9^{th} TRIENNIAL SYMPOSIUM ON TRANSPORTATION ANALYSIS (TRISTAN IX), Aruba

Multi-class speed-density relationship for pedestrian traffic

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Outline

1. Introduction
2. Methodology
3. Case study
   - Empirical analysis
   - Model specification and estimation
4. Conclusion and future work

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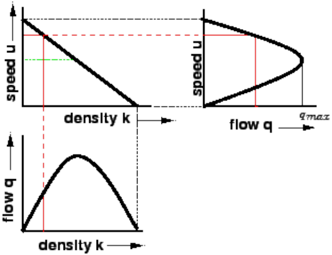
Fundamental relationships

- Play an important role in the filed: design and planing; model input or calibration criterion
- Modeling assumption: the traffic system is at equilibrium - homogenous and stationary



Speed-density relationships for pedestrian traffic

Deterministic approach

- Empirically derived models [Older, 1968; Tregenza, 1976; Weidmann, 1993; Rastogi et al., 2013]
- Simulation-based models [Blue and Adler, 1998]
- Theory-based models [Flötteröd and Lämmel, 2015]

Empirical observations

- Scatter: violation of the equilibrium assumptions

Probabilistic approach

- Data-driven PedProb-vk [Nikolić et al., 2016]
- Superior compared to deterministic approaches from the literature

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Behavioral approach

Assupmtions

- Pedestrian population is heterogeneous (e.g. trip purpose, age, gender, etc.)
- Heterogeneity leads to the existence of multiple pedestrian classes
- Classes are characterized by different types of behavior
- Latent class modeling approach to capture unobserved heterogeneity

Multi-class speed-density relationship (MC-vk)

Model structure

$$P(v_i|k_i) = \sum_{c=1}^{C} P(v_i|k_i, c)P(c|X_i)$$

$P(v_i|k_i, c)$: class-specific model

$P(c|X_i)$: class membership model

i: pedestrian identifier, $i = 1, ..., N$

v_i: speed of pedestrian i

k_i: density for pedestrian i

c: class identifier, C - number of classes

X_i: characteristics associated to pedestrian i

Class-specific speed-density relationship

Social Force Model

$$\vec{a}_i = \frac{\vec{v}_i^f - \vec{v}_i}{\tau_i} - C_i \sum_j \exp(-\frac{R_{ij}}{B_i})\vec{n}_{ij}(\lambda_i + (1-\lambda_i)\frac{1+\cos(\phi_{ij})}{2})$$

[Helbing and Molnar, 1995]

Class-specific speed-density relationship

Isotropy ($\lambda_i = 1$)

$$a_i = \frac{v_i^f - v_i}{\tau_i} - C_i \sum_j \exp(-\frac{R_{ij}}{B_i}) = \frac{v_i^f - v_i}{\tau_i} - C_i k_i$$

Stationatity ($a_i = 0$)

$$v_i = v_i^f - \gamma_i k_i$$

Homogeneity (all pedestrians have the same movement parameters)

$$v_i = v = v_f - \gamma k_i$$

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Class membership model

- It cannot be deterministically identified to which class a pedestrian belongs
- Probability that a pedestrian i, associated with characteristics X_i (e.g. trip purpose, age, gender, etc.), belong to a latent class c: for each pedestrian there is a utility associated to each class c

Specification of utilities

$$U_i^c = \underbrace{ASC^c + \beta^c X_i}_{V_i^c} + \xi_i^c$$

V_i^c: deterministic part of utilities
ξ_i^c: error term

Multi-class speed-density relationship (MC-vk)

Class-specific model: $P(v_i|k_i, c)$

$$v_i^c = v_f^c - \gamma^c k_i + \epsilon_i^c$$

$P(v_i|k_i, c)$ is determined by ϵ_i^c

Class membership model: $P(c|X_i)$

$$U_i^c = \underbrace{ASC^c + \beta^c X_i}_{V_i^c} + \xi_i^c$$

$P(c|X_i)$ is determined by ξ_i^c

Likelihood of the sample

$$\mathcal{L} = \prod_{i=1}^{N} P(v_i|k_i) = \prod_{i=1}^{N} \sum_{c=1}^{C} P(v_i|k_i, c) P(c|X_i)$$

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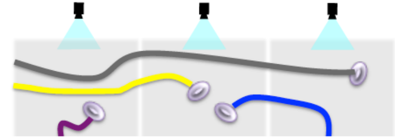
Lausanne railway station

Data set

Pedestrian underpass

- A large-scale network of smart sensors: a sparsity driven tracking framework [Alahi et al., 2014]
- Dataset: 25,603 trajectories, collected between 07:00 and 08:00 on February 12, 13, 14, 15 and 18, 2013
- The average length of the trajectories: 78 meters
- The duration of a pedestrians' stay: from 15 seconds to 2.2 minutes



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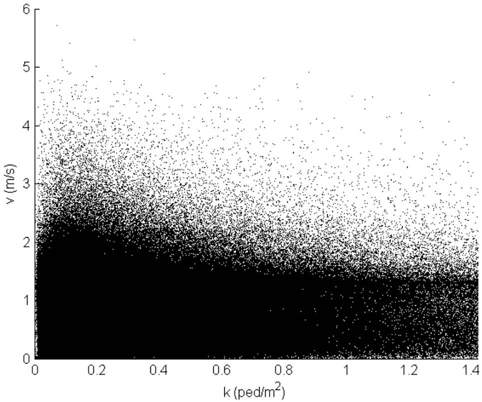
Speed-density relationship



Pedestrian types

Classification based on origins and destinations

1: Arriving passenger - pedestrians originating from a platform and exiting the station

2: Departing passenger - pedestrians walking to a platform to embark on their trains

3: Transferring passenger - pedestrians whose origin and destination are different platforms

4: Non-passenger - pedestrians whose origin and destination are different from a platform (e.g. pedestrians that go shopping in the station)

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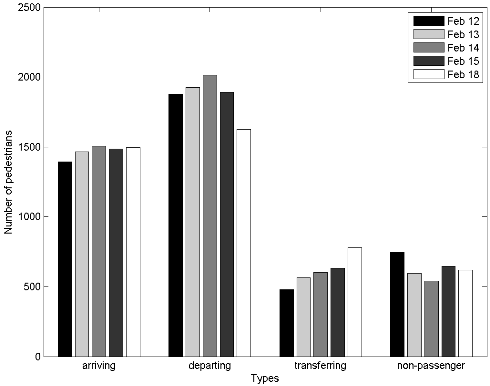
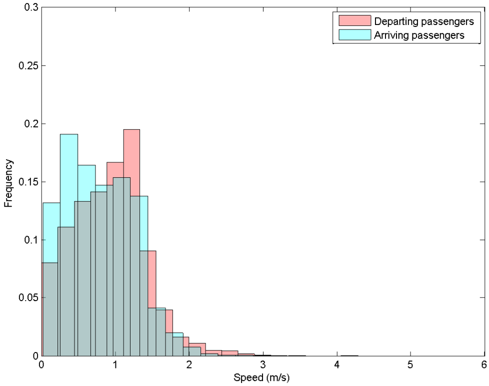
Pedestrian types

Number of pedestrians per pedestrian type

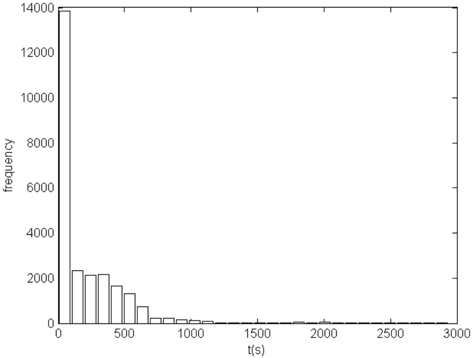


Speed distribution per pedestrian type



Train timetable

Time to departure



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Specification issues

Panel data

- Data collected over multiple time periods for the same sample of individuals

Serial correlation

- The observations across time for a single pedestrian are likely to be correlated, due to the unobserved factors related to a pedestrian that exist over time
- $\epsilon^c_{i(t-1)}$ cannot be assumed independent from ϵ^c_{it}
- If ignored - consistent but not efficient estimators

Multi-class speed-density relationship (MC-vk)

Class-specific model: $P(v_i|k_i, c)$

$$v_{it}^c = v_f^c - \gamma^c k_{it} + \alpha_{\mathbf{i}}^{\mathbf{c}} + \epsilon_{it}'^c$$

$P(v_i|k_i, c)$ is determined by $\epsilon_{it}'^c$, α_i^c is an agent effect

Class membership model: $P(c|X_i)$

$$U_i^c = \underbrace{ASC^c + \beta^c X_i}_{V_i^c} + \xi_i^c$$

$P(c|X_i)$ is determined by ξ_i^c

Likelihood of the sample

$$\mathcal{L} = \prod_{i=1}^{N} \sum_{c=1}^{C} \{\frac{1}{R} \sum_{r}^{R} exp(\sum_{t=1}^{T} \log P(v_i|k_i, c, \alpha_r^c))\} P(c|X_i)$$

Assumptions

Number of classes

1. Pedestrians sensitive to congestion
2. Rushing pedestrians
3. Pedestrians non-sensitive to congestion

Class membership model

- Explanatory variables: time to dipарture, type of pedestrian
- Logit model

Class specific model

- The same functional form of v-k for each class
- $\epsilon_{it}'^{c} \sim \mathcal{N}(o, \sigma^c)$
- $\alpha_i'^{c} \sim \mathcal{N}(o, \eta^c)$

Estimation results

Class membership model

Parameter	Value	Std.err.
ASC^S	2.37	$5.18e^{-06}$
β^S_{TTD}	$5.12e^{-06}$	$7.54e^{-06}$
β^S_{AP}	0.445	$1.03e^{-05}$
β^S_{DP}	0.820	$2.11e^{-05}$
β^S_{TP}	-0.466	$1.73e^{-05}$
β^R_{TTD}	-0.0159	$1.57e^{-05}$
β^R_{AP}	-0.575	$1.54e^{-05}$
β^R_{DP}	0.701	$1.93e^{-05}$
β^R_{TP}	-0.790	$1.20e^{-05}$
ASC^{NS}	0.402	$1.84e^{-05}$

Class specific model

Parameter	Value	Std.err.
v^S_f	0.991	$1.32e^{-05}$
γ^S	0.197	$1.73e^{-05}$
v^R_f	1.797	$9.37e^{-06}$
γ^R	0.0549	$1.28e^{-05}$
v^{NS}_f	1.298	$1.21e^{-05}$
α^S	0.421	$2.67e^{-06}$
α^R	0.811	$1.40e^{-05}$
α^{NS}	0.139	$1.66e^{-05}$
σ^S	0.439	$1.94e^{-05}$
σ^R	0.745	$2.72e^{-05}$
σ^{NS}	0.0401	$1.38e^{-05}$

S - Pedestrians sensitive to congestion
R - Rushing pedestrians
NS - Pedestrians non-sensitive to congestion

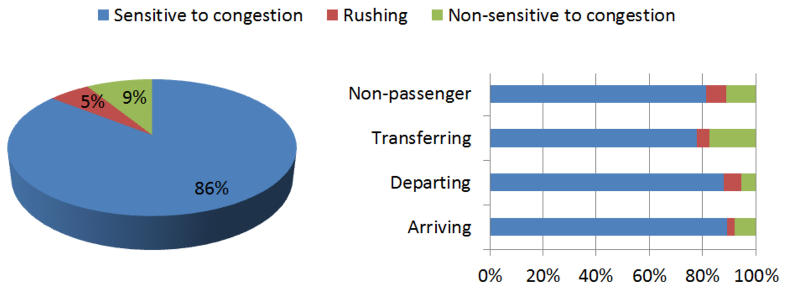
How many classes?

Bayesian information criterion - *BIC*

Model	1 class	2 classes	3 classes
$\log \mathcal{L}$	588534.224	562655.524	534569.219
$\#observations$	828018	828018	828018
$\#parameters$	3	13	21
BIC	1177109.329	1125488.196	1069424.602

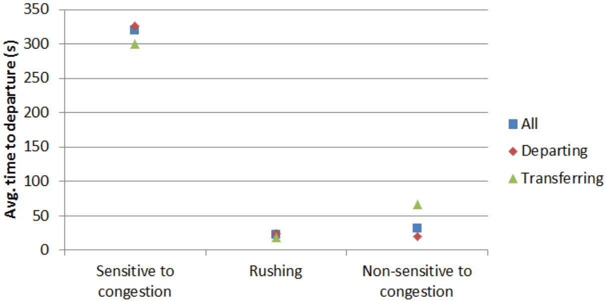
Class profiling

Shares



Class profiling

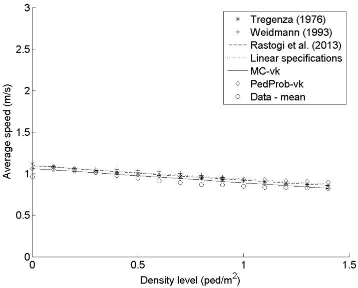
Average time to departure



Model comparison

Average behavior

$$\bar{v}_{MC-vk} = \sum_{c=1}^{C} \left\{ \frac{1}{N} \sum_{i=1}^{N} P(c|X_i; \beta^c) v^c(k; \theta^c) \right\}$$



Model	Weidmann	Tregenza	Rastogi	Linear	*PedProb-vk*	*MC-vk*
MSE	$5.34e^{-03}$	$4.82e^{-03}$	$4.42e^{-03}$	$5.59e^{-03}$	$4.02e^{-03}$	$1.72e^{-03}$
$\bar{R}^2$	$2.38e^{-01}$	$3.12e^{-01}$	$3.69e^{-01}$	$2.02e^{-01}$	$4.29e^{-01}$	$7.54e^{-01}$

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Conclusion and future work

Conclusion

- MC-vk: latent class modeling approach to capture heterogeneity in pedestrian population
- Satisfying behavioral interpretation
- Good performance at the aggregate level

Future work

- Additional factors
  - Walking in groups
  - Peak intervals
  - Attractiveness of origins/destinations

Thank you

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Pedestrian underpass West

1: South entrance

2 - 4: Stairs (resp. ramp) to platform 9

3: Coop Pronto Supermarket

5 - 6: Stairs (resp. ramp) to platform 7 and 8

7 - 8: Stairs (resp. ramp) to platform 5 and 6

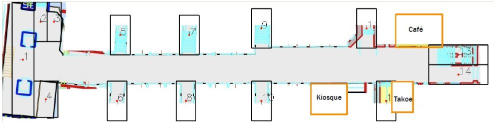
9 - 10: Stairs (resp. ramp) to platform 3 and 4

11: Stairs to platform 1 and out of the station

12: Access ramp

13: Stairs to or out of the train station and to buses

14: Pathway leading to buses and metro (M2)



Group behavior

A group of pedestrians walking together

Given spatial threshold ε, speed threshold θ, directional threshold φ and temporal threshold k a group of at least 2 pedestrians that are density-connected w.r.t. ε, θ, φ during at least k time periods (not necessarily consecutive time periods) represent a group of pedestrians walking together

Spatial clustering

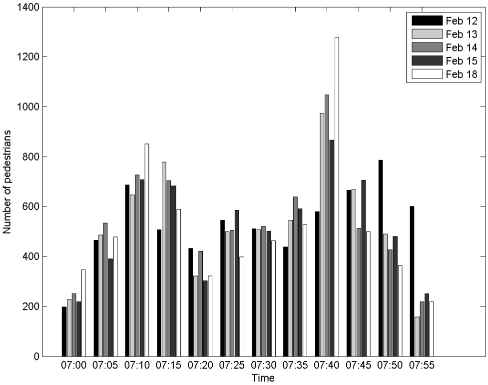
Density-based clustering - grouping of data into categories based on ε (2.1336m), θ (0.1524m/s), φ (3°)

Temporal clustering

Frequent pattern analysis - finds sets of density-based clusters that are frequently observed together (w.r.t k - temporal threshold, relative to the total time a pedestrian travels in the corridor)

Peak periods during morning rush hour

Number of pedestrians over time



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Peak periods per day

February 12

07:10 - 07:15, 07:25 - 07:30, 07:50 - 07:55

February 13

07:15 - 07:20, 07:40 - 07:45

February 14

07:10 - 07:15, 07:40 - 07:45

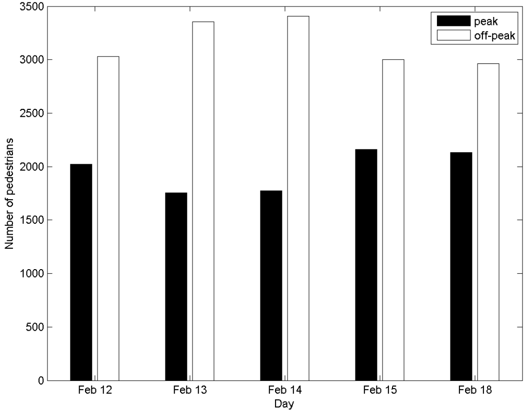
February 15

07:10 - 07:15, 07:25 - 07:30, 07:40 - 07:45

February 18

07:10 - 07:15, 07:40 - 07:45

Peak/off-peak analysis



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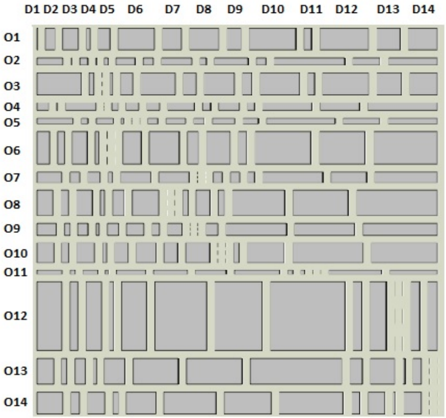
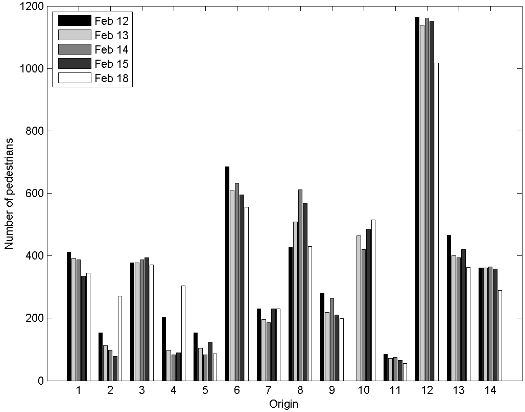
Weather

Day	Temperature	Rain/Sun
12 February	0.4°C	Sun
13 February	-1.6°C	Rain
14 February	-3.2°C	Rain
15 February	0.5°C	Sun
18 February	-0.3°C	Sun

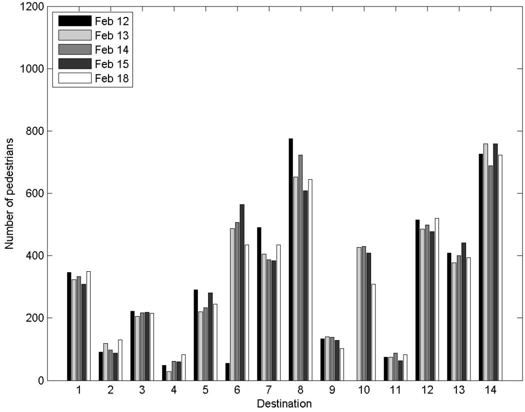
OD pattern


D1 D2 D3 D4 D5 D6 D7 D8 D9 D10 D11 D12 D13 D14
O1
O2
O3
O4
O5
O6
O7
O8
O9
O10
O11
O12
O13
O14

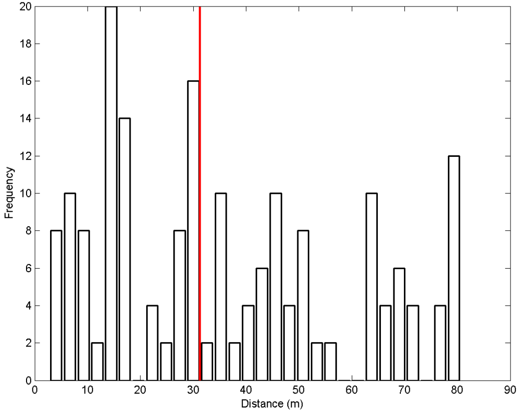
Number of pedestrians per origin



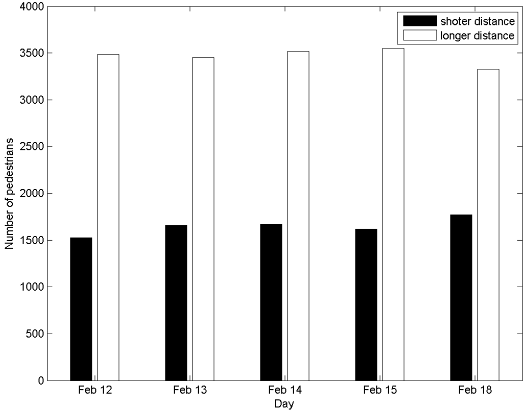
Number of pedestrians per destination



OD distances



OD distances analysis



PIW

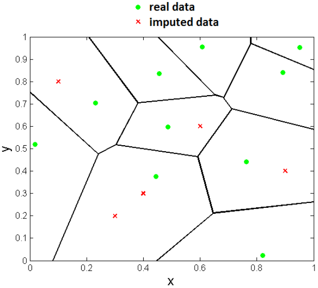
Indicators

Trajectory - a finite collection of triples

$p_{is} = (x_{is}, y_{is}, t_s), t_s = (t_0, t_1, \ldots, t_f)$

Density

$$k_{is} = \frac{n_{is}^{real} + n_{is}^{imputed}}{|V_{is}|}$$



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Indicators

Trajectory - a finite collection of triples

$p_{is} = (x_{is}, y_{is}, t_s), t_s = (t_0, t_1, \ldots, t_f)$

Speed

$$v_{is} = \sqrt{\left(\frac{\Delta x_{is}}{\Delta t}\right)^2 + \left(\frac{\Delta y_{is}}{\Delta t}\right)^2}$$

$\Delta x_{is} = x_{i,s+1} - x_{i,s-1}$, $\Delta y_{is} = y_{i,s+1} - y_{i,s-1}$

$\Delta t = t_{s+1} - t_{s-1}$