpha(p, p_{is}) \leq d_\alpha(p, p_{js}), \forall j\}$$

- $Vol(V_{is})$ - the volume of a Voronoi cell V_{is} associated with the point p_{is} with the unit square meters times seconds



Voronoi-based traffic indicators

Density indicator

- The set of all points in V_{is} corresponding to a given location (x, y) is a set of dimension 1

$$V_{is}(x, y) = \{(x, y, t) \in V_{is}\}$$

- $V_{is}(x_{is}, y_{is})$ - a time interval occupied by pedestrian i

$$k_{is} = \frac{V_{is}(x_{is}, y_{is})}{Vol(V_{is})} \quad [\text{ped}/\text{m}^2]$$

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Voronoi-based traffic indicators

Flow indicator

- The set of all points in V_{is} corresponding to a specific time t is a set of dimension 2

$$V_{is}(t) = \{(x, y, t) \in V_{is}\}$$

- $V_{is}(t_s)$ - a physical area on the floor belonging to pedestrian i
- d_{is} - a maximum distance in $V_{is}(t_{is})$ in the movement direction of pedestrian i

$$q_{is} = \frac{d_{is}}{Vol(V_{is})} \quad [\text{ped/ms}]$$

Speed indicator

$$v_{is} = \frac{d_{is}}{V_{is}(x_{is}, y_{is})} \quad [\text{m/s}]$$

Voronoi-based traffic indicators

Disaggregated

$$k_{is} = \frac{V_{is}(x_{is}, y_{is})}{Vol(V_{is})}$$

$$q_{is} = \frac{d_{is}}{Vol(V_{is})}$$

$$v_{is} = \frac{d_{is}}{V_{is}(x_{is}, y_{is})}$$

Aggregated

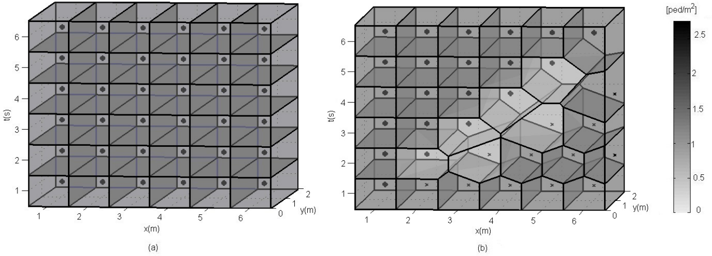
$$k(V) = \frac{\sum_i V_{is}(x_{is}, y_{is})}{\sum_i Vol(V_{is})}$$

$$q(V) = \frac{\sum_i d_{is}}{\sum_i Vol(V_{is})}$$

$$v(V) = \frac{\sum_i d_{is}}{\sum_i V_{is}(x_{is}, y_{is})}$$

Simulation experiment

Multiple pedestrians

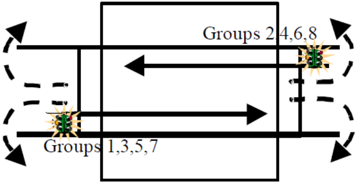


Reproduces settings with uniform and non-uniform movement

Delft case study

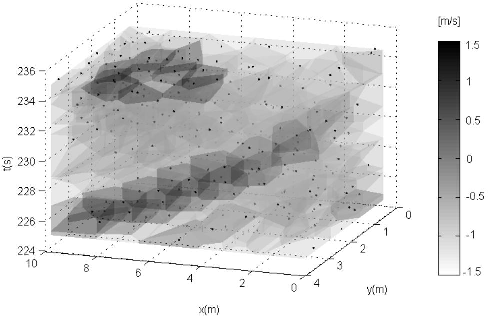
Bidirectional flow [Daamen and Hoogendoorn, 2003]

- Trajectories extracted from the digital video sequences
- The position of each individual is available every 0.1s
- Total number of trajectories: 1,123
- The average length of the trajectories: 10 meters
- The average time of the trajectories: 10 seconds.



Delft case study

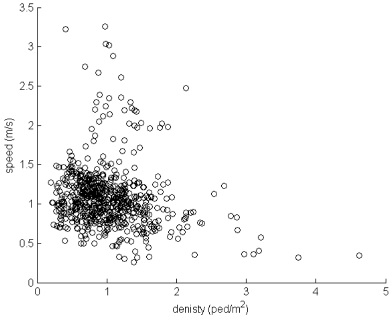
Lane formation



Allows to correlate the momentary speed of an individual pedestrian (or a group of pedestrians) with the availability of space

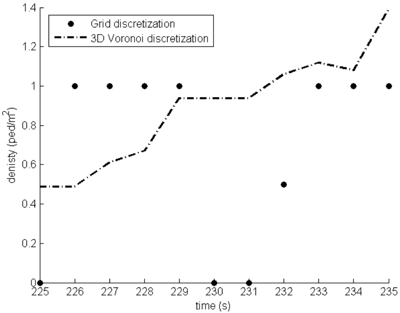
Delft case study

Speed-density profile



Capable to reflect the heterogeneity of pedestrians

Comparison with grid-based method



Voronoi-based approach leads to smooth transitions in measured characteristics

Conclusions

- The framework for pedestrian-oriented flow characterization
- Edie's definitions adapted through a data-driven discretization
  - Reproduce the settings with uniform and non-uniform movement
  - Reflect the self-organization phenomena and pedestrian heterogeneity
  - Allow for the analysis of congestion at the microscopic level
  - Lead to smooth transitions in measured traffic characteristics

Future research

- More numerical analysis directed towards
  - The investigation of the role of conversion constant α
  - Potential numerical instability of results and dealing with obstacles
- Real case study: train stations in Lausanne and Basel [Alahi et al., 2014]
- Stream-based definitions of indicators and their interaction [Nikolić and Bierlaire, 2014]
- Stream-based fundamental relationships for pedestrians

Thank you for your attention

Stream-based approach

- Pedestrian traffic composed of different streams
- A stream definition: direction-based and exogenous

$$(\varphi_j)_{j=1}^{S}, S \geq 2$$

- Trajectories are assumed to contribute to the streams to some extent
- The contribution is related to the angle between a movement direction of a pedestrian and the corresponding stream

Stream-based approach

- Pedestrian trajectory: $p(t) = (x(t), y(t), t)$
- Tangential direction associated with each point $p(t)$ of a trajectory

$$\nabla p(t) = (\frac{dx(t)}{dt}, \frac{dy(t)}{dt}, 1)$$

- Pedestrian movement direction - normalized vector e composed of the first two components of $\nabla p(t)$
- The individual contribution to the stream

$$c_i^{\varphi_j} = \begin{cases} \|e\| \, \|\varphi_j\| \, cos\theta & : 0^\circ < \theta \leq 90^\circ \\ 0 & : 90^\circ < \theta \leq 180^\circ. \end{cases}$$

θ - the angle between the vectors e and φ_j

Stream-based Voronoi definitions

Disaggregated

$$k(p_i) = \frac{V_i(x_i, y_i)}{Vol(V_i)}$$

$$q_{\varphi_j}(p_i) = \frac{d_i^{\varphi j}}{Vol(V_i)} \varphi j$$

$$v_{\varphi_j}(p_i) = \frac{d_i^{\varphi j}}{V_i(x_i, y_i)} \varphi j$$

Aggregation

$$k(V) = \frac{\sum_i k(p_i) \cdot Vol(V_i)}{\sum_i Vol(V_i)}$$

$$q_{\varphi_j}(V) = \frac{\sum_i q_{\varphi_j}(p_i) \cdot Vol(V_i)}{\sum_i Vol(V_i)} \varphi j$$

$$v_{\varphi_j}(V) = \frac{\sum_i q_{\varphi_j}(p_i) \cdot Vol(V_i)}{\sum_i k(p_i) \cdot Vol(V_i)} \varphi j$$

Simulation experiment

Single pedestrian

$$p(t) = (x(t), y(t), t) = (0.02t^2 + 0.9t + 0.1, 1, t)$$