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Initiating lane and band formation in heterogeneous pedestrian dynamics

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Collective behaviors in pedestrian dynamics

- Many examples of collective behaviors in pedestrian dynamics: lane, band, chevron and stripe formation, stop-and-go waves, intermittent flow, etc.
- Non-linear effects, phase transition, metastability

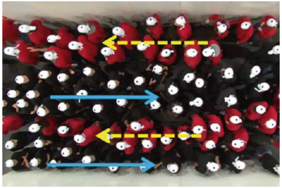
  D Chowdhury et al. Statistical physics of vehicular traffic and some related systems. *Phys Rep* **329** (2000)

  C Castellano et al. Statistical physics of social dynamics. *Rev Mod Phys* **81**, 591 (2009)

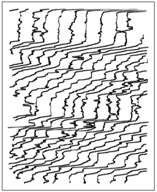
  M Boltes et al. Empirical results of pedestrian and evacuation dynamics. *Encyclopedia of Complexity & Systems Science* (2018)

- **Objective :** Explain macroscopic collective dynamics from microscopic behaviors/interactions

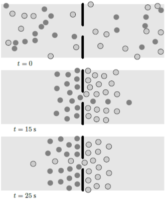
Lane formation



Stop-and-go waves



Intermittent flow



Models of heterogeneity

- Agent's motion: Model F (e.g. Social Force model) depending on state variables $\mathbf{X}$ (e.g. distances to the neighbours) and parameters $\mathbf{p}$ (e.g. maximal speed, agent size)
- Two types $k = 1, 2$ of agents and two different setting $\mathbf{p}_1$ and $\mathbf{p}_2$ for the model parameters

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Model 1 *Heterogeneity of the agents*: Static (quenched) attribution of the two parameter setting $\mathbf{p}_1$ and $\mathbf{p}_2$ to the two types of agents

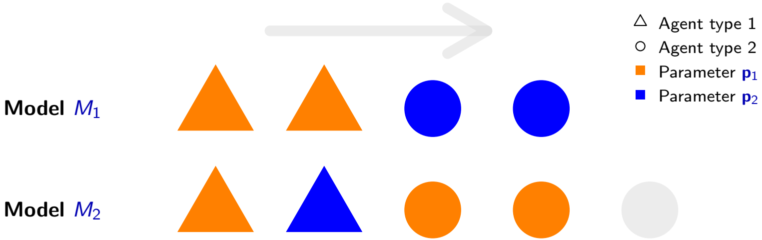
$$M_1(\mathbf{X}, k) = F(\mathbf{X}, \mathbf{p}_k) \tag{1}$$

Model 2 *Heterogeneity of the interactions*: Dynamic (annealed) attribution of the parameter setting $\mathbf{p}_1$ and $\mathbf{p}_2$ according to the interaction:

$$M_2(\mathbf{X}, k) = \begin{cases} F(\mathbf{X}, \mathbf{p}_1), & \text{if } \tilde{k}(\mathbf{X}) = k \\ F(\mathbf{X}, \mathbf{p}_2), & \text{otherwise} \end{cases} \tag{2}$$

with $\tilde{k}(\mathbf{X})$ the type of the closest agent in front

Models of heterogeneity



The heterogeneity statically relies on the agent type within the model M_1 (quenched disorder)
It dynamically depends on the type of the agent in front for the heterogeneity model M_2 (annealed disorder).

Simulation results

- Simulation of uni-directional flows in a $w \times h$ rectangle with periodic boundary conditions
- Collision-free model (CFM) — Main parameters :
  - Desired speed V — maximum scalar speed
  - Desired time gap T — distance/speed ratio
  - Agent size ℓ — agent's radius
- One denotes $\mathbf{p}_1 = (V_1, T_1, \ell_1)$ and $\mathbf{p}_2 = (V_2, T_2, \ell_2)$ the two sets of parameter values.
- Models M_1 and M_2 tend respectively to describe lane and band formation as

$$|V_2 - V_1| \gg 0, \qquad |T_2 - T_1| \gg 0 \qquad \text{or} \qquad |\ell_2 - \ell_1| \gg 0$$

- **Online simulation with NetLogo:**

  vzu.uni-wuppertal.de/en/simulation-with-netlogo

Monte-Carlo simulation

- Monte-Carlo simulation from random initial positions
- Measurement during one minute of the agent mean speed and mean lane and band order parameters after a simulation time of $t_0 = 10$ min
  - Order parameter for lane formation: M Rex & H Löwen, *Phys Rev E* 75 (2007)

$$\left|\begin{array}{l} N = \text{card}(m, |y - y_m| < \Delta, k = k_m) \\ \bar{N} = \text{card}(m, |y - y_m| < \Delta, k \neq k_m) \end{array}\right. \qquad \Phi_L = \left[\frac{N - \bar{N}}{N + \bar{N}}\right]^2$$

  - Order parameter for band formation:

$$\left|\begin{array}{l} M = \text{card}(m, |x - x_m| < \Delta\, w/h, k = k_m) \\ \bar{M} = \text{card}(m, |x - x_m| < \Delta\, w/h, k \neq k_m) \end{array}\right. \qquad \Phi_B = \left[\frac{M - \bar{M}}{M + \bar{M}}\right]^2$$

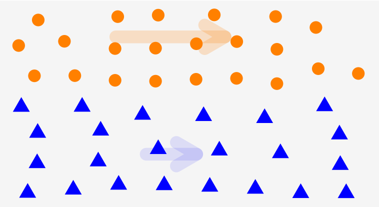
- Starting from the default values $(T, V) = (1\text{ s}, 1.5\text{ m/s})$, we vary the time gap T and desired speed V to reproduce an heterogeneity of agent speed characteristics:

$$T_1 = T + 0.05\delta, \quad T_2 = T - 0.05\delta, \quad V_1 = V - 0.025\delta, \quad V_2 = V + 0.025\delta$$

  for heterogeneity index $\delta = 0, 1, 2 \ldots, 19$.

Self-organisation in lanes

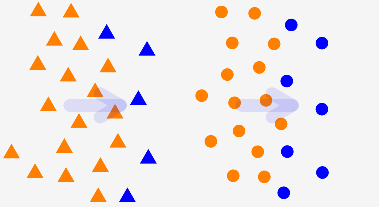
Model M_1: *Heterogeneity in agent characteristics*



$\Phi_L \approx 1$ and $\Phi_B \approx 0$

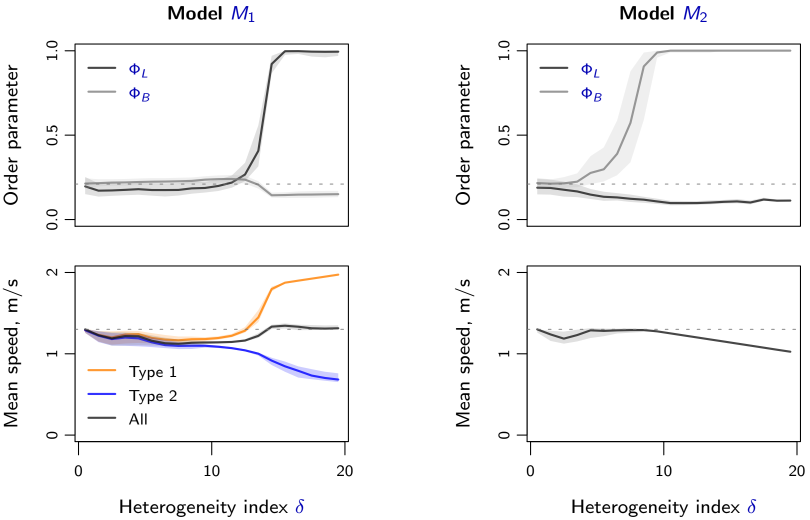
Self-organisation in bands

Model M_2: *Heterogeneity in the interactions*



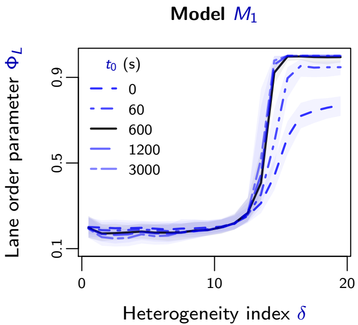
$\Phi_L \approx 0$ and $\Phi_B \approx 1$

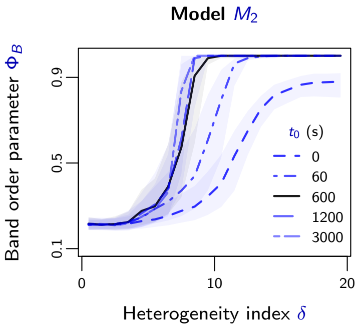
Phase transition as heterogeneity index increases

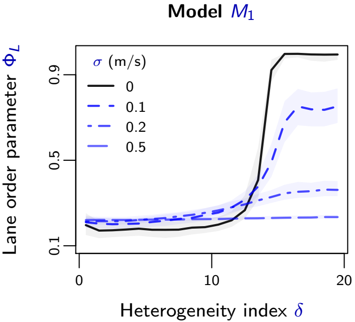


Transient states

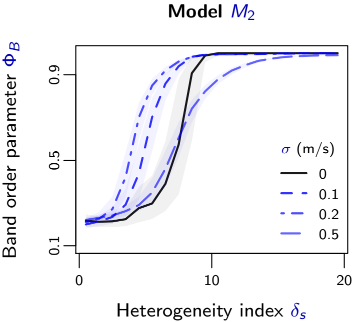
Lanes and bands emerge during the first minutes of simulation







Model M_1
Lane order parameter Φ_L
σ (m/s)
0
0.1
0.2
0.5
0.1
0.5
0.9
0
10
20
Heterogeneity index δ



Model M_2
Band order parameter Φ_B
σ (m/s)
0
0.1
0.2
0.5
0.1
0.5
0.9
0
10
20
Heterogeneity index δ_s

Summary and work perspectives

Summary

- Identification of two heterogeneity mechanisms for mixed traffic
  M_1 : Static heterogeneity in the agent characteristics
  M_2 : Dynamic heterogeneity in the interaction
- ≪Universal≫ mechanisms for the formation of lanes (M_1) or bands (M_2)
  $\rightarrow$ Features observed with CFM and SFM models and different agent characteristic (desired speed, agent' size, etc.)

Work perspectives

- Analysis of geometries (corridor, bottleneck): segregation effects for slower/bigger agents
- Analytic description of the phase transition
  - Lattice or cellular automaton representation of the model
  - Critical heterogeneity index by means of linear instability of corresponding mean-field solutions

J Cividini et al. EPL **102(2)**, 20002 (2013)
A Della Noce et al. arXiv:1906.01368 (2019)

Thank you for your attention !

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