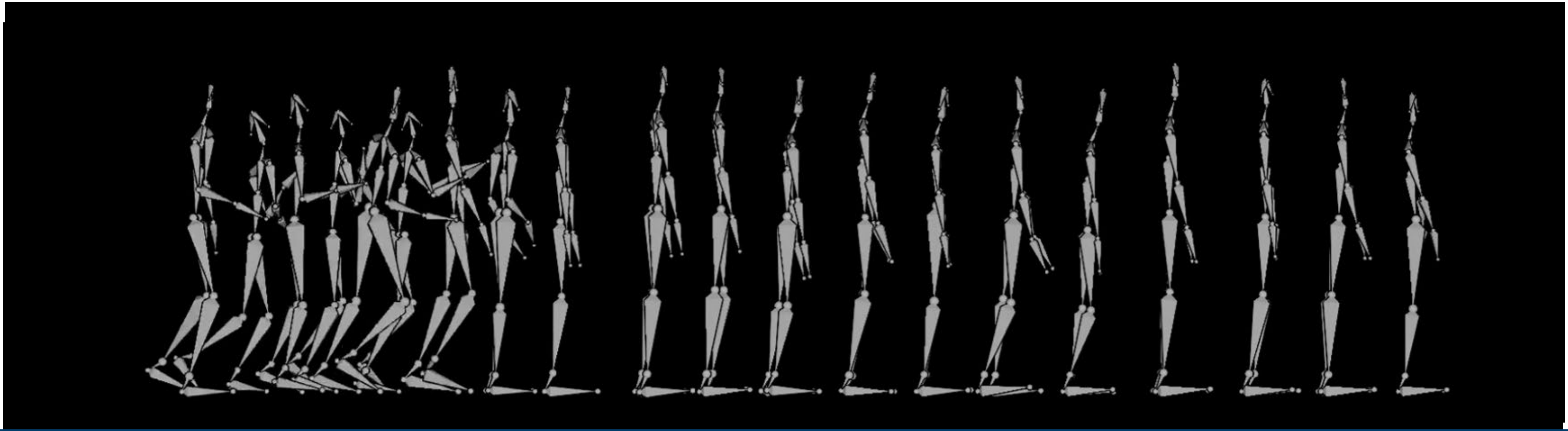

MOVEMENT AND WAITING OF CROWDS

STATE OF THE ART MODELS AND DATA

Mai 13th 2025, SUMO User Conference 2025, Berlin, Armin Seyfried

JÜLICH Forschungszentrum

OVERVIEW

- Crowd dynamics - objectives of modelling
  - Collective phenomena and transport characteristics
  - Complexity and diversity of perspectives
- Modelling approaches
  - Types and origins of models
  - AI models, Force models, Velocity models
- Discussion of models
  - Equation of motions
  - Model zoo
  - Superposition of interactions, superposition of operations,
  - Minimal models
- Summary, outlook and recommendations

MOTIVATION AND PHENOMENA

Viewpoint of a traffic or safety engineer and physicist

- Self-driven and interacting particles
  - Pedestrians (vehicles, animals, …)
- Interests
  - Collective phenomena
    - Lane formation in bidirectional streams

Credits: M Chraibi

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    - Density waves and collective oscillations

Gu, F., et al., 2025, Emergence of collective oscillations in massive human crowds. Nature 638, 112–119

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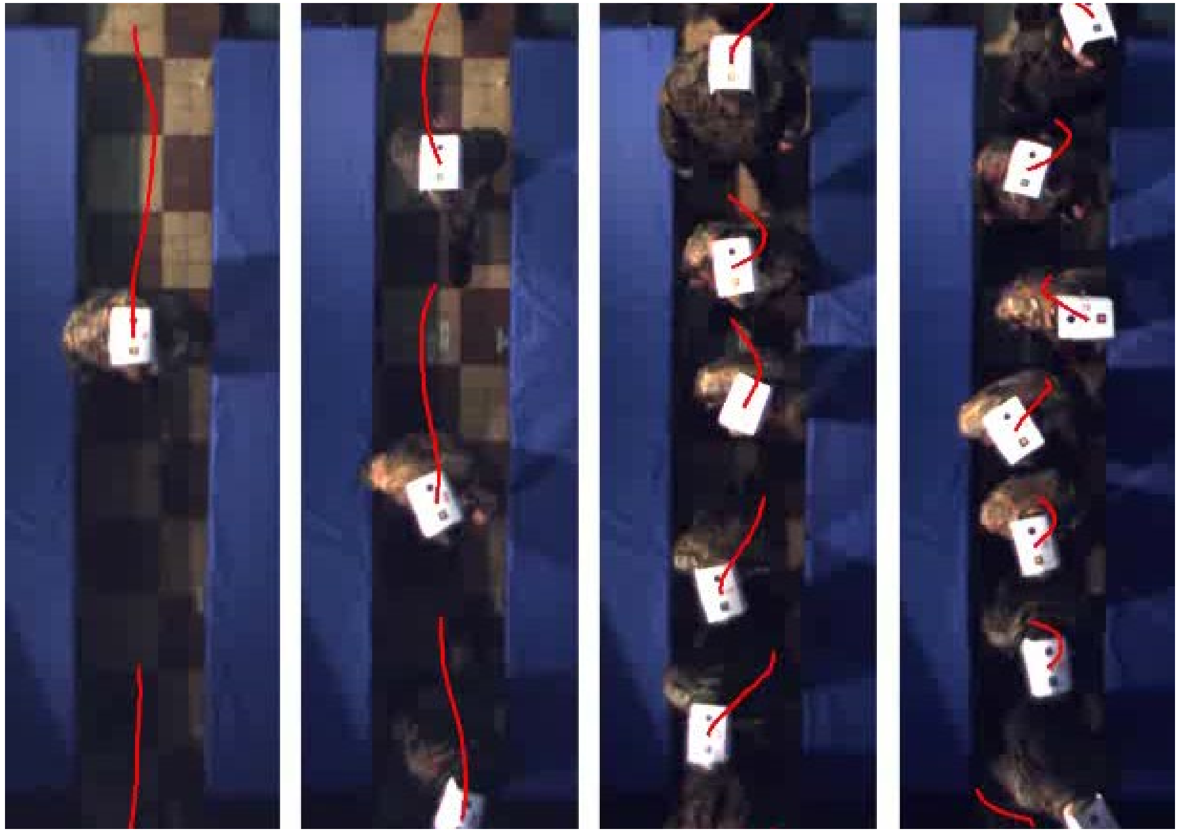
    - Clogging
    - Stop and go waves
  - Transport properties
    - Speed-flow-density relation (congestion)



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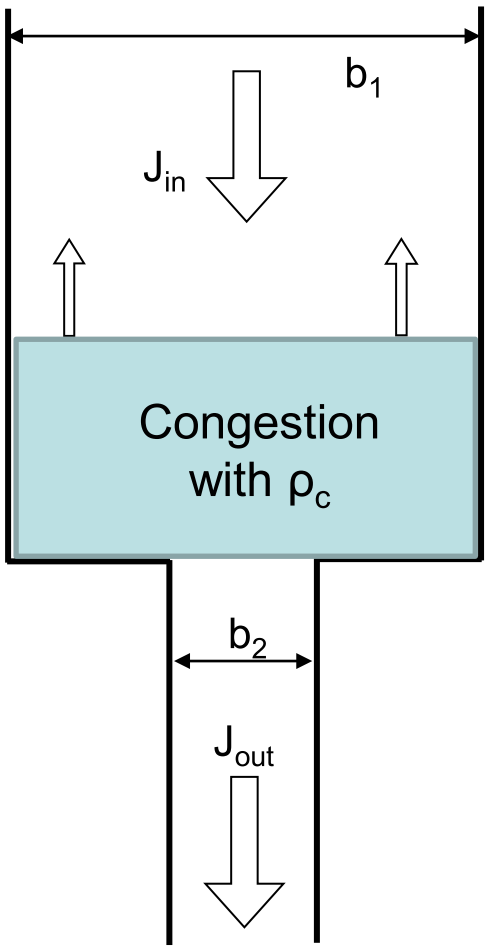
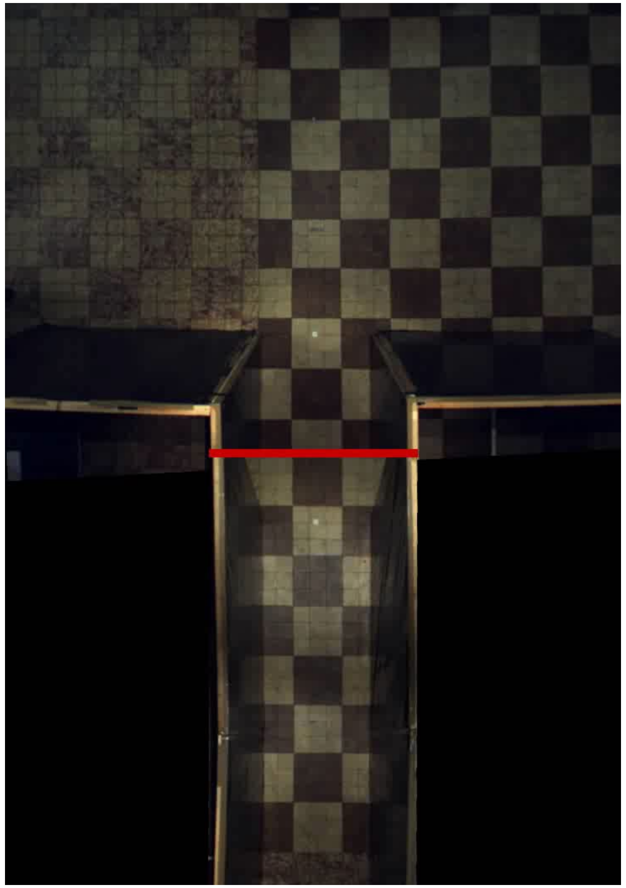
  - Transport properties
    - Speed-flow-density relation (congestion)
    - Bottleneck flow





TRANSPORT PROPERTIES

Relation between speed, flow and density

- To describe crowds density, speed and flow are useful concepts
  - Density ρ [m^{-2}],
  - Flow J [s^{-1}],
  - Speed v [m/s]
- They are helpful to rate e. g.
  - Performance of pedestrian facilities (flow)
  - Level of service (density)
  - Travel or waiting times (speed)

TRANSPORT PROPERTIES

Quantitative description of crowd dynamics

- To describe crowds density, speed and flow are useful concepts
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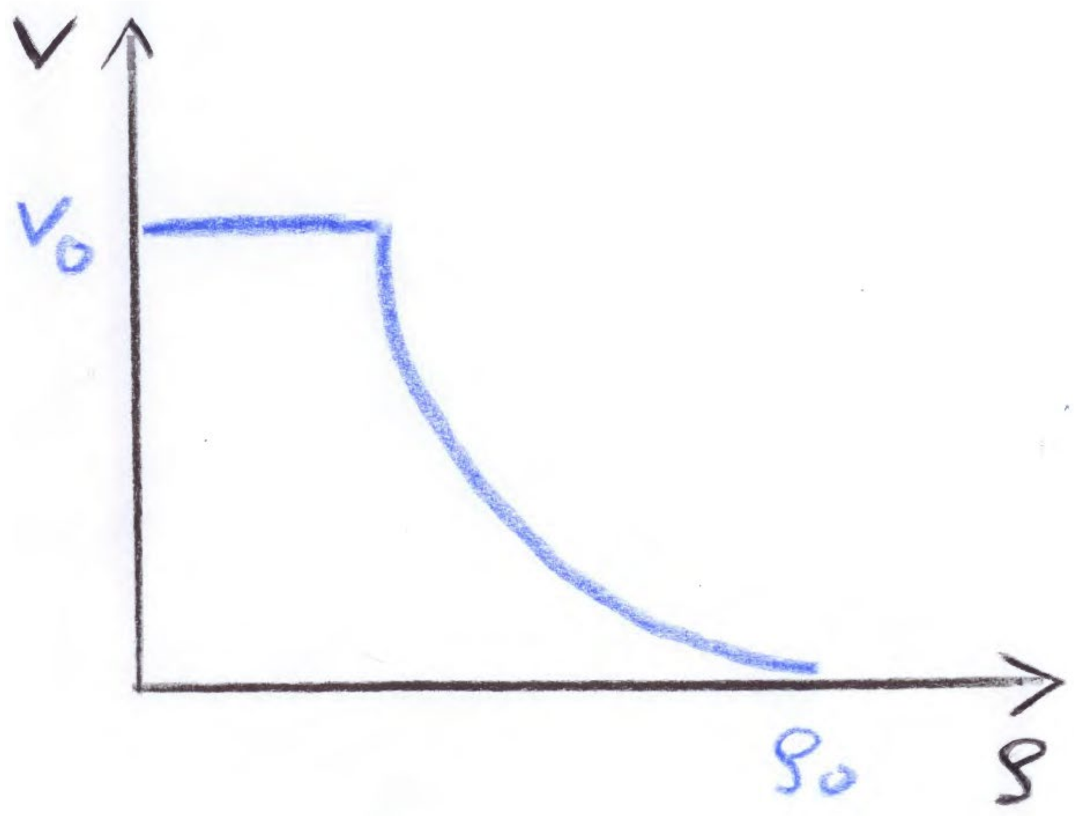
  - Performance of pedestrian facilities (flow)
  - Level of service (density)
  - Travel or waiting times (speed)
- Speed, Flow and density are related
  - Speed decreases with density
  - Free flow and congested regime



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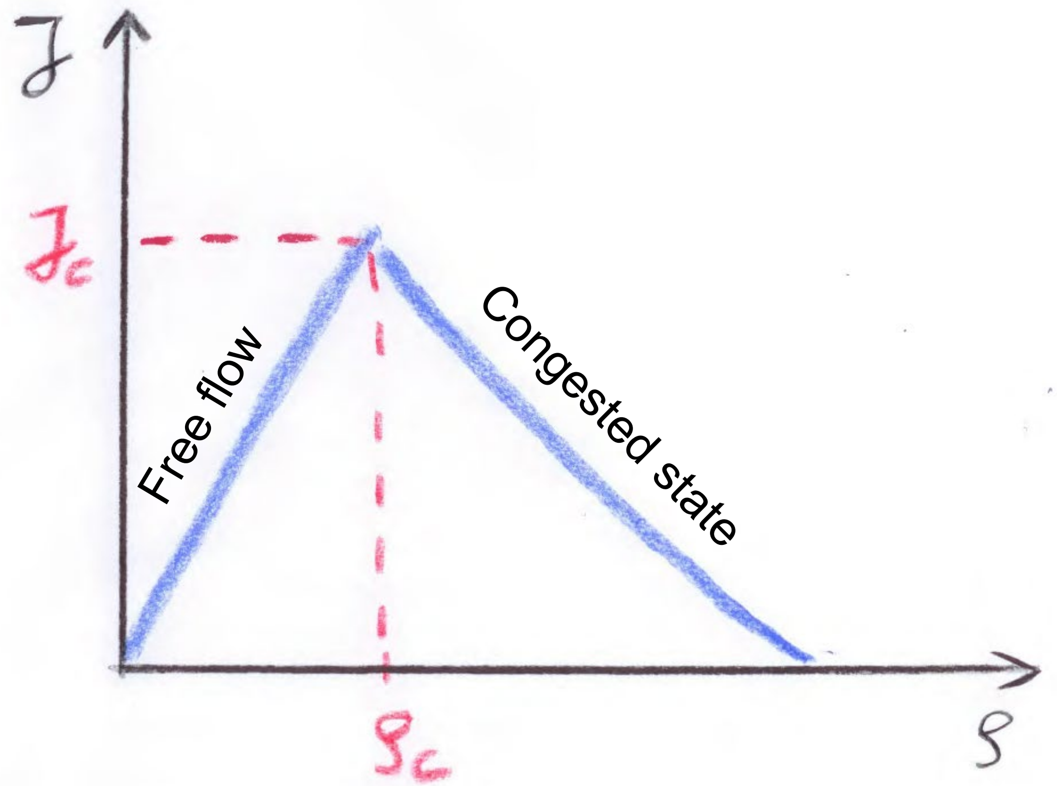
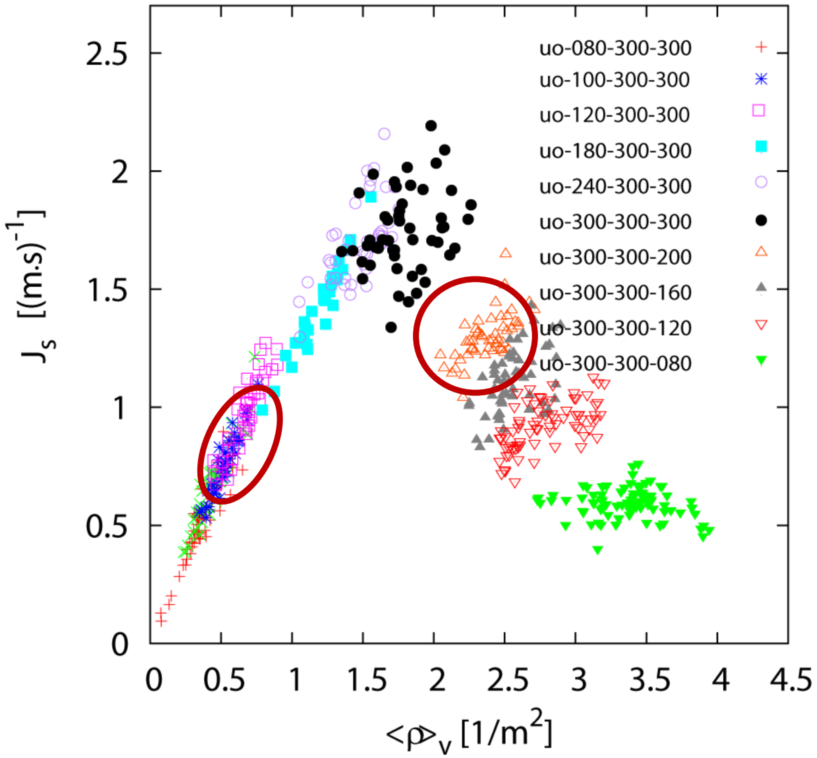


TRANSPORT PROPERTIES

Unidirectional stream

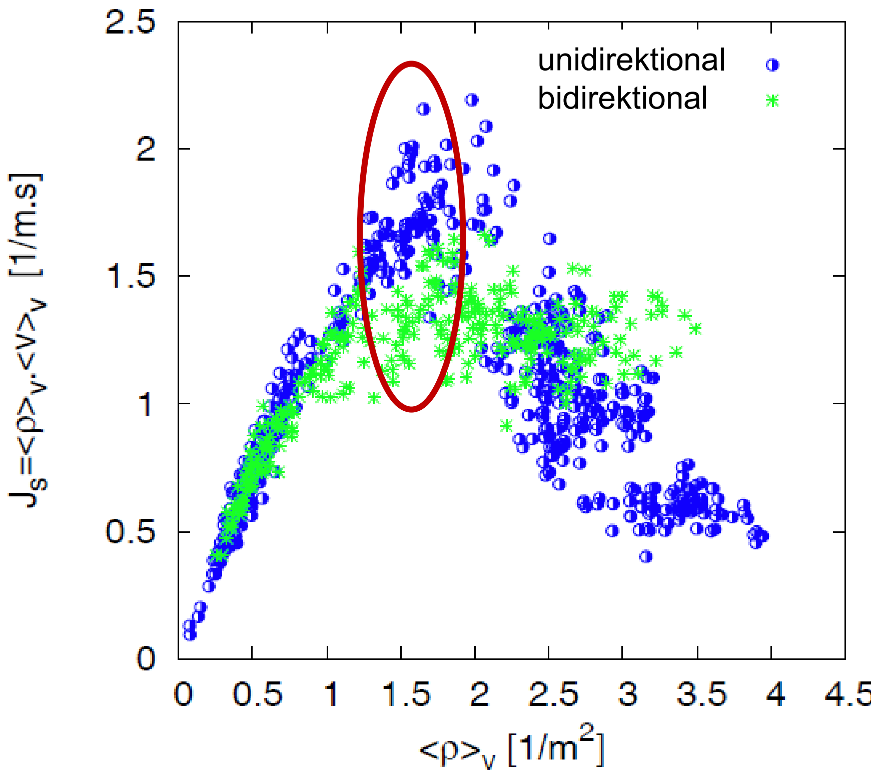
- Free flow condition
- Congested condition



TRANSPORT PROPERTIES

Comparison of unidirectional and bidirectional streams

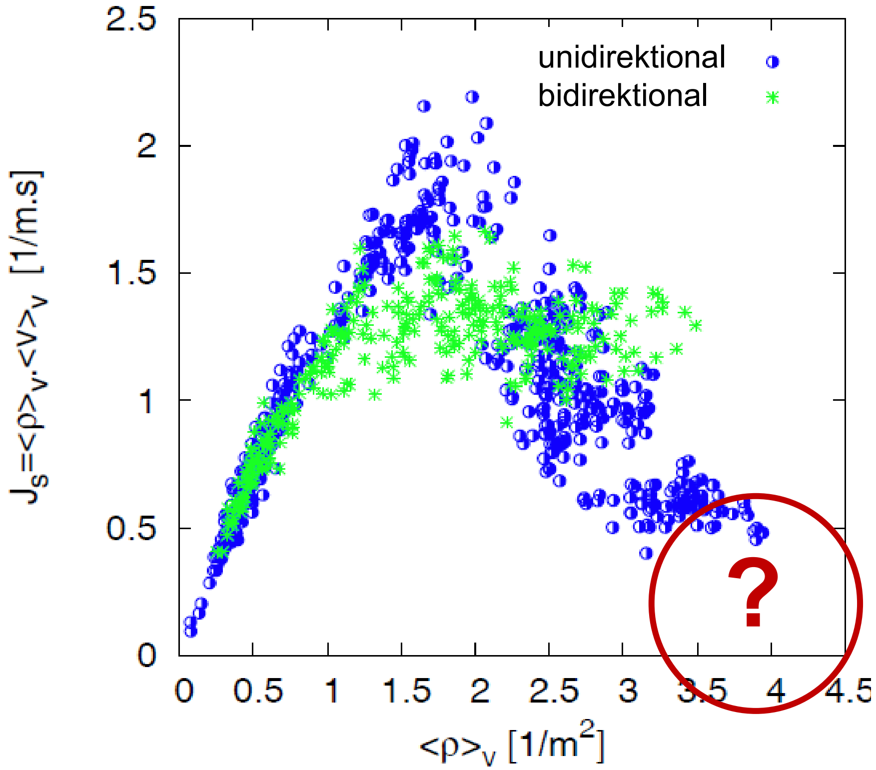
- Free flow condition
- Congested condition
- Bidirectional streams: reduced capacity



TRANSPORT PROPERTIES

Comparison to bidirectional streams

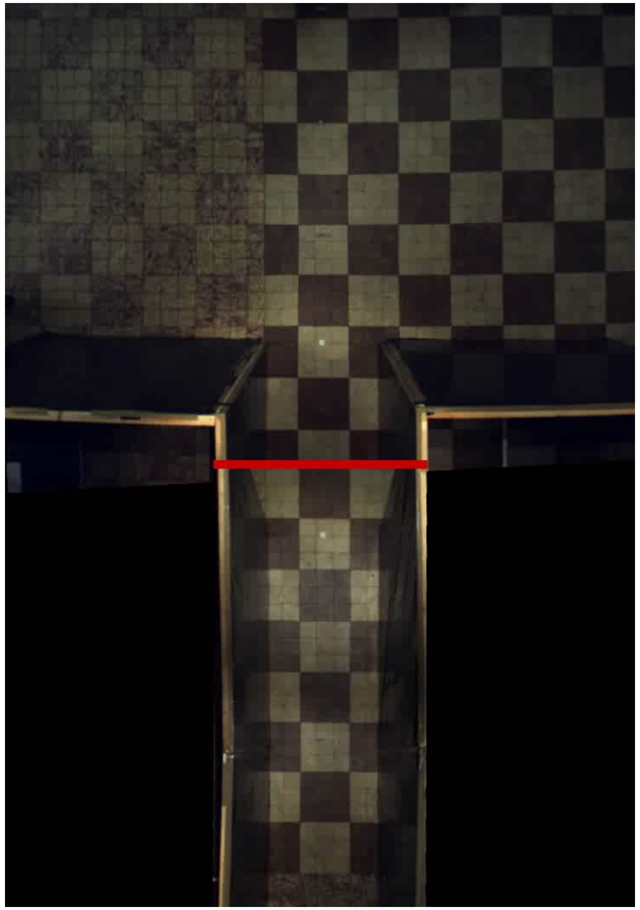
- Free flow condition
- Congested condition
- Bidirectional streams: reduced capacity
- To date, there is no measurement of the deadlock for uni- and bidirectional flows (even if it occurs in the field).



TRANSPORT PROPERTIES

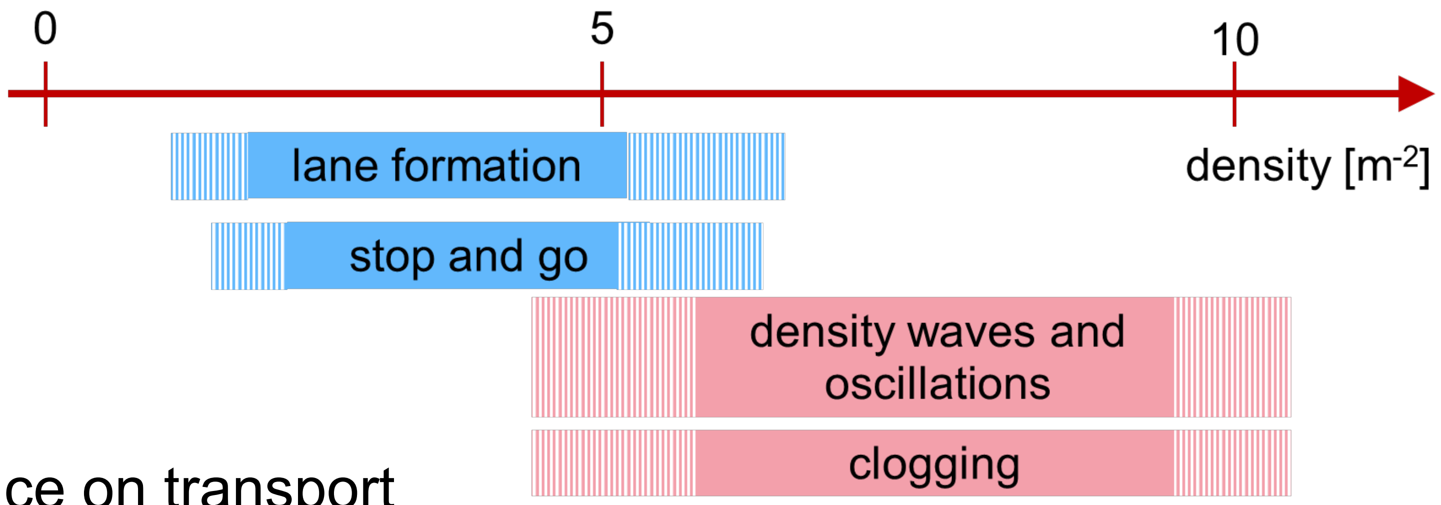
Not discussed!

- Types of facilities
  - Bottlenecks
  - Escalators and stairs
  - Ramps, …
- Human factors
  - People with disabilities
  - Motivation
  - Cultural factors
  - Age, height, gender, …
- Waiting at platforms, boarding and alighting, luggage, …



NOTE!

Collective phenomena and interaction



- Collective phenomena have influence on transport properties
- The phenomena occur in different density ranges and are the result of different interactions
- Lane formation in bidirectional streams
- Stop and go waves
- Density waves and turbulences -
- Clogging

}

no body contact,
visual perception and steering

}

body contact
impulse transfer, forces, …

COMPLEXITY OF CROWD DYNAMICS

Entrance to a concert

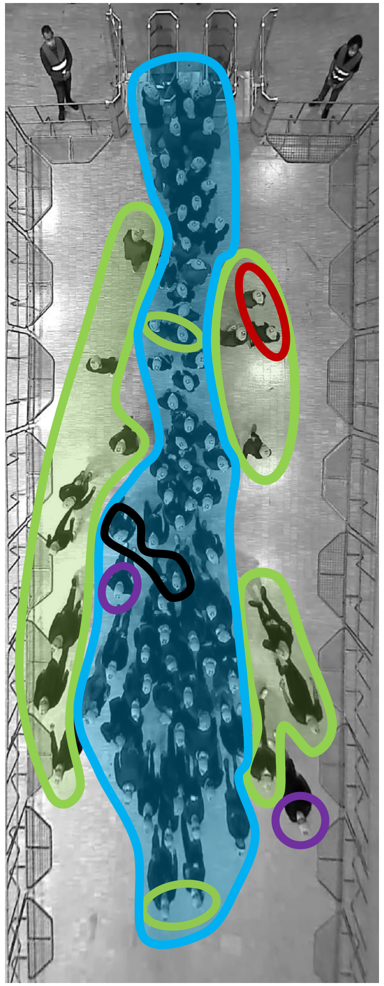
Sieben, Anna; Postmes, Tom; 2025, R. Soc. Open Sci. 12, 241561

DIVERSITY OF PERSPECTIVES

What could be observed and what questions arise?

- System capacity, Level of Service, speed, density, flow, ….
- Behaviour: queuing, huddling, overtaking, joining, not joining, …
- Motions: collision avoidance, stopping, get going, keeping distance, closing gaps, body contact and pushing
- Transition from queuing to huddling
  - What do people perceive and how it triggers their action?
  - Which social norms are relevant and how it interrelates with individual motivation?, …

Queuing
Overtaking
Joining
Not joning
Leaving the joining



Pedestrian dynamics – a melting pot of disciplines

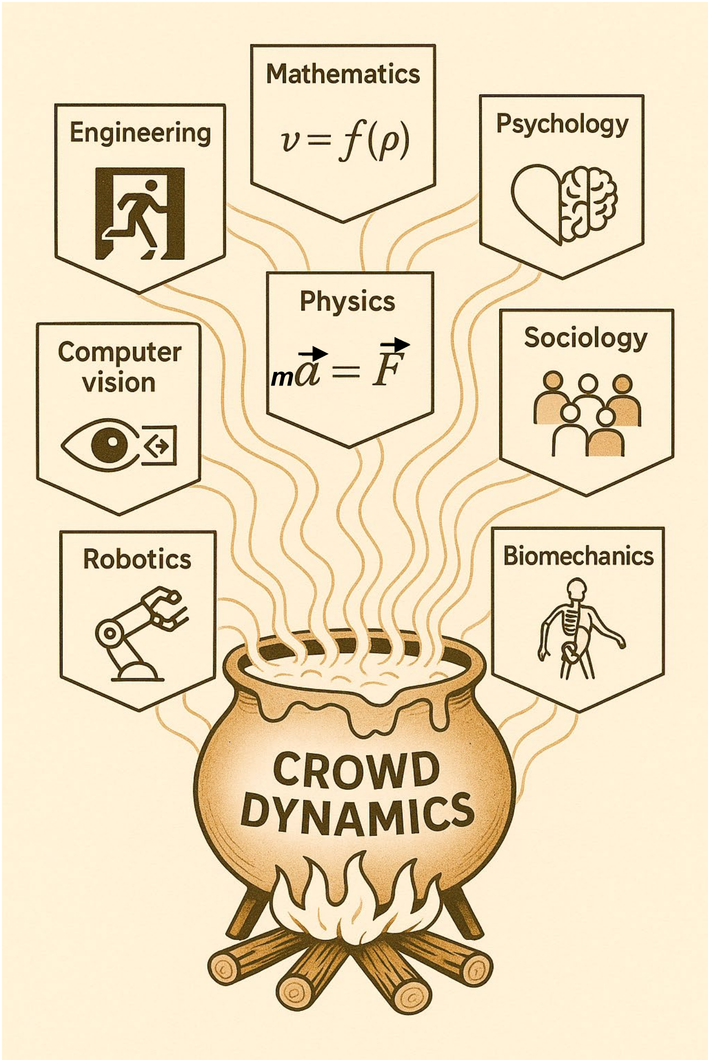
But, all disciplines have their own perspective

Sieben, A., Postmes, T., 2025. R. Soc. Open Sci. 12

RESEARCH FIELDS

Moving crowds – a wide range of research fields

- Traffic, safety and mechanical engineering
  - Public transport, event safety, autonomous driving, …
- Mathematics and physics
  - Collective phenomena, transport, transitions, …
- Computer science (robotics, computer vision, VR, …)
  - Steering of robots, detection and counting of pedestrians, …
- Psychology
  - Perception, action, motivation, …
- Social psychology and sociology
  - Social norms, social identity, group dynamic, …
- Biomechanics, sport science, …
  - Balance, …



Modelling approaches

A model is always a simplified representation of reality

LEVEL OF MODELS

Time scales and options for navigation and decisions

- Strategical
  - Time scale: ‘long’
  - E.g. decisions on activities
- Tactical
  - Time scale: ‘medium’
  - How (when, where, …) to perform the activities
- Operational
  - Time scale ‘short’
  - How to share the space with others

This weekend I will visit my mother and travel by train. I decide to walk to the station and buy a newspaper and a sandwich.

At the bakery there is a long queue, so I buy newspaper first and than the sandwich.

Interaction with others, motion operations and collision avoidance: accelerating, decelerating, stopping, changing directions, queuing, …

These levels of modelling are not clearly separable and merge into one another!

TYPES AND ORIGIN OF MODELS

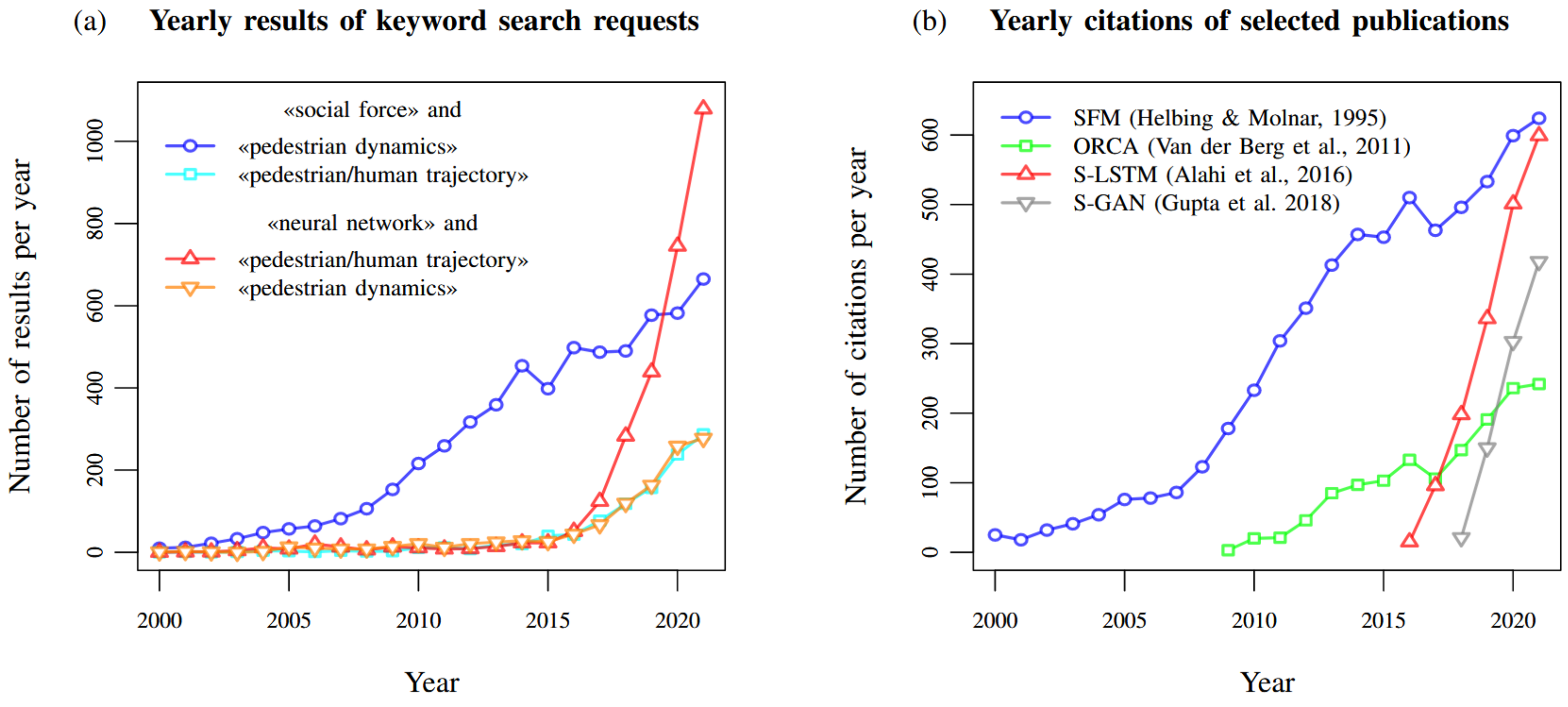
Focus on operational models

- PDE's, e.g. continuity equation – mathematics, …
- Cellular automata – physics, engineering, …
- Vison models – Psychology of perception and action
- AI models – computer vision, mechanical engineering, …
- Force models – physics, engineering, …
- Velocity models – traffic engineering, robotics, …
- Hybrid and mixture of model types: CA with forces, AI with physics, …

AI MODELS

Mostly from computer vision (autonomous driving)

- In recent years increasing numbers of publications

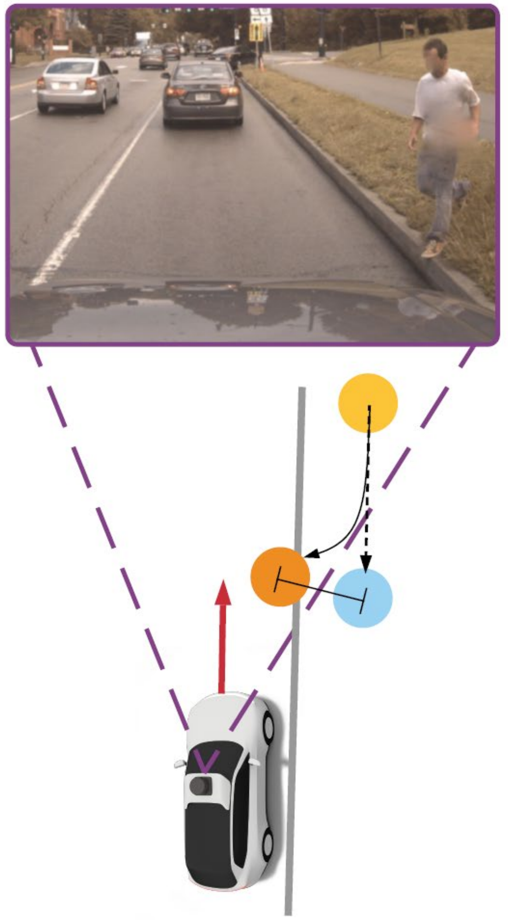


Korbmacher, R., Tordeux, A., 2022. Review of Pedestrian Trajectory Prediction Methods https://doi.org/10.1109/TITS.2022.3205676

AI MODELS

Mostly from computer vision (autonomous driving)

- In recent years increasing numbers of publications
- Prediction of future trajectories of pedestrian to e.g. detect pedestrians
- Deep Learning methods



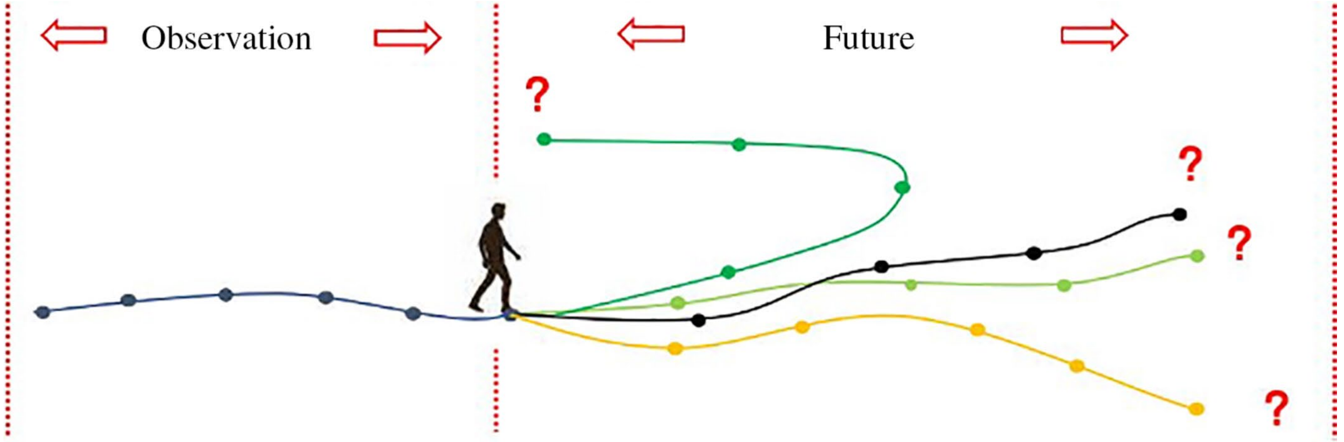
(a) $P(\lambda_{actor})$ flags this as unsafe.

Skanda Shridhar, et. al. 2021. Beelines: Motion Prediction Metrics for Self-Driving Safety and Comfort. IEEE International Conference on Robotics and Automation (ICRA) https://doi.org/10.1109/ICRA48506.2021.9560950

AI MODELS

Mostly from computer vision (autonomous driving)

- In recent years increasing numbers of publications
- Prediction of future trajectories of pedestrian to e.g. detect pedestrians
- Deep Learning methods
- Input: past trajectories
- Output: future trajectories
- Time scale of trajectory prediction < 10 sec



Li, D., Lin, Z. and Hu, J. (2025), A Specialized Variational Autoencoder for Cost-Efficient Pedestrian Trajectory Prediction. IEEJ Trans Elec Electron Eng. https://doi.org/10.1002/tee.70053

FORCE MODELS

Acceleration models, Social Force Models, 2nd order models, …

- Equation of motion inspired by classical mechanics (Newtonian laws)

$$\ddot{\vec{x}}_i(t) = \dot{\vec{v}}_i(t) = \vec{F}\left(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_i(t), \vec{v}_j(t), \dots\right)$$

- Physical model of attractive and repulsive forces (inspired by Lewin's social fields).

$$\ddot{\vec{x}}_i(t) = \vec{F} = \vec{F}_i^{drv} + \sum_{j \in N} \vec{F}_{i,j}^{rep} + \sum_{w \in W} \vec{F}_{i,w}^{rep} + \vec{F}_i^{others}$$

$\vec{F}_i^{drv}$: Driving force

$\vec{F}_{i,j}^{rep}$: Repulsive force between pedestrian i and pedestrian j

$\vec{F}_{i,w}^{rep}$: Repulsive force between pedestrian i and walls W

$\vec{F}_i^{others}$: Others E.g.: Group force, attraction force, friction forces, noise, …

VELOCITY MODELS

- Instantaneous change of velocity

$$\dot{\vec{x}}_i(t) = \vec{v}_i(t) = \vec{f}\big(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_i(t), \vec{v}_j(t), \dots\big)$$

- Two origins
  - Robotics – focus on collision avoidance in systems with multiple moving objects

$$\dot{\vec{x}}_i(t) = \vec{v}_i(t) = \vec{f}\big(\vec{x}_i(t), \vec{x}_j(t), \vec{x}_i(t+t_c), \vec{x}_j(t+t_c), \vec{v}_i(t), \vec{v}_j(t), \dots\big)$$

  - Vehicle traffic – focus on speed-density relation and overtaking

$$\dot{\vec{x}}_i(t) = \vec{v}_i(t) = \vec{f}\big(s = \left\|\vec{x}_i(t) - \vec{x}_j(t)\right\|, \vec{e}_i(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_j(t) \dots), \dots\big)$$

VELOCITY MODELS – ROBOTICS

Collision avoidance with multiple moving obstacles

- Concept
  - Determine whether a collision is to be expected if the speed is remained unchanged
  - Collision cone: Which velocities lead to collisions?
  - Selecting a suitable velocity outside the cone
  - Model variants: Selection criteria

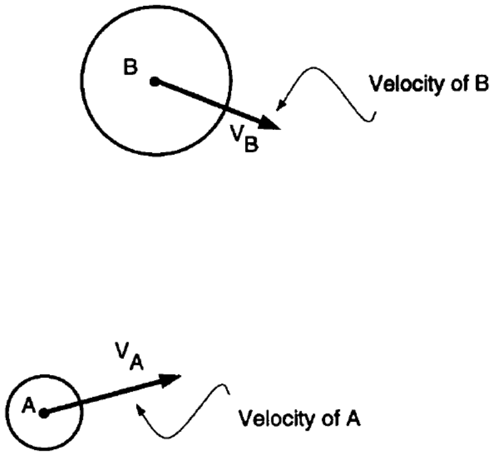


Fig. 1. The robot and a moving obstacle.

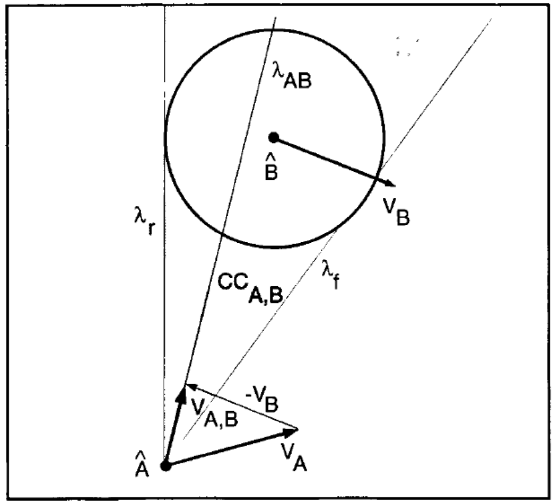


Fig. 2. The relative velocity $\mathbf{v}_{A,B}$ and the collision cone $CC_{A,B}$.

Fiorini and Shiller Int. J. Robot. Res. 17(7):760 (1998)

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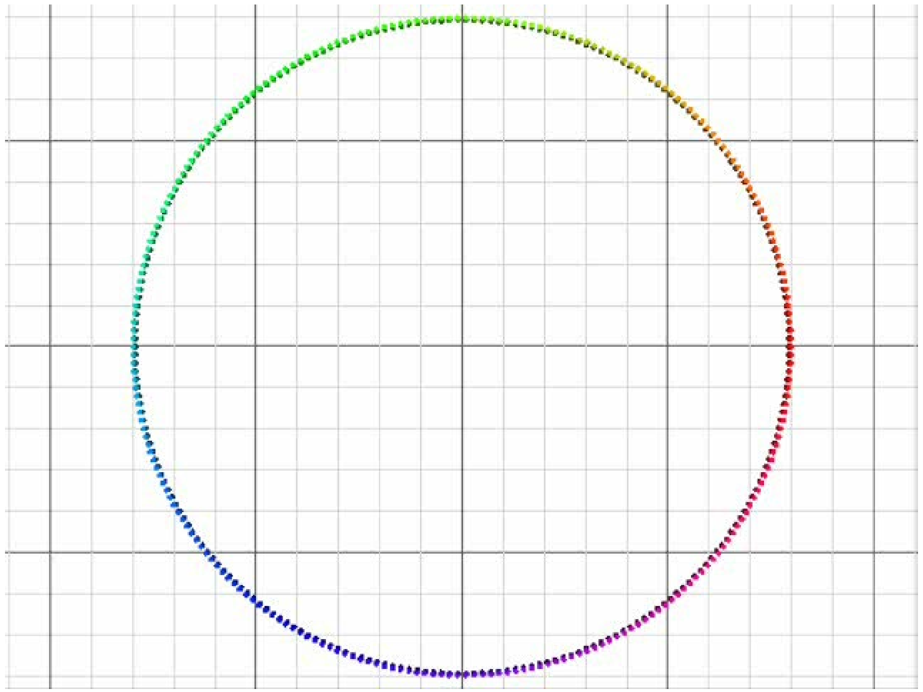
  - Determine whether a collision is to be expected if the speed is remained unchanged
  - Collision cone: Which velocities lead to collisions?
  - Selecting a suitable velocity outside the cone
  - Model variants: Selection criteria of a suitable velocity
    - Vision based: Bearing-angle and its derivative
    - Time-to-interaction
    - Reciprocal velocity to avoid oscillation
    - Deviation from intended velocity
    - Minimization of detour, energy, …



Jur van den Berg, et al. (2008) "Reciprocal Velocity Obstacles for Real-Time Multi-Agent Navigation" http://gamma.cs.unc.edu/RVO/

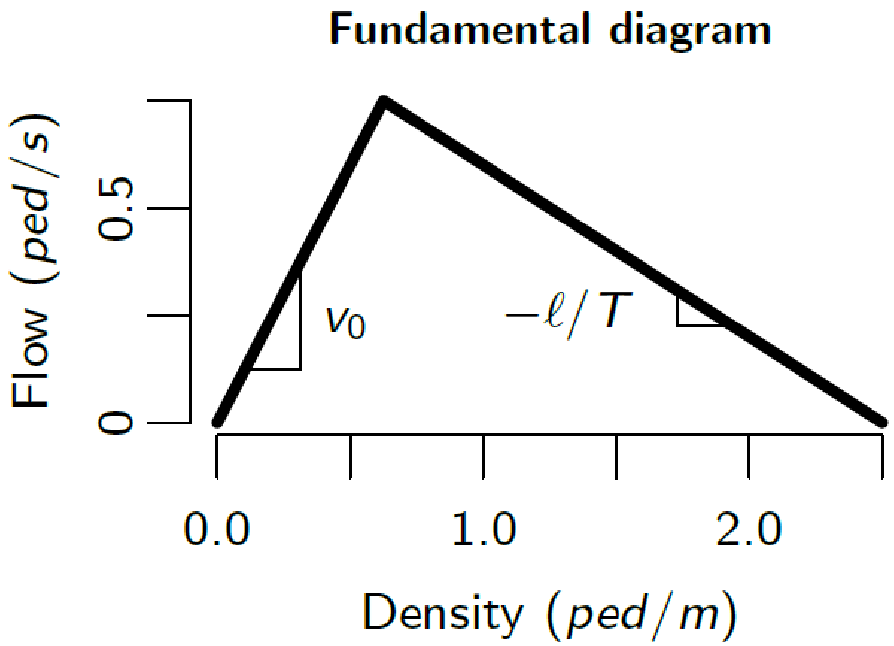
VELOCITY MODELS

Borrowed from vehicle traffic

- Velocity described by speed and directional changes

$$\vec{v}_i = V(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_j(t), \dots) \times \vec{e}_i(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_j(t) \dots)$$

- Concept for speed changes
  - Combination of a collision free models and a Optimal Velocity model



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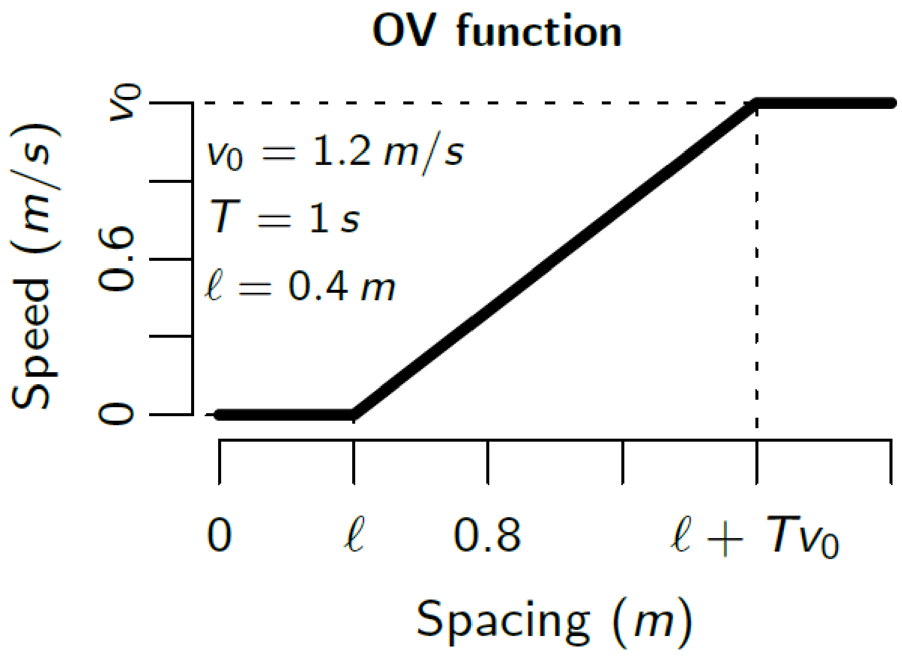
- Concept for speed changes
  - Combination of a collision free models and a Optimal Velocity model
  - Models based on the relation between the speed and distance (OV Function, for 1 d micro fundamental diagram)
  - Initially introduced in traffic flow
  - Simple control of fundamental diagrams (speed is given by the spacing)



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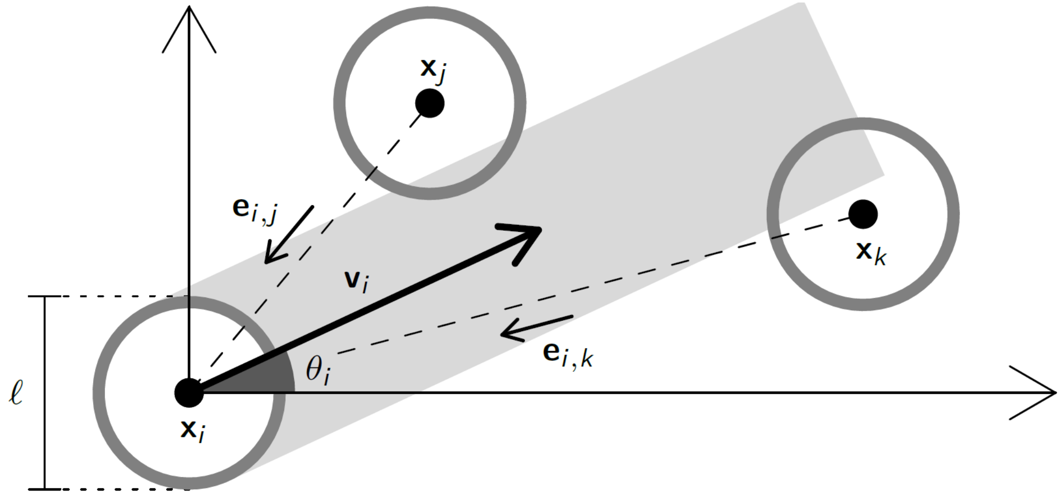
VELOCITY MODELS

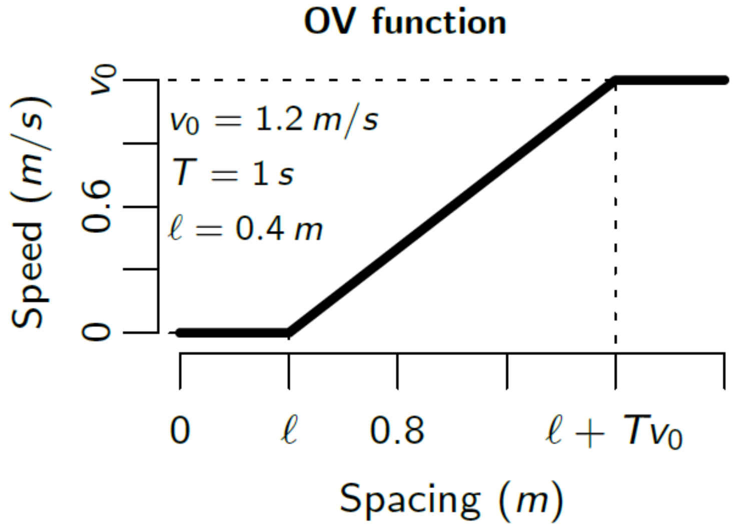
Collision-free OV in 2d – speed changes

- Calculate all distance in front $s_{i,j} = \|\vec{x}_i(t) - \vec{x}_j(t)\|$
- Determine the minimum

$$s_i = \min_{j \in J_i} s_{i,j}$$

- Choose the speed according to OV function





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VELOCITY MODELS

Collision-free OV in 2d – directional changes

- Function to model the direction

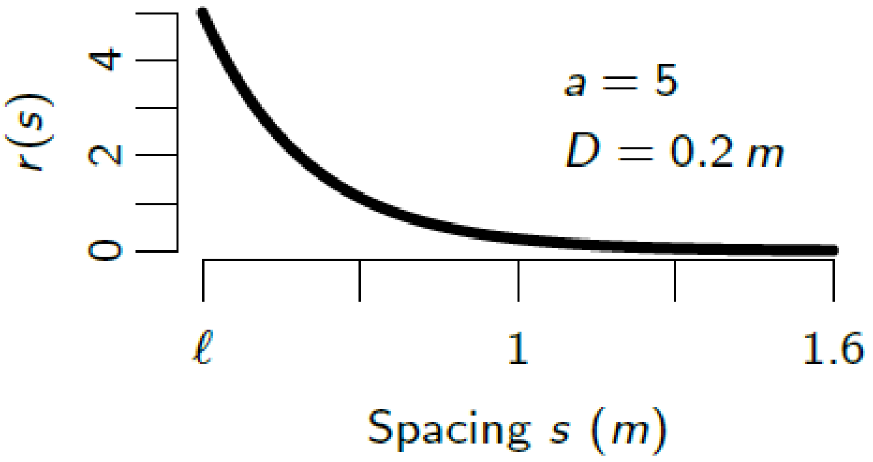
$$\vec{v}_i = V(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_j(t), \ldots) \times \vec{e}_i(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_j(t) \ldots)$$

- Repulsion function

$$r(s) = \exp((l - s)/D)$$

- Choose a direction to avoid collision with neighbors

$$\vec{e}_i\big(\vec{x}_i(t), \vec{x}_j(t), \ldots\big) = \frac{1}{N}(\vec{e}_o + \sum_j r(s_{i,j})\, \vec{e}_{i,j})$$



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VELOCITY MODELS – ROBOTICS AND VEHICLE TRAFFIC

Combine the collision-free OV model with velocity models from robotics

- Instead of using actual position

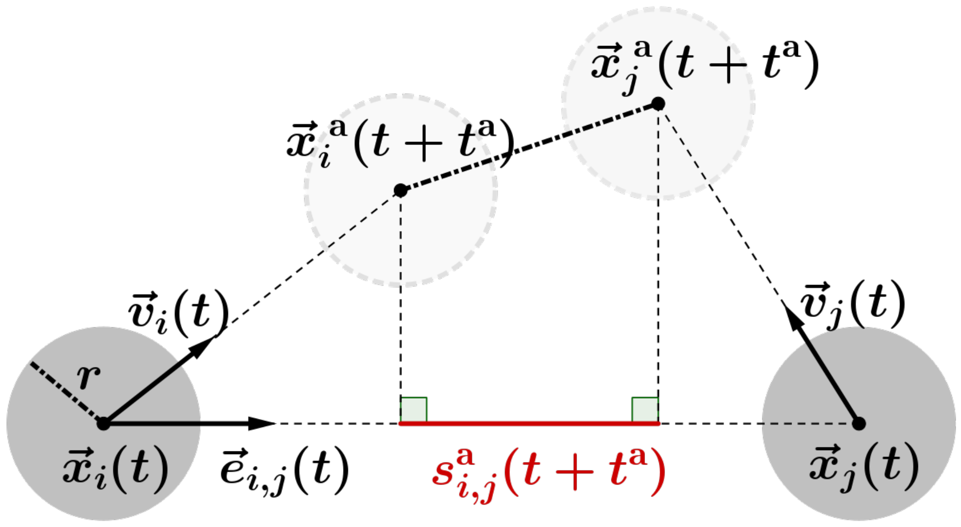
$$\vec{v}_i(t) = \vec{f}\big(\vec{x}_i(t), \vec{x}_j(t), \vec{v}_i(t), \vec{v}_j(t), \dots\big)$$

  use future position to calculate a direction to avoid collision with neighbours

$$\vec{v}_i(t) = \vec{f}\big(\vec{x}_i(t+t_c), \vec{x}_j(t+t_c), \vec{v}_i(t), \vec{v}_j(t), \dots\big)$$

$$r(s) = \exp((l - s(t+t_c)/D)$$

$$\vec{e}_i\big(\vec{x}_i(t), \vec{x}_j(t), \dots\big) = \frac{1}{N}\Big(\vec{e}_o + \sum_j r(s_{i,j}(t+t_c))\,\vec{e}_{i,j}\Big)$$

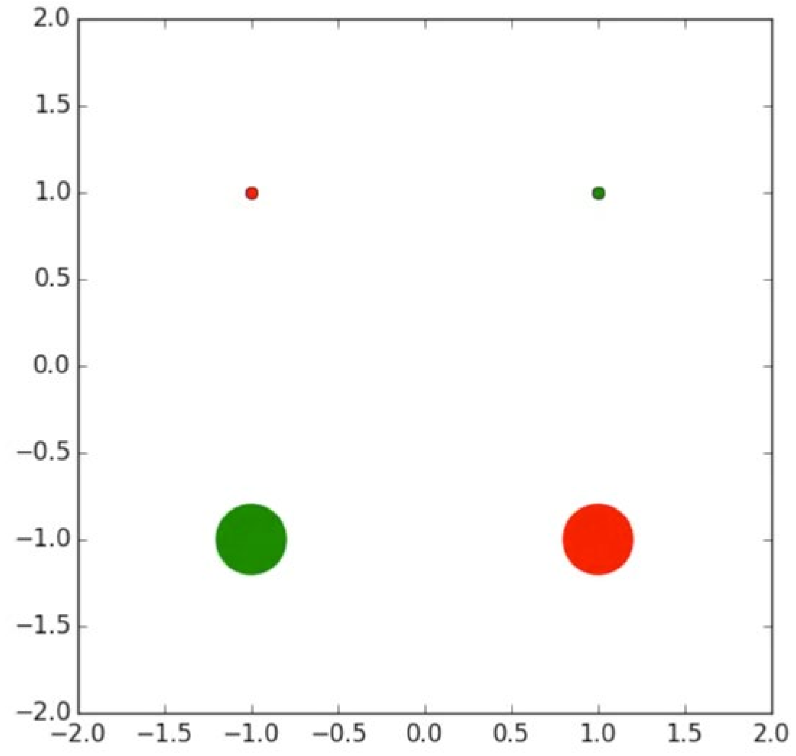


Discussion of models

EQUATION OF MOTIONS

Comparing velocity and force models

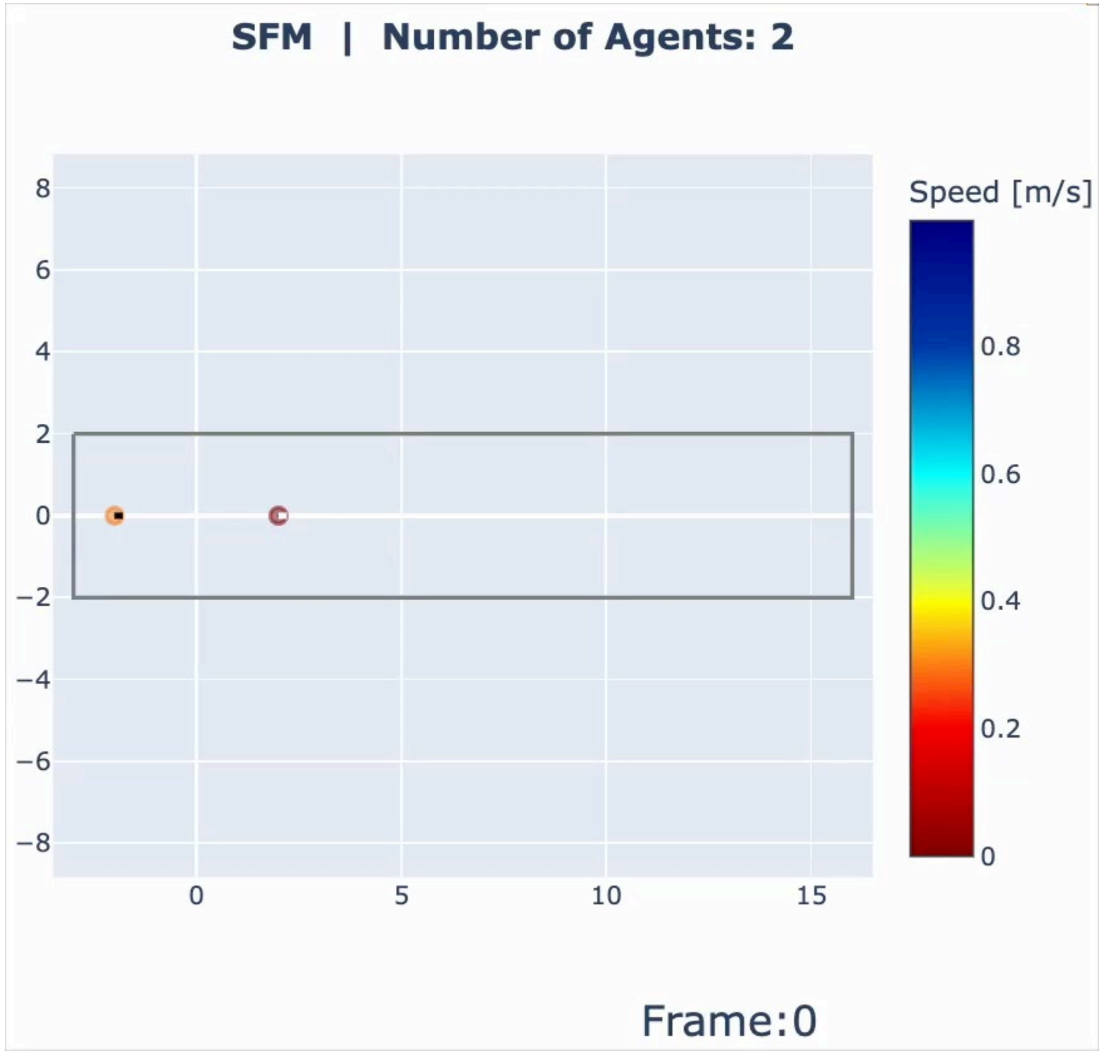
- Force models $\ddot{\vec{x}}_i(t) = \dot{\vec{v}}_i(t) = \vec{F}$
  - Particles with inertia -> oscillations and intrinsically not overlapping free!
  - Numerically unstable - small time steps necessary



EQUATION OF MOTIONS

Comparing velocity and force models

- Force models $\ddot{\vec{x}}_i(t) = \dot{\vec{v}}_i(t) = \vec{F}$
  - Particles with inertia -> oscillations and intrinsically not overlapping free!
  - Numerically unstable - small time steps necessary
  - Intrinsic transfer of forces (e.g. pushing)
  - Stop and Go waves (only if well calibrated)



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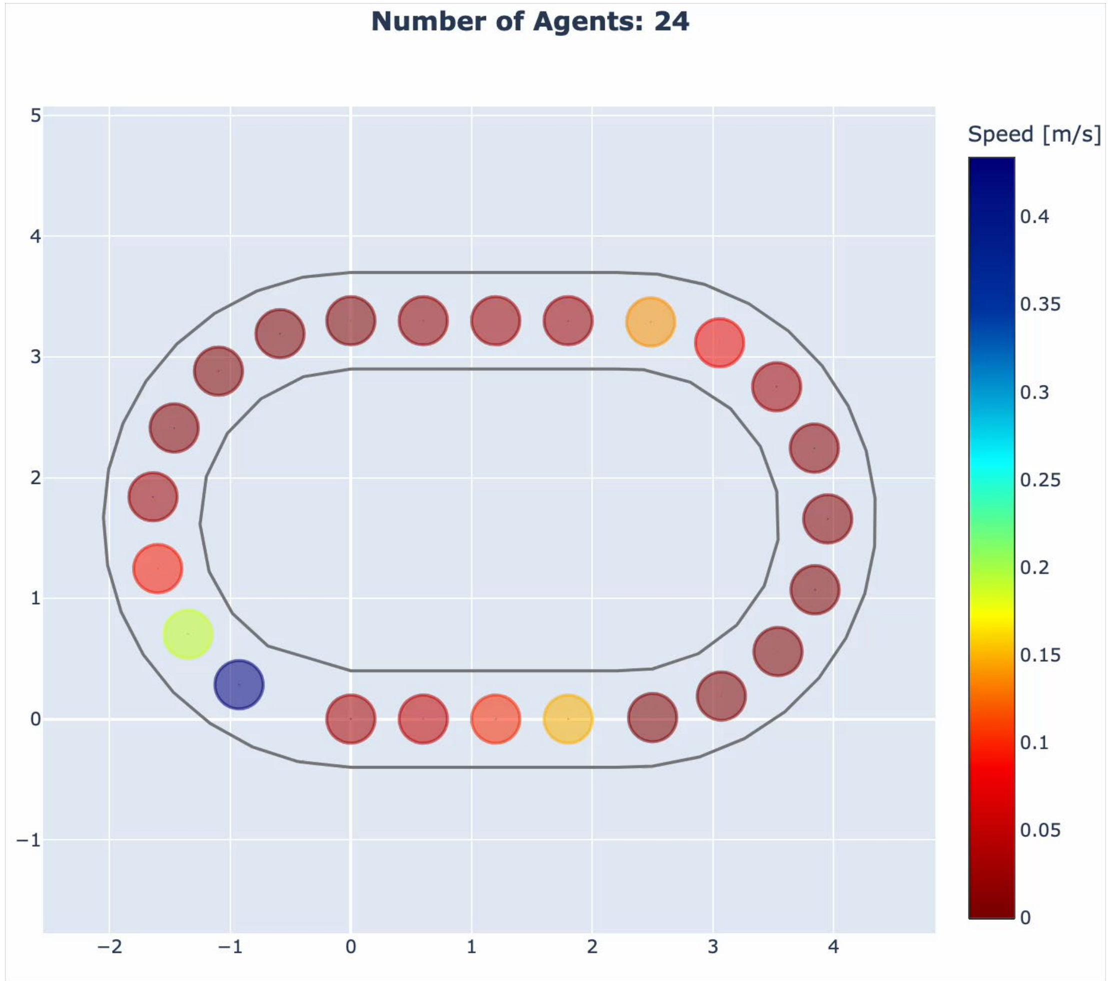
EQUATION OF MOTIONS

Comparing velocity and force models

- Velocity models $\dot{\vec{x}}_i(t) = \vec{v}_i(t) = \vec{f}$
  - Intrinsically collision free
  - instantaneous change of velocity - no acceleration and deceleration
  - Numerically stable - large timesteps possible
  - No transfer of forces
  - Too simplistic: e.g. additional complexity necessary to model Stop and Go waves



THE MODEL ZOO

Every phenomenon requires a specific set of parameter or a specific variant of a model

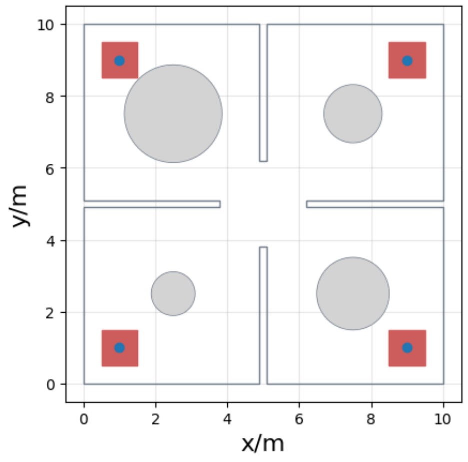
- For each model class a multitude of model variants has been developed (> 50)
- Many publications show how the parameters of the new model can be calibrated so that the new model describes a phenomenon better than other models E.g.
  - a certain transport relation: speed density relation OR flow at corners OR bottleneck flow and width OR …
  - a certain collective phenomenon: stop and go wave OR lane formation in bidirectional streams OR clogging, …
  - a certain behaviour: queuing OR huddling OR overtaking OR waiting, …
- There are hardly any (if any) studies showing that a particular variant can solve more than a specific problem!

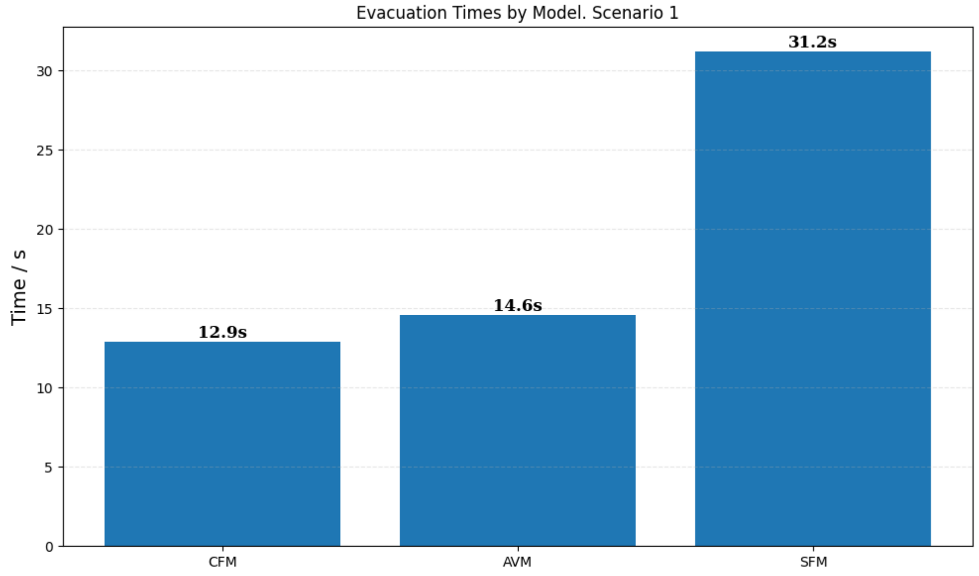
* for Force Models: Xu Chen, Martin Treiber, Venkatesan Kanagaraj & Haiying Li (2017): Social force models for pedestrian traffic – state of the art, Transport Reviews, DOI: 10.1080/01441647.2017.1396265

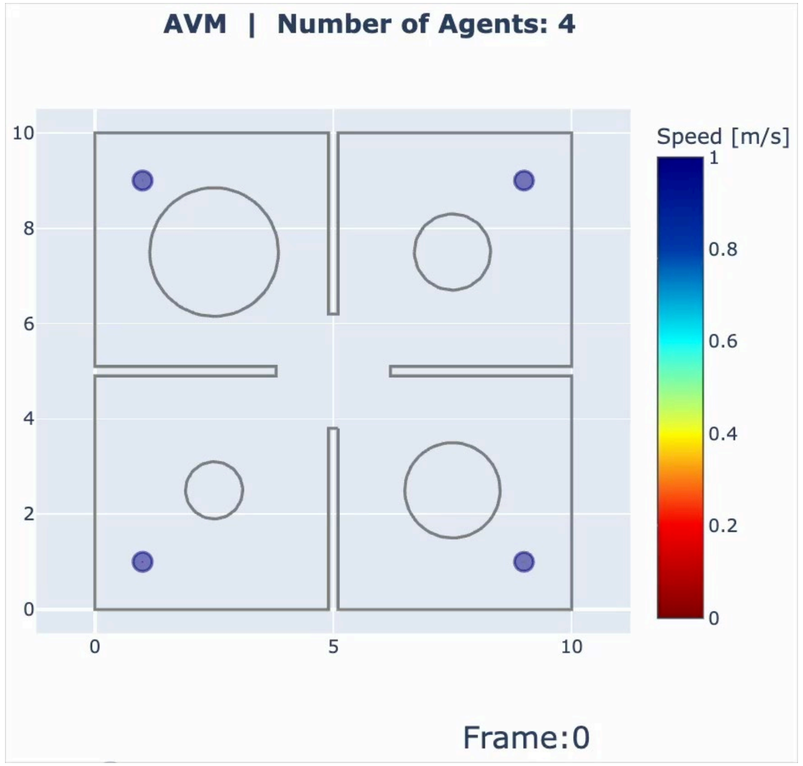
THE MODEL ZOO

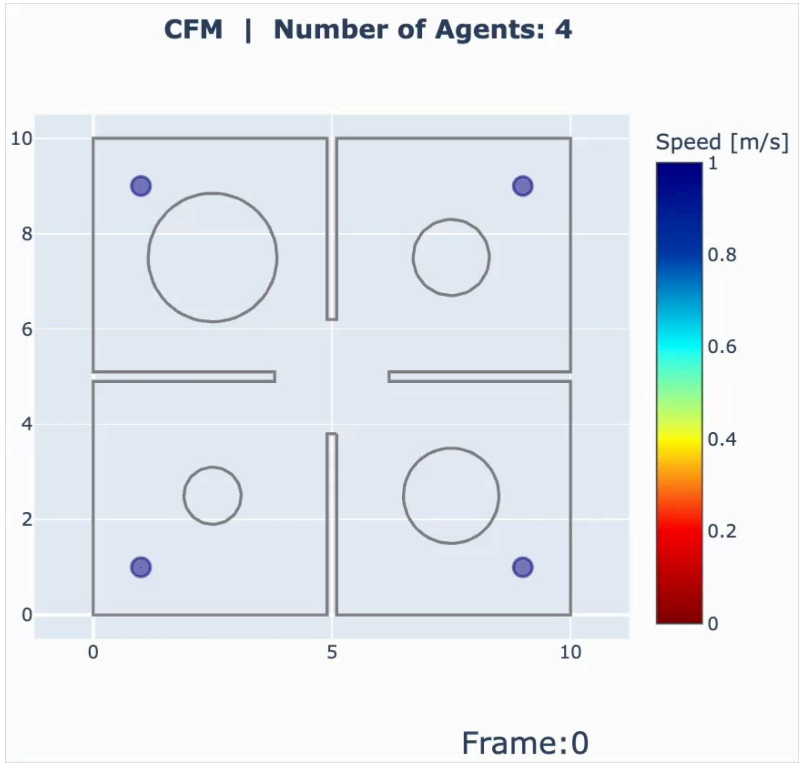
Collision avoidance complex

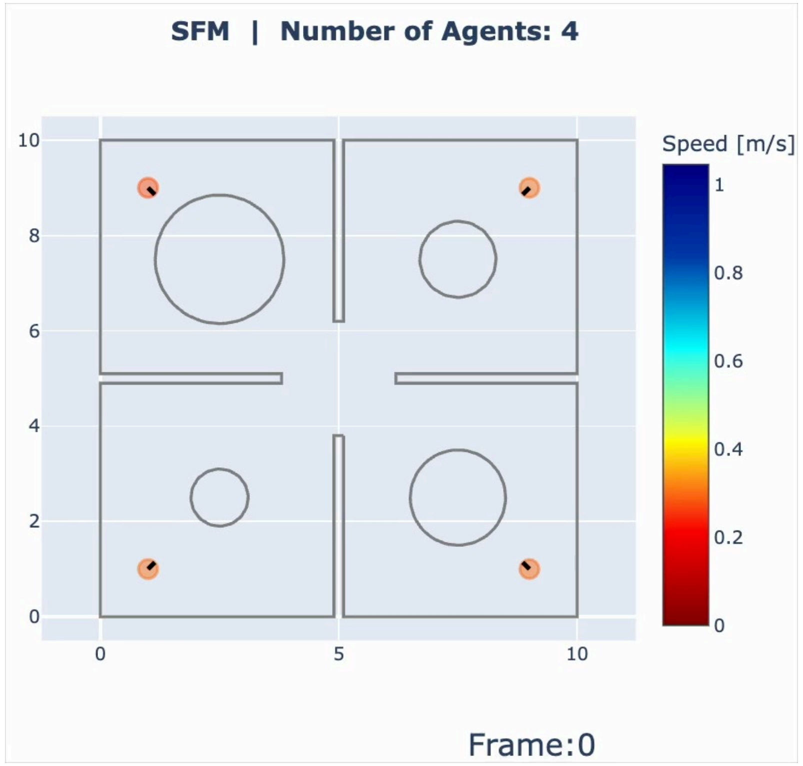
AMV: Collision Free OV Model with anticipation
CFM: Collision Free OV Model
SFM: Force model





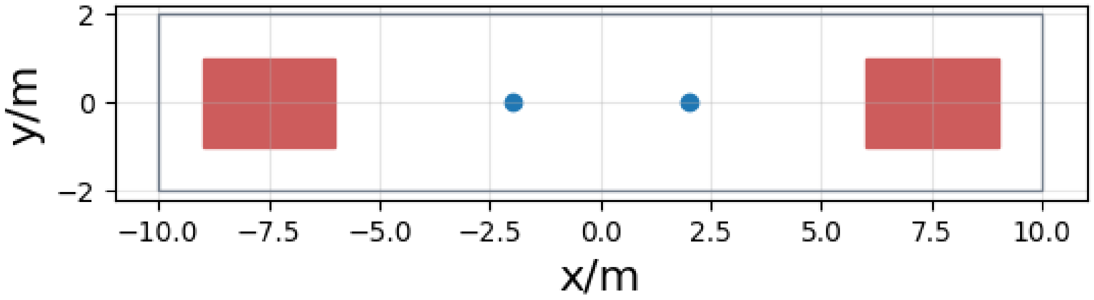


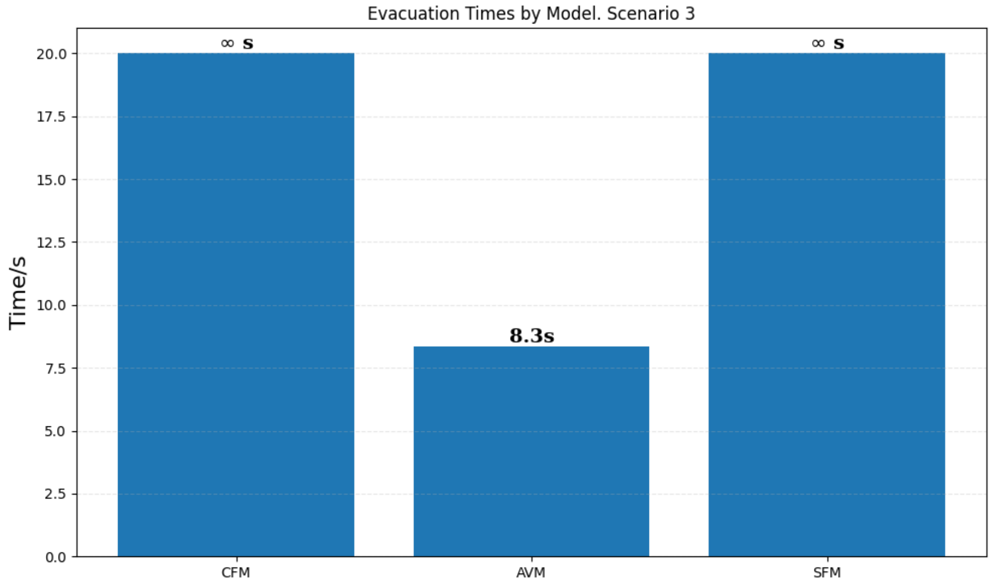


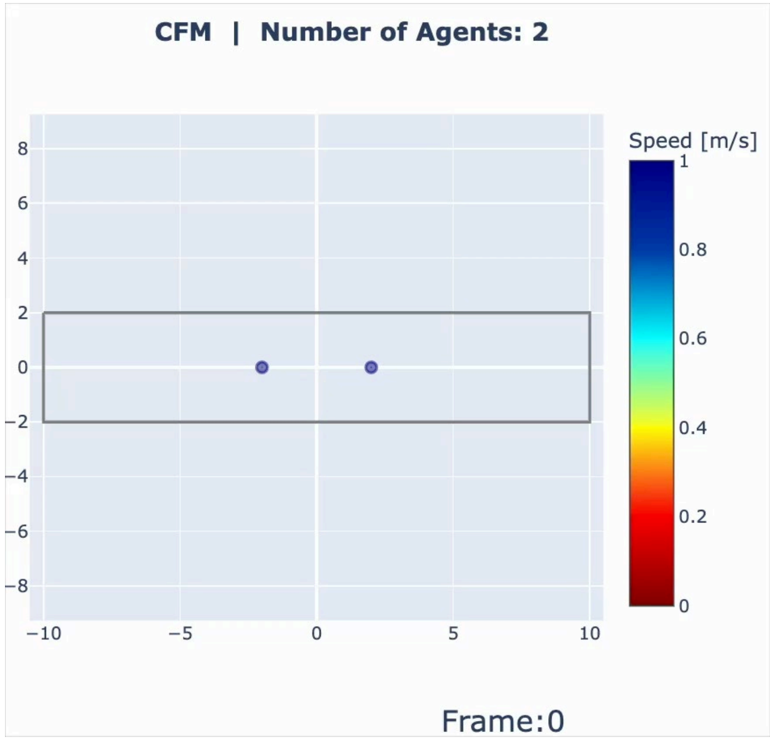


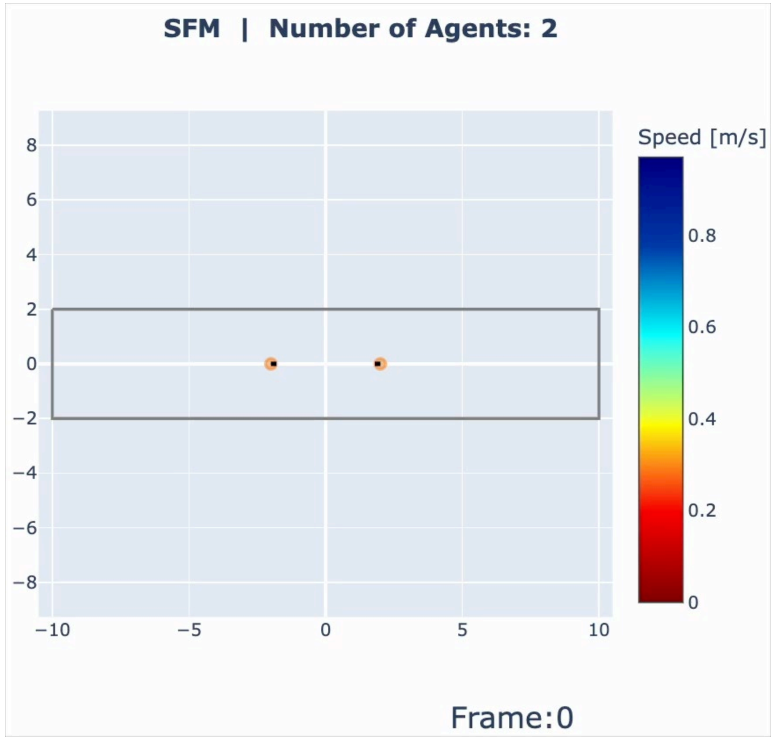
THE MODEL ZOO

Collision avoidance simple









MODELLING – SUPERPOSITION

The dream of empowering models by superposition of forces (or velocity functions)

- Force models

$$\vec{F} = \vec{F}_{drv} + \vec{F}_{rep} + \vec{F}_{attract} + \vec{F}_{group}$$

- Superposition of a collection of attractive and repulsive physical forces (contrary to Lewin's social field theory where social fields ≠ physical fields)

MODELLING – SUPERPOSITION OF INTERACTIONS

A simple example

Social Force Model: Superposition

$$\vec{F}_i^{\text{drv}} = \frac{v_i^0 \vec{e}_i^0 - \vec{v}_i}{\tau} \qquad \vec{F}_{ij}^{\text{rep}} = A_i \exp\left(\frac{r_{ij} - d_{ij}}{B_i}\right)$$

MODELLING – SUPERPOSITION OF INTERACTIONS

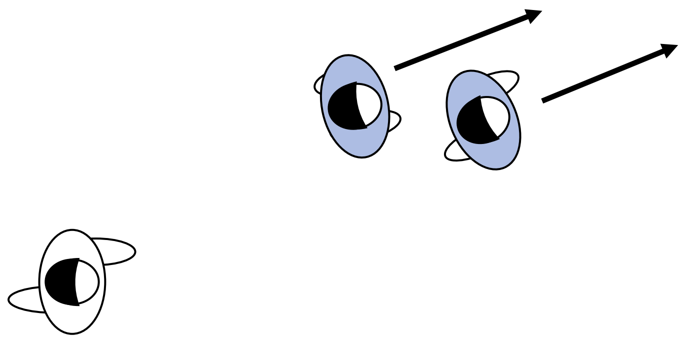
A more complex example

$$\vec{F} = \vec{F}_{drv} + \vec{F}_{rep} + \vec{F}_{attract} + \vec{F}_{group}$$

- $\vec{F}_{drv}$: Driving force: $\vec{F}_i^{drv} = \frac{\vec{v}_o - \vec{v}(t)}{\tau}$
  - $\vec{v}_o$: Intended velocity to a goal or immediate goal
  - τ: Speed adaption time
- $\vec{F}_{rep}$: Repulsive force: Keep distance to other pedestrians (volume exclusion)
- $\vec{F}_{group}$: Group force: Stay near to your friends
- $\vec{F}_{attract}$: Attraction force, e.g. interest in a shopping window

MODELLING – SUPERPOSITION OF INTERACTIONS

A more complex example

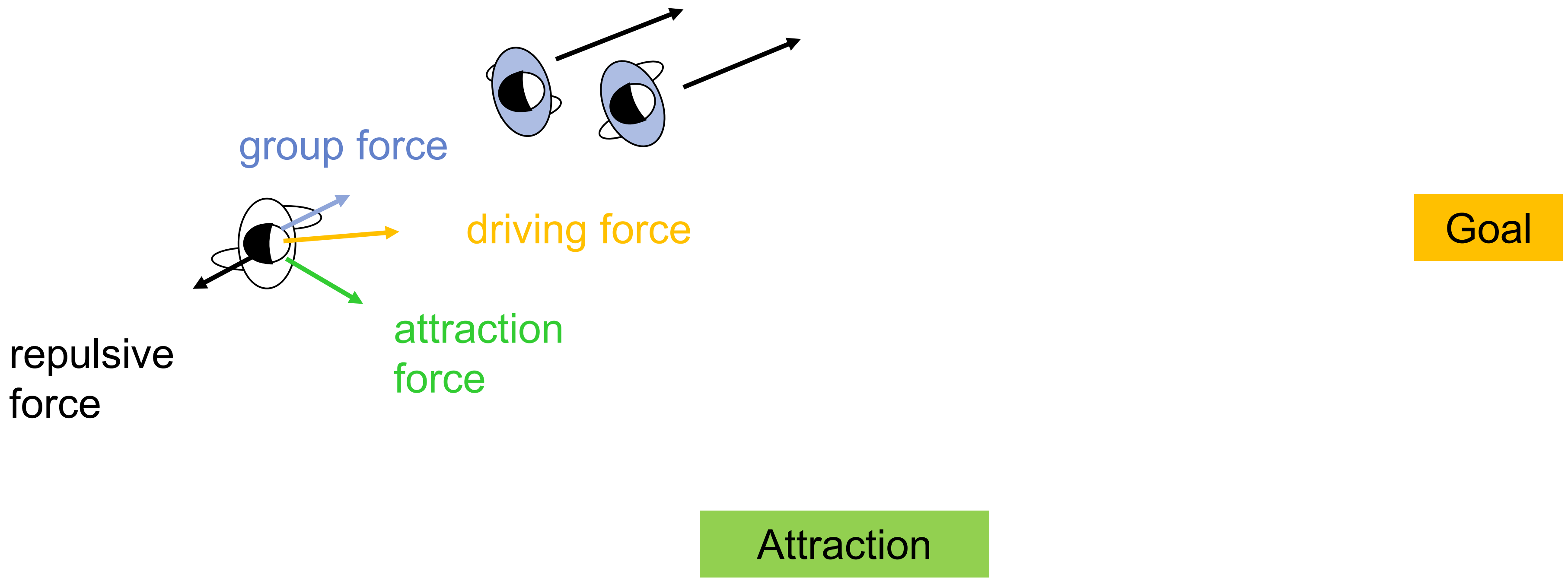


Goal

Attraction

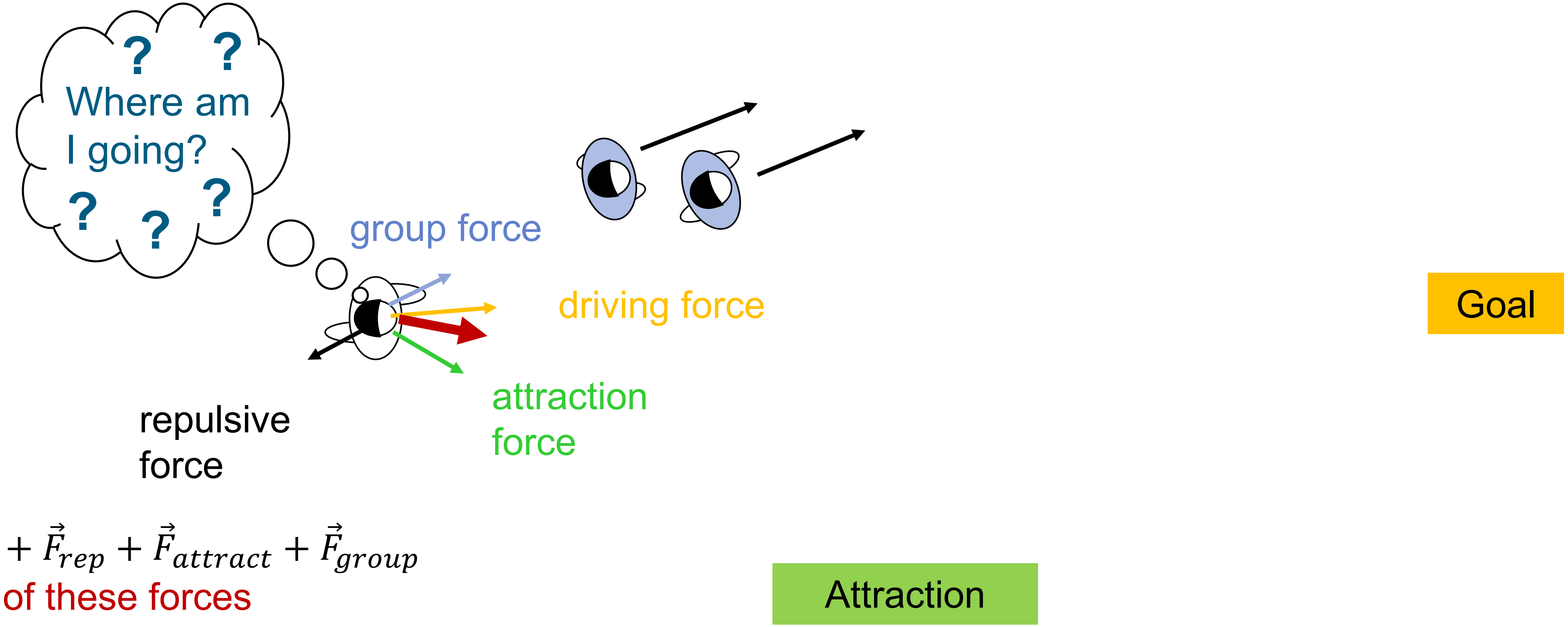
MODELLING – SUPERPOSITION OF INTERACTIONS

A more complex example



MODELLING – SUPERPOSITION OF INTERACTIONS

A more complex example

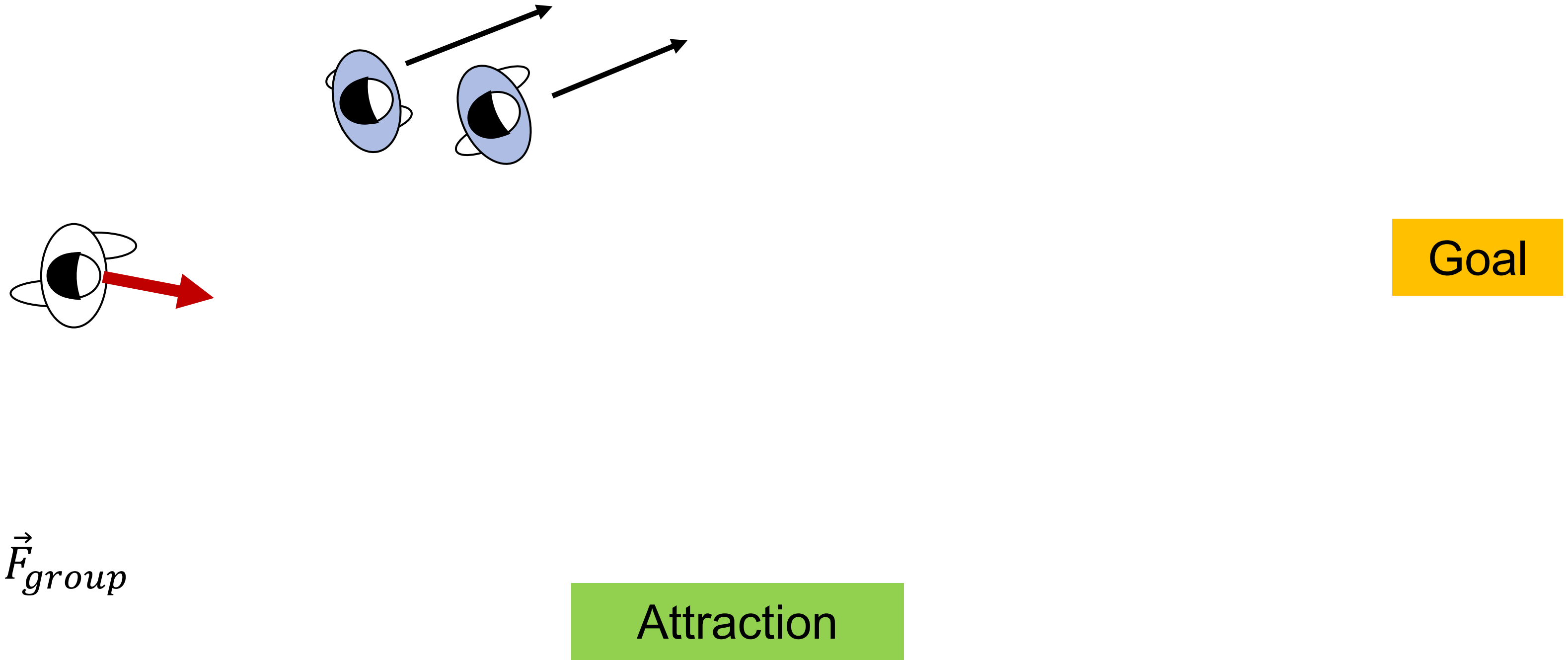


$$\vec{F} = \vec{F}_{drv} + \vec{F}_{rep} + \vec{F}_{attract} + \vec{F}_{group}$$

The sum of these forces
- do not point to the goal!
- do not point to the attraction!
- do not point to the group!

MODELLING – SUPERPOSITION OF INTERACTIONS

A more complex example

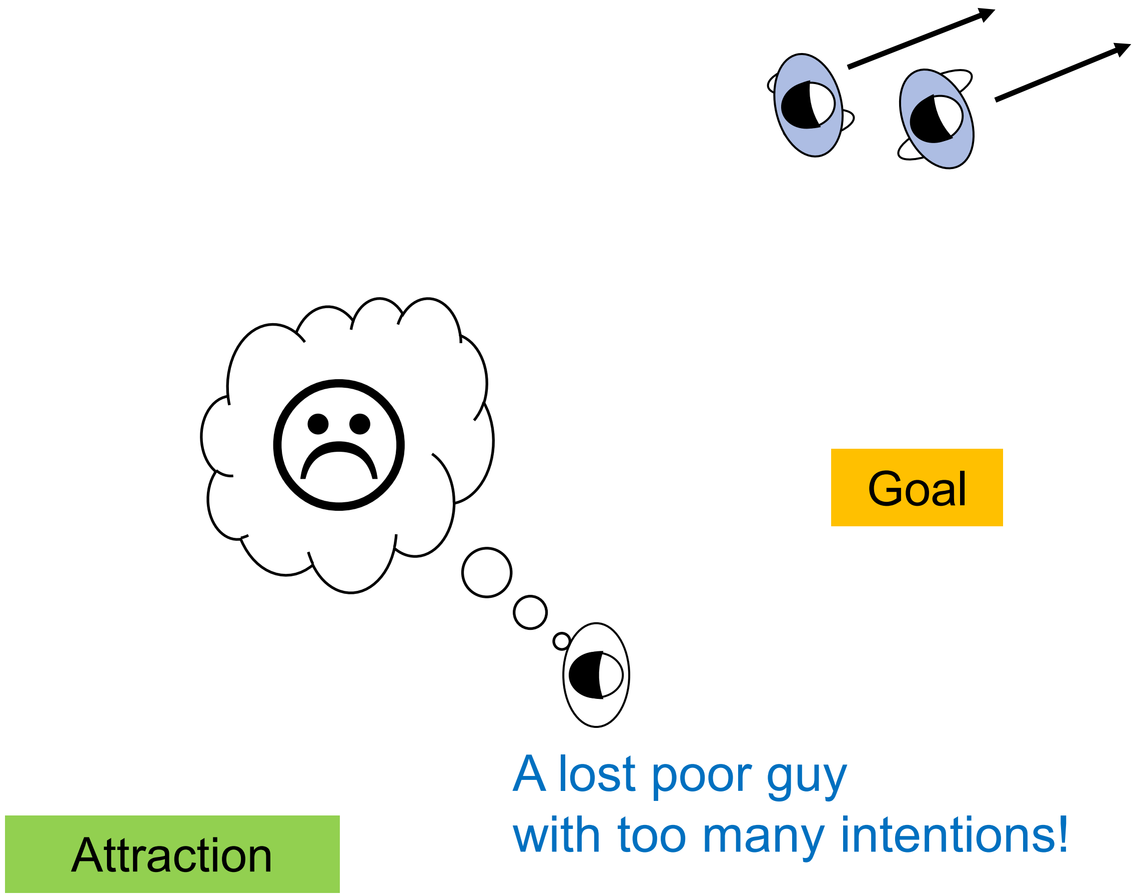


$$\vec{F} = \vec{F}_{drv} + \vec{F}_{rep} + \vec{F}_{attract} + \vec{F}_{group}$$

The superposition of the forces do not model realistic decision making

MODELLING – SUPERPOSITION OF INTERACTIONS

A more complex example



SUPERPOSITION OF OPERATIONS

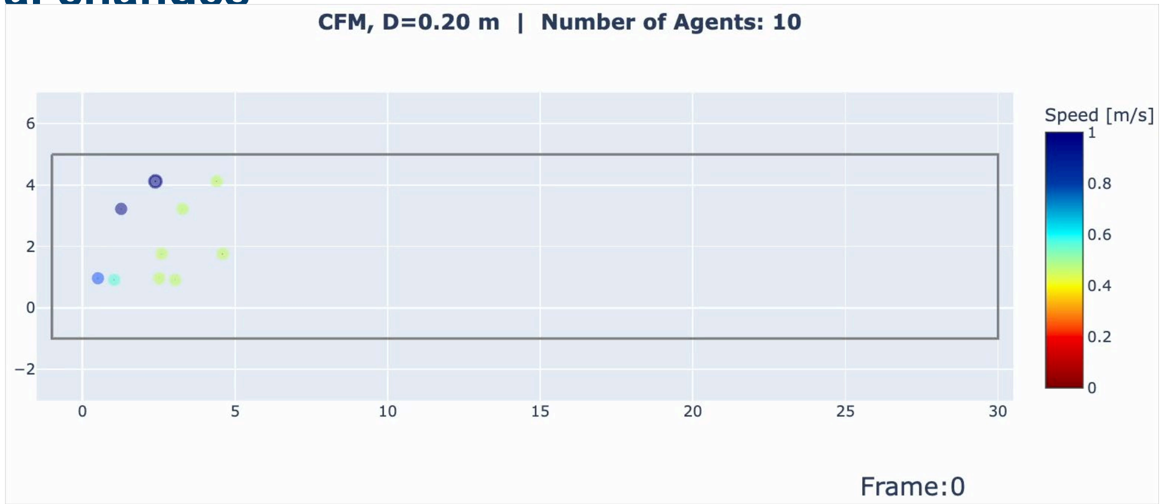
Comparison of models on the level of speed and directional changes

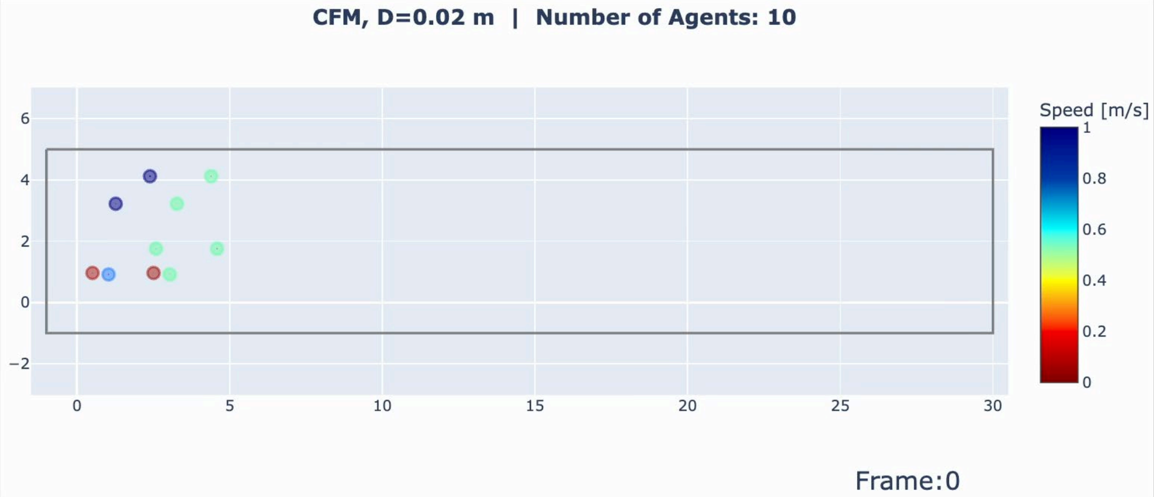
- Collision free Optimal Velocity Model
- Velocity described by speed and directional changes

$$\vec{v}_i(t) = V(\vec{x}_i, \vec{x}_j, \vec{v}_j, \dots) \times \vec{e}_i(\vec{x}_i, \vec{x}_j, \vec{v}_j \dots)$$

- Not all situations need both operations!
  - At low density: overtaking need directional changes:

    D=0,2 realistic, D=0,02 **un**realistic





SUPERPOSITION OF OPERATIONS

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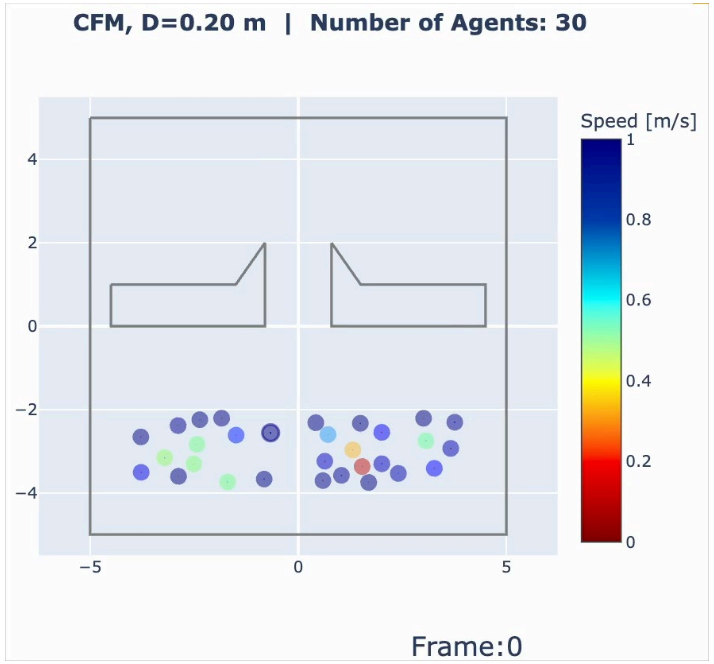
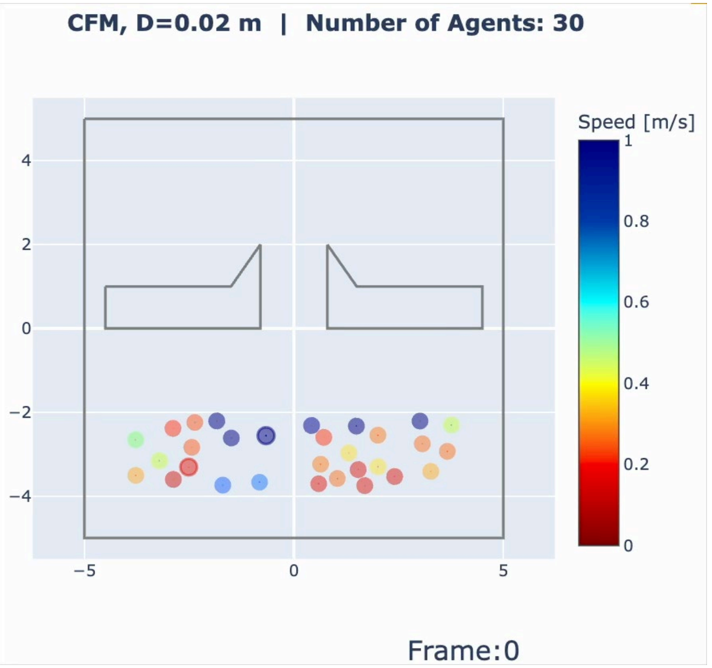
- Not all situations need both operations!
  - At low density: overtaking need directional changes:

    D=0,2 realistic, D=0,02 **unrealistic**
  - At high density: directional changes are unrealistic

    D=0,2 **unrealistic**, D=0,02 realistic





MINIMAL MODELS

Is a minimal model the best option?

- Minimal models came along with less parameter to calibrate. That could ease the enhancement of the model
- Even if a minimal model has been found that describes a phenomenon, this does not mean that it correctly describes the interaction!
- Example: Velocity models are not able to model Stop and Go. To options:
  - Include a certain noise (time related random number)*
  - Extend the interaction to the agent in front of the agent's predecessor**

*A Tordeux, A Schadschneider (2016) White and relaxed noises in optimal velocity models for pedestrian flow with stop-and-go waves, Journal of Physics A 49 (18), 185101

**A Tordeux, A Seyfried (2014) Collision-free nonuniform dynamics within continuous optimal velocity models, Physical Review E 90 (4), 042812

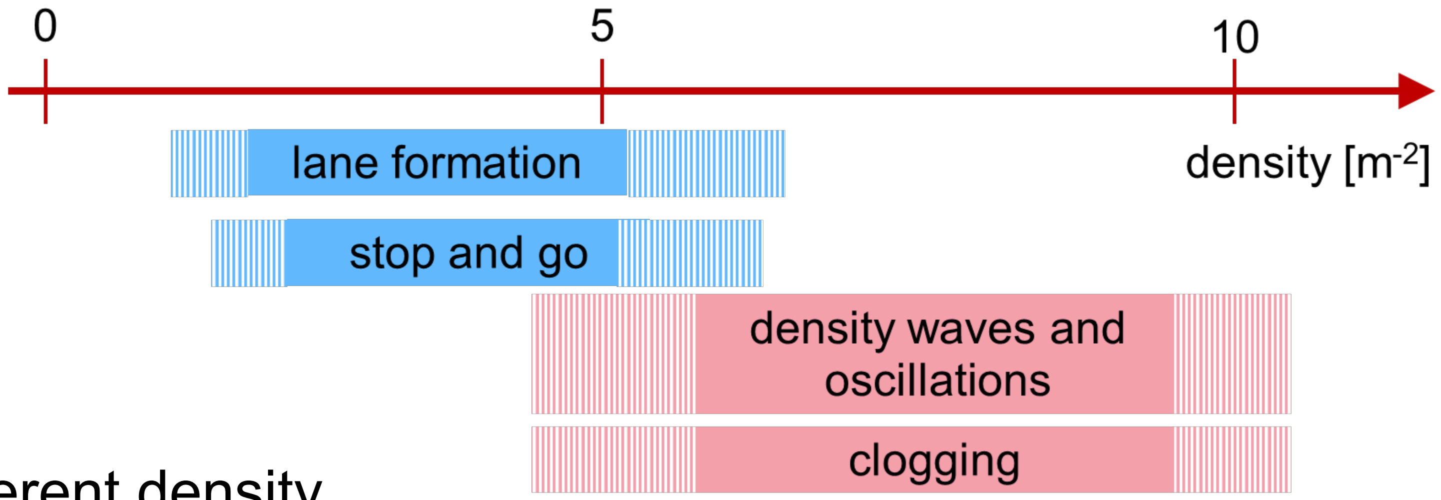
SUMMARY

Objectives of modeling

- Crowd dynamics
  - Collective phenomena and transport characteristics
  - Transport characteristics depend on the types of facility (corridor, bottleneck, stairs, …) flow structure (uni- or multidirectional) and human factors
  - Behaviour: queuing, huddling, overtaking, joining, not joining, …
  - Operations and interactions depend on the density

SUMMARY

Collective phenomena



- Collective phenomena occur in different density ranges and result from different interactions.
- Lane formation in bidirectional streams
- Stop and go waves
- Density waves and turbulences -
- Clogging

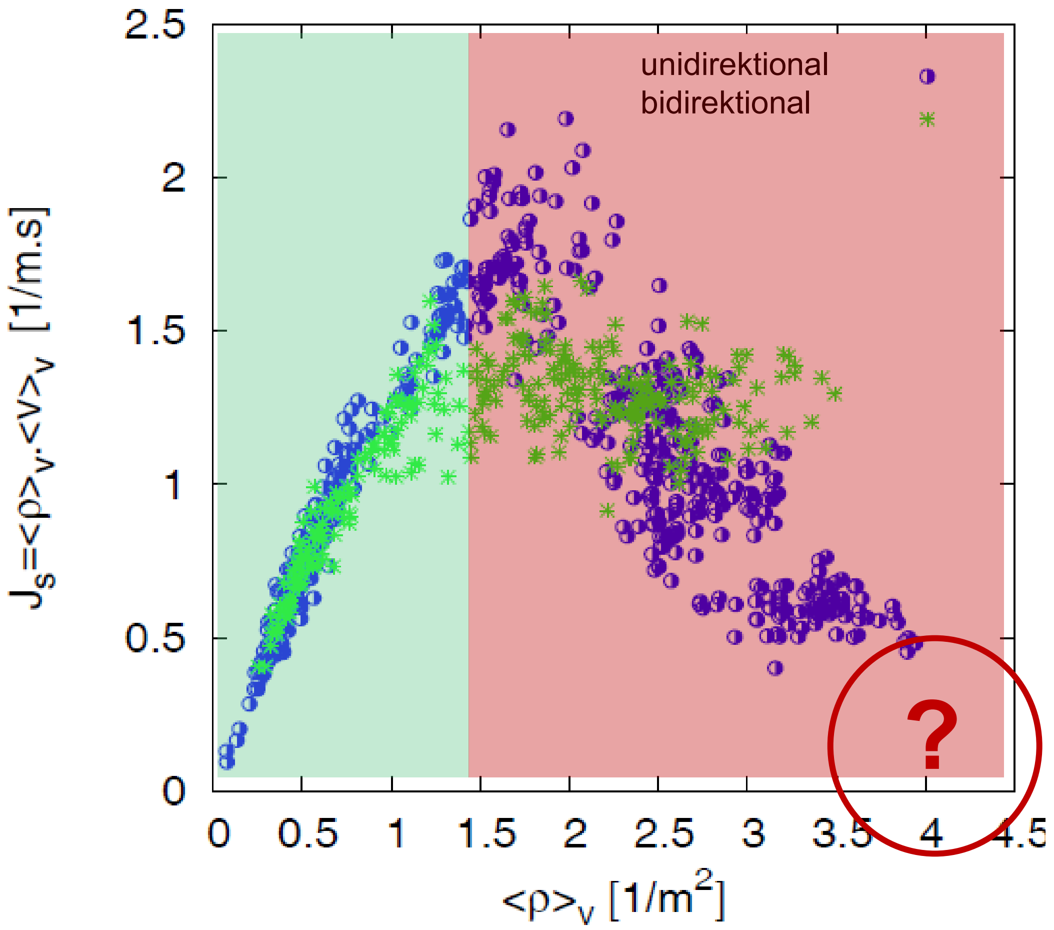
no body contact,
visual perception and steering

body contact
impulse transfer, forces, …

SUMMARY

Transport properties

- Collective phenomena influence transport properties
- Free flow
- Congested regime
- Different types of flow have different transport properties
- Open questions about the emergence of deadlock (J=0 and v=0) and it's relation with clogging



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SUMMARY AND OUTLOOK

- Modelling
  - Every model class has its advantages (capabilities) and drawbacks (limitations)
  - Each model class offers a multitude of variants
  - Each variant designed to model one property or one phenomenon well
  - There are hardly any studies showing that a variant can solve more than a specific problem!
  - Superposition of interactions or operations do not cover the complexity
  - No model describes reality!
- Necessary enhancements (Current design goal of JuPedSim)
  - The parameters of a model must be able to be adjusted dynamically during a simulation
  - Simulation software should be able to use different models simultaneously
- Current research question
  - Which changes in the environment lead to a change in the parameters of the model or to a change of model?

RECOMMENDATIONS

for the usage of models in multimodal or mixed traffic simulation

- Use a velocity model for its stability - > large timesteps (and short simulation time)
- Minimal model guaranteeing volume exclusion -> fulfils transport properties in general
- Use model parameter to describe different behaviour
- Use **SUMO** coupled with **JuPedSim*** for transparency and the commitment to staying at the cutting edge. (Visit the following session of the conference)

SUMO
SIMULATION OF URBAN MOBILITY

JuPedSim

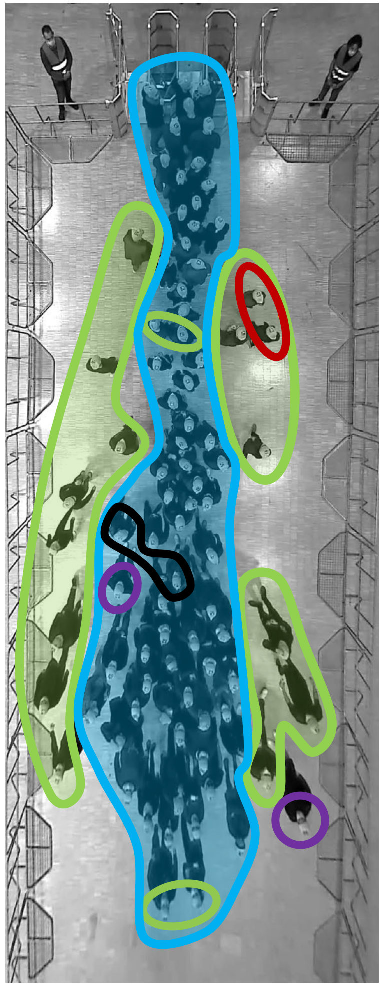
*Credits JuPedSim : Mohcine Chraibi, Jette Schumann, Kai Kratz, Tobias Schrödter, et al.

DIVERSITY OF PERSPECTIVES

What could be observed and what questions arise?

- System capacity, Level of Service, speed, density, flow, ….
- Behaviour: queuing, huddling, overtaking, joining, not joining, …
- Motions: collision avoidance, stopping, get going, keeping distance, closing gaps, body contact and pushing
- Transition from queuing to huddling
  - What do people perceive and how it triggers their action?
  - Which social norms are relevant and how it interrelates with individual motivation?, …

Queuing
Overtaking
Joining
Not joning
Leaving the joining



Pedestrian dynamics – a melting pot of disciplines

But, all disciplines have their own perspective

Sieben, A., Postmes, T., 2025. R. Soc. Open Sci. 12

JÜLICH Forschungszentrum

CONTRIBUTIONS OF IAS 7 TO THE AI STRATEGY

Open source, open data und open access

- *Open source* framework **JuPedSim** for pedestrian simulations
  http://www.jupedsim.org
- *Open source* software **PeTrack** for the automatic extraction of trajectories
  http://ped.fz-juelich.de/petrack
- *Open source* library **PedPy** for analysing the movement
  http://ped.fz-juelich.de/pedpy
- *Open data archive* for **data** from experiments with pedestrians
  http://ped.fz-juelich.de/da
- Support des *diamond open access journal* **Collective Dynamics**
  http://www.collective-dynamics.eu/
- Experimental and simulation **data of fire dynamics**
  https://zenodo.org/communities/fire-safety-engineering-and-evacuation
- **Fire simulation tools**, presentations and reference implementations
  https://github.com/FireDynamics

JuPedSim
DOI: 10.5281/zenodo.11093061

PeTrack
DOI: 10.5281/zenodo.6320753

PedPy
DOI: 10.5281/zenodo.11778532

DOI: 10.34735/ped.da

OJS
ISSN: 2366-8539

zenodo

INTRODUCTION

Applications and research fields

- Applications
  - Fire and smoke
  - Moving crowds
- Context
  - Safety: Growing cities and crowd management
  - Fire protection: Complex buildings and new materials
  - Mobility: Pedestrian traffic and public transport

RESEARCH FIELDS

Dynamics of moving crowds – a wide range of research fields

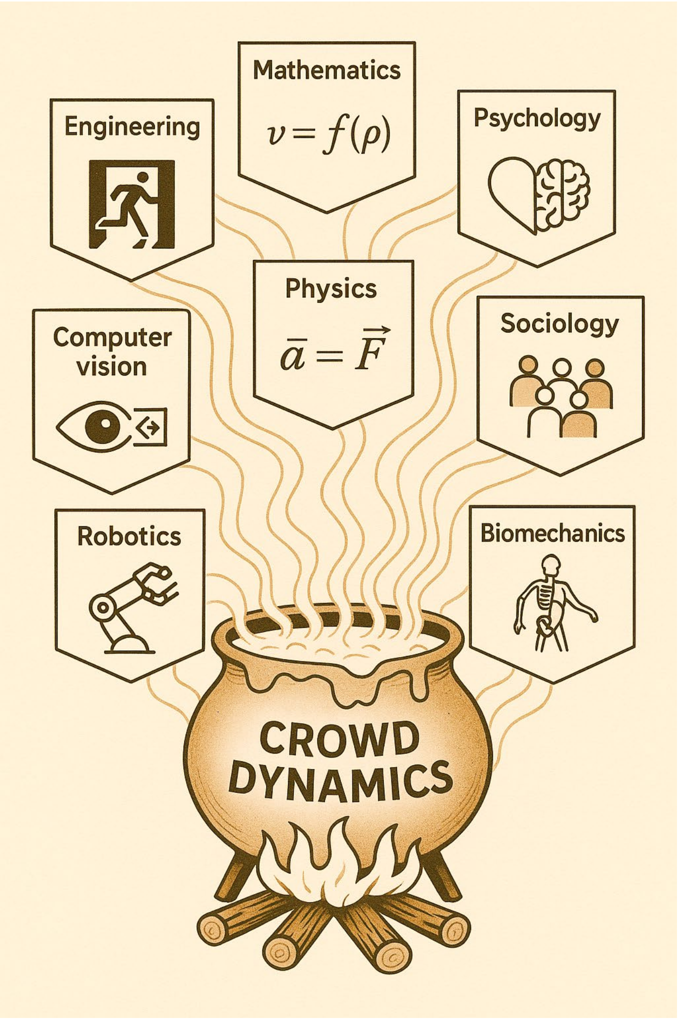
- Psychology
  - Perception, action, …
- Social Psychology and Sociology
  - Social norms, social identity, group dynamic, …
- Mathematics and physics
  - Collective phenomena, transport, transitions, …
- Traffic, safety and mechanical engineering
  - Public transport, event safety, autonomous driving, …
- Computer science (robotics, computer vision, VR, …)
- Biomechanics, sport science, …

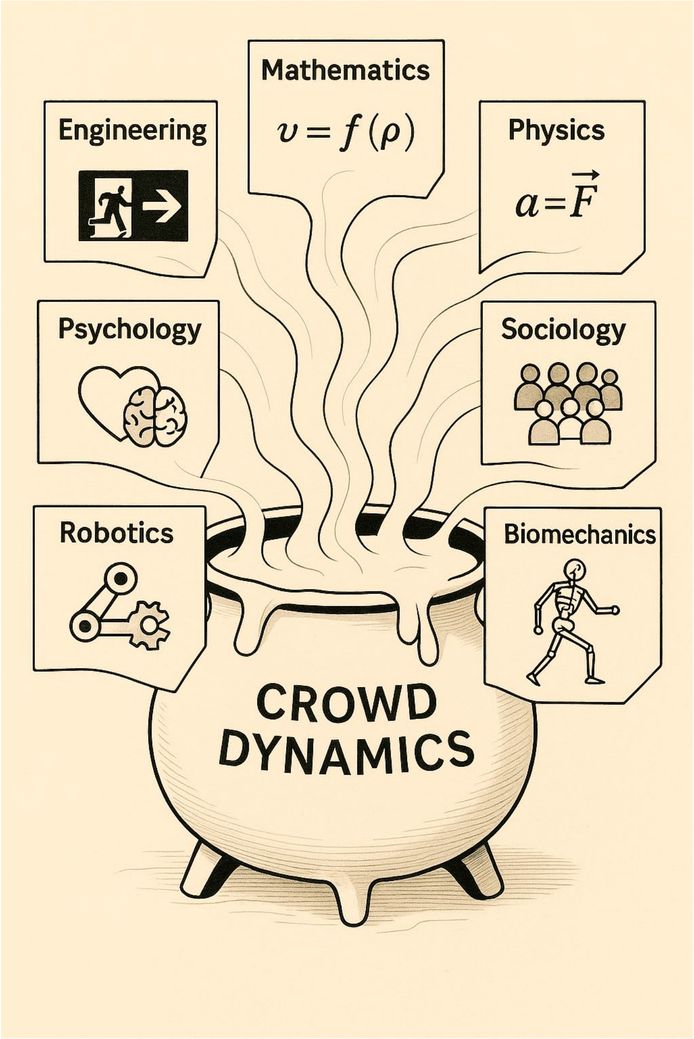
https://youtu.be/IFFCLtCB7Ag

RESEARCH FIELDS

Moving crowds – a wide range of researc

- Traffic, safety and mechanical engi
  - Public transport, event safety, auton
- Mathematics and physics
  - Collective phenomena, transport, tra
- Computer science (robotics, compu
  - Steering of robots, detection and co
- Psychology
  - Perception, action, motivation, …
- Social psychology and sociology
  - Social norms, social identity, group
- Biomechanics, sport science, …
  - Balance, …





LEVEL OF MODELS

Time scales and options for navigation and decisions

- Strategical
  - Time scale: ‘long’
  - E.g. Decisions on activities
- Tactical
  - Time scale: ‘medium’
  - How (when, where, …) to perform the activities
- Operational
  - Time scale ‘short’
  - How to share the space with others

I hear a fire alarm and will therefore leave the building.

After leaving my office, I see that the way to the right is blocked by smoke. So I turn left.

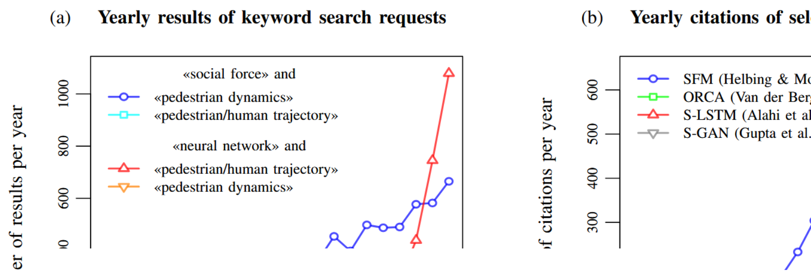
There is a congestion at the exit door. I stand at the back and do not push.

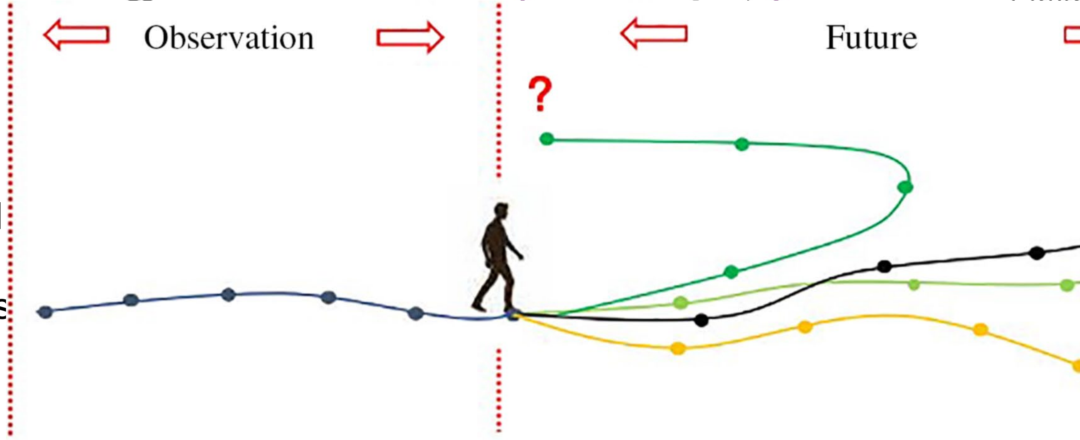
These levels of modeling are not clearly separable and merge into one another!

AI MODELS

Model from computer vision (autonomous driving) for predicting traject

- Prediction of future trajectories of pedestrian
- Deep Learning methods
- Input: past trajectories
- Output: future trajectories

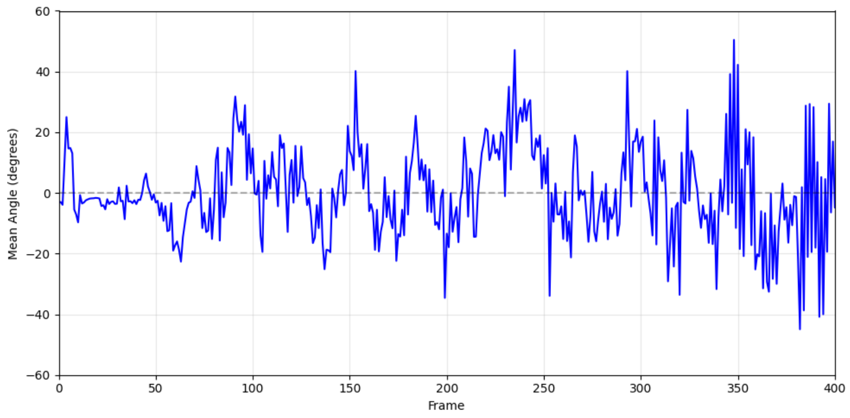


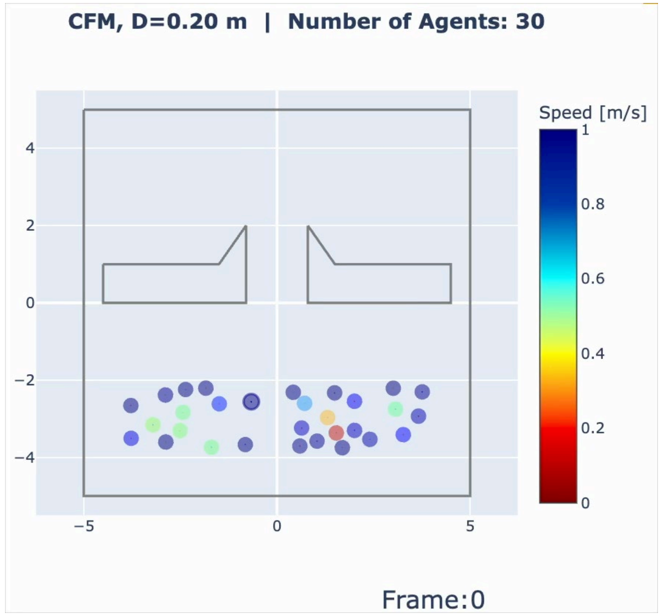


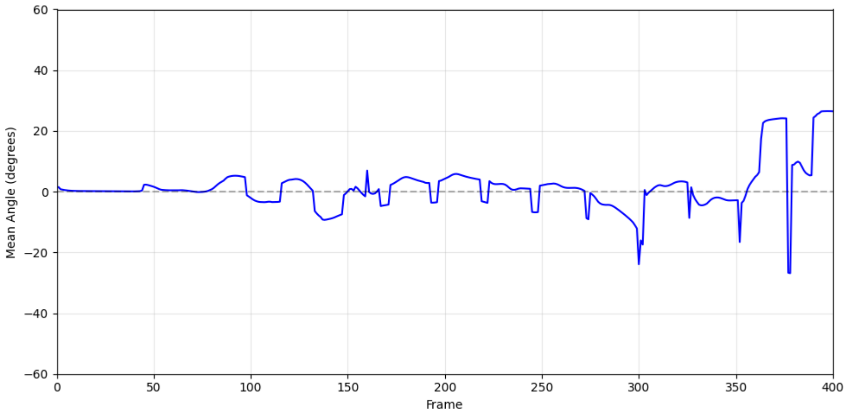
Korbmacher, R., Tordeux, A., 2022. Review of Pedestrian Trajectory Prediction Me
https://doi.org/10.1109/TITS.2022.3205676

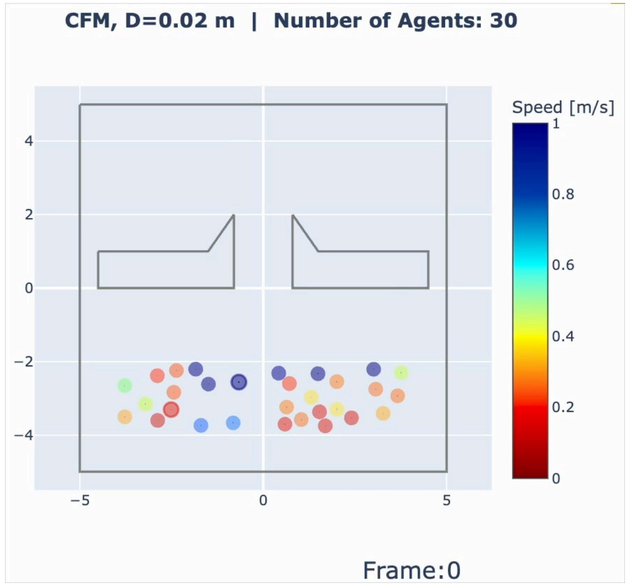
Skanda Shridhar, Yuhang Ma, Tara Stentz, Zhengdi Shen, Galen Clark Haynes, and
Traft. 2021. Beelines: Motion Prediction Metrics for Self-Driving Safety and Comfort.
2021 IEEE International Conference on Robotics and Automation (ICRA). IEEE Pres
881–887. https://doi.org/10.1109/ICRA48506.2021.9560950

Li, D., Lin, Z. and Hu, J. (2025), A Specialized Variational Autoen
Efficient Pedestrian Trajectory Prediction. IEEJ Trans Elec Electr
https://doi.org/10.1002/tee.70053


Mean Angle (degrees)
Frame


CFM, D=0.20 m | Number of Agents: 30
Speed [m/s]
Frame:0


Mean Angle (degrees)
Frame


CFM, D=0.02 m | Number of Agents: 30
Speed [m/s]
Frame:0

DATA COLLECTION AND AGENT BASED MODELLING

1900
Dieckmann, Rieken

Clock, measuring tape, photo

Intervals: ΔN, Δx, Δt
Mean values: J, v, ρ

Macroscopic models
Analysis of single cross sections (door, corridor, staircase)

Legal regulations:
Number of exits, minimum widths, ...

2000
Hogendoorn & Damen; Boltes et. al.

Video

Trajectories in 2d: $\vec{x}_i(t)$
$\forall i \in N \; in \; obs.area$

Agenda-based models (2d):
Analysis of a network of pedestrian facilities

Dynamics of congestion:
Planning of mass transit, building evacuation, events, ...

2020
CrowdDNA

Video & Motion Capturing

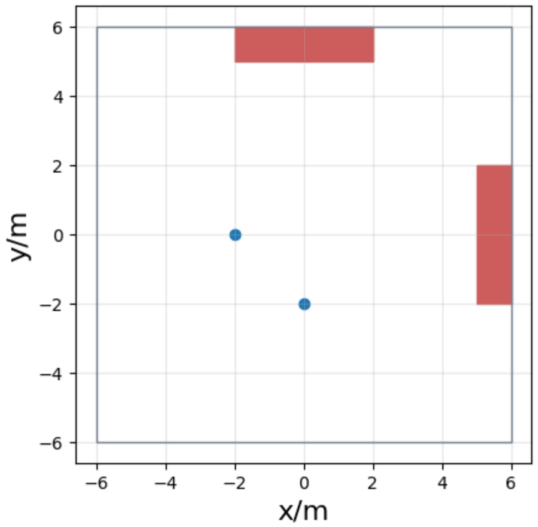
Trajectories (3d): $\vec{x}_{i,k}(t)$
$\forall i \in N \; in \; obs.area$
$\forall k \in$ {hand, feed, arm, pelvis, …}

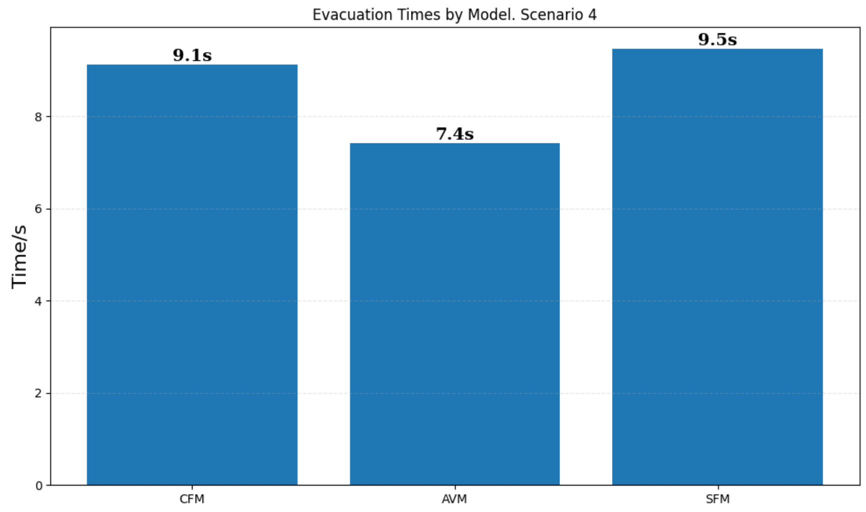
Agenda-based models (3d):
Interaction of torso and extremities with spatial structures of the surrounding

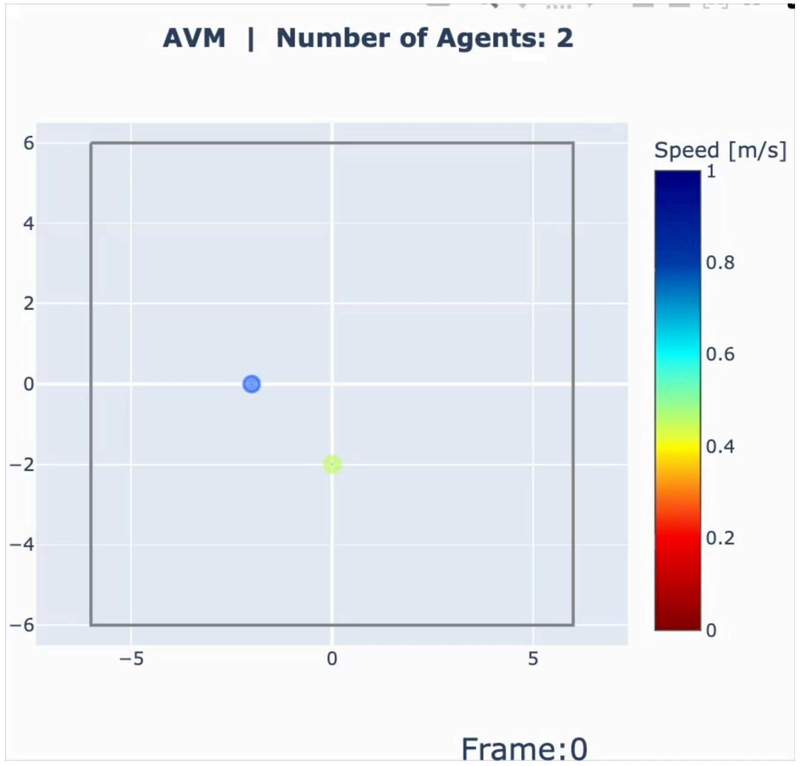
Body and collective phenomena (clogging, lanes, …), balance, design of barriers or interior of coaches, aircrafts, busses, …

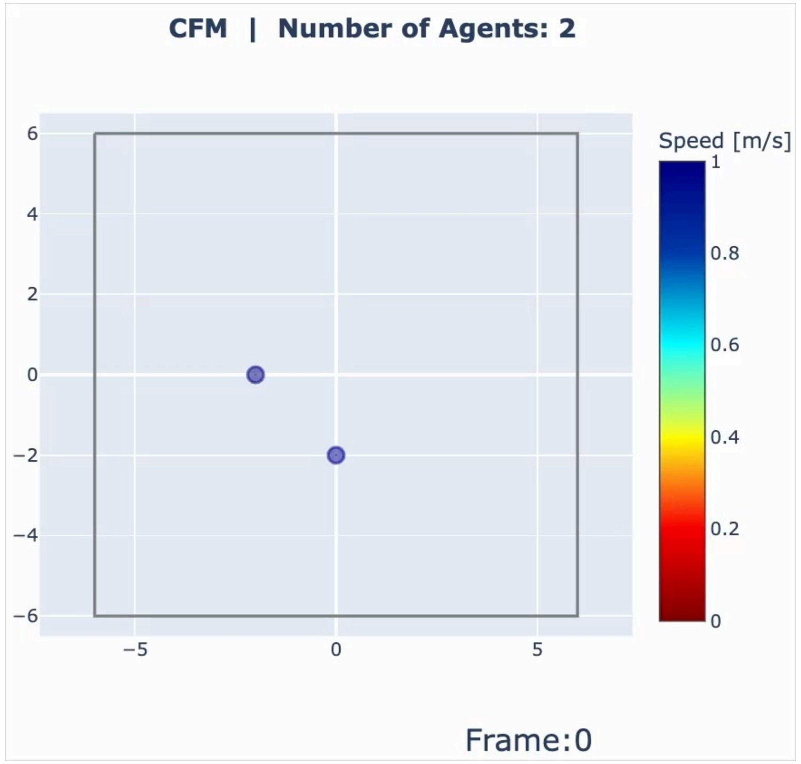
The Model Zoo

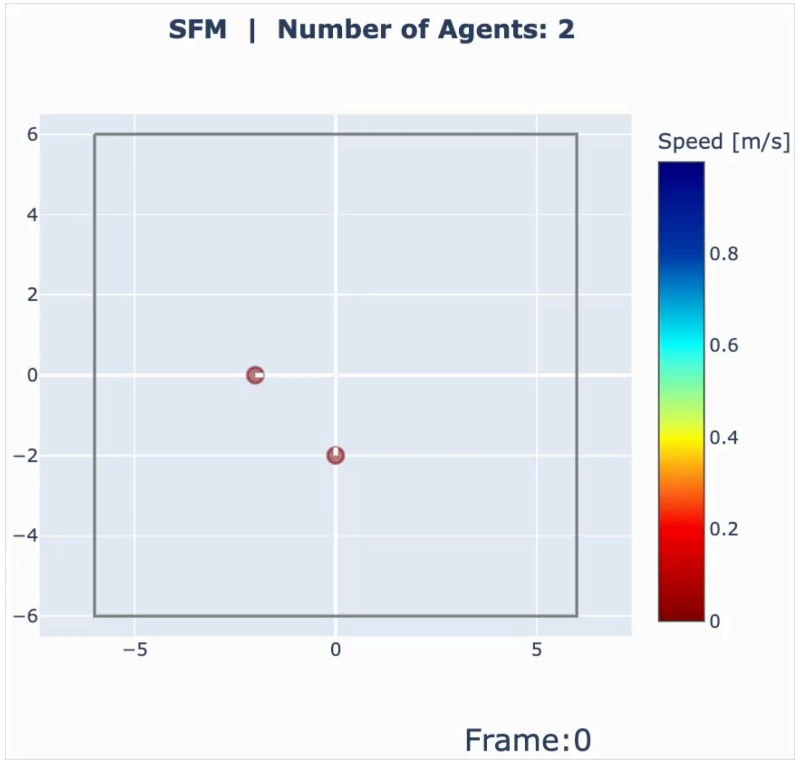
Collision avoidance











MOTIVATION AND PHENOMENA

Viewpoint of a traffic or safety engineer and physicist

- Self-driven and interacting particles
  - Pedestrians (vehicles, animals, …)
- Interests
  - Collective phenomena
    - Lane formation in bidirectional streams
    - Density waves

Credits: Julien Pettre, Inria, France