Swarm-Performance of Heterogeneous Multi-Agent Systems Across Scales

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01/24/2024

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Partial Support:

DOE DE-EE000887 (EERE, VTO)

Army Research Laboratory W911NF-22-2-0001

Introduction/Motivation

Focus of this Talk

Some fundamental questions:

- Does equity need to be based on an ethical/moral argument, or are there setups/measures where increasing equity also increases a suitable system-level performance metric? [thus, equity could be a proxy for a too complex-to-formulate societal objective function]
- In a tradeoff of efficiency vs. equity, are there higher principles for how to balance them?

A broader perspective on transportation. Systems with non-trivial emergent phenomena:

- A convoy transports goods to a disaster area. How to balance system objectives (maximize #delivered-goods within time budget) vs. moral objectives (assist broken-down agents)?
- Traffic flow dynamics (e.g., traffic waves), with heterogeneous levels of automation.
- Biological systems, e.g., swarms travel to reproduction grounds. Species present today must maximize reproductive value (#agents(n+1)/#agents(n), under abundant resources). Why would evolution produce species that have ethics/morals/empathy?

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Existing Performance Metrics Related to Equity

Scenario	Equity theory	The school of thought behind the approach	The considered criteria of the approach	Motivation
A	Utilitarianism	Utilitarian Liberalism, Scholastic Philosophy	$Max \sum_i Ac_i$	To Maximize the Total Final Benefits (Utilities) of the Society
B	Rawls's theory of Justice	John Rawls	$Max \sum_k Ac_k$ $k \in P$ (P: the poorest group)	To Maximize the Total Final Benefits of the Poorest Group of the Society
C	Egalitarianism	Socialism	$Min \frac{\sum_i \sum_j \mid Ac_i - Ac_j \mid}{2n^2 \overline{Ac}}$	To Maximally Achieving Equality in the Final Benefits, Using Unequal Distribution of Added Benefits in the Community
D	Equal Sharing	Socialism	$Min \frac{\sum_i \sum_j \mid \Delta Ac_i - \Delta Ac_j \mid}{2n^2 \overline{\Delta Ac}}$	To Maximally Achieving Equality in the Distribution of Added Benefits in the Community
E	Narrowing the Gap in Final Benefits	Socialism, Deontological Liberalism, Sadr	$Max \sum_i Ac_i$ $s.\ t.:$ $Ac_i > m_1 * Ac_j \ \forall\ i,j$	To Maximize the Total Final Benefits, with the Consideration of Narrowing the Gap in Final Benefits of the Groups in the Community
F	Limiting the Variance in Added Benefits	Socialism, Deontological Liberalism, John Rawls, Sadr	$Max \sum_i Ac_i$ $s.\ t.:$ $\Delta Ac_i > m_2 * \Delta Ac_j \ \forall\ i,j$	To Maximize the Total Final Benefits, with the Consideration of Limiting the Variance in Added Benefits For All Groups in the Community (to Protect the Poor)
G	Sadr's theory of Justice	Sadr	$Max \sum_i Ac_i$ $s.t.:$ $Ac_i > m_3 * Ac_j \ \forall\ i,j$ $\frac{\sum_i \sum_j \mid Ac_i - Ac_j \mid}{2n^2 \overline{Ac}} < m_4$	To Maximize the Total Final Benefits of the Society, while Ensuring a Minimum Final Benefit for the Poorest Group, and Narrowing the Gap in Total Final Benefits

where:
Ac_i, distributable benefit for the group i,
$\overline{Ac}$, the average of Ac,
n, number of groups,
ΔAc_i, added benefits for the Group i,
m_1, m_2, m_3, & m_4, the gap parameters.

No clear recipe how to transfer these concepts to dynamic multi-agent systems.

Discuss swarm-performance metrics that mimic these concepts.

Non-trivial system dynamics can notably complicate the mapping from control to performance.

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Example 1:
Traffic Flow Smoothing via Sparse Automation

Instabilities Cause Phantom Jams and Traffic Waves

Traffic waves can arise even if all agents are identical and behave fully predictably – due to dynamic instability.

What could one do against that?

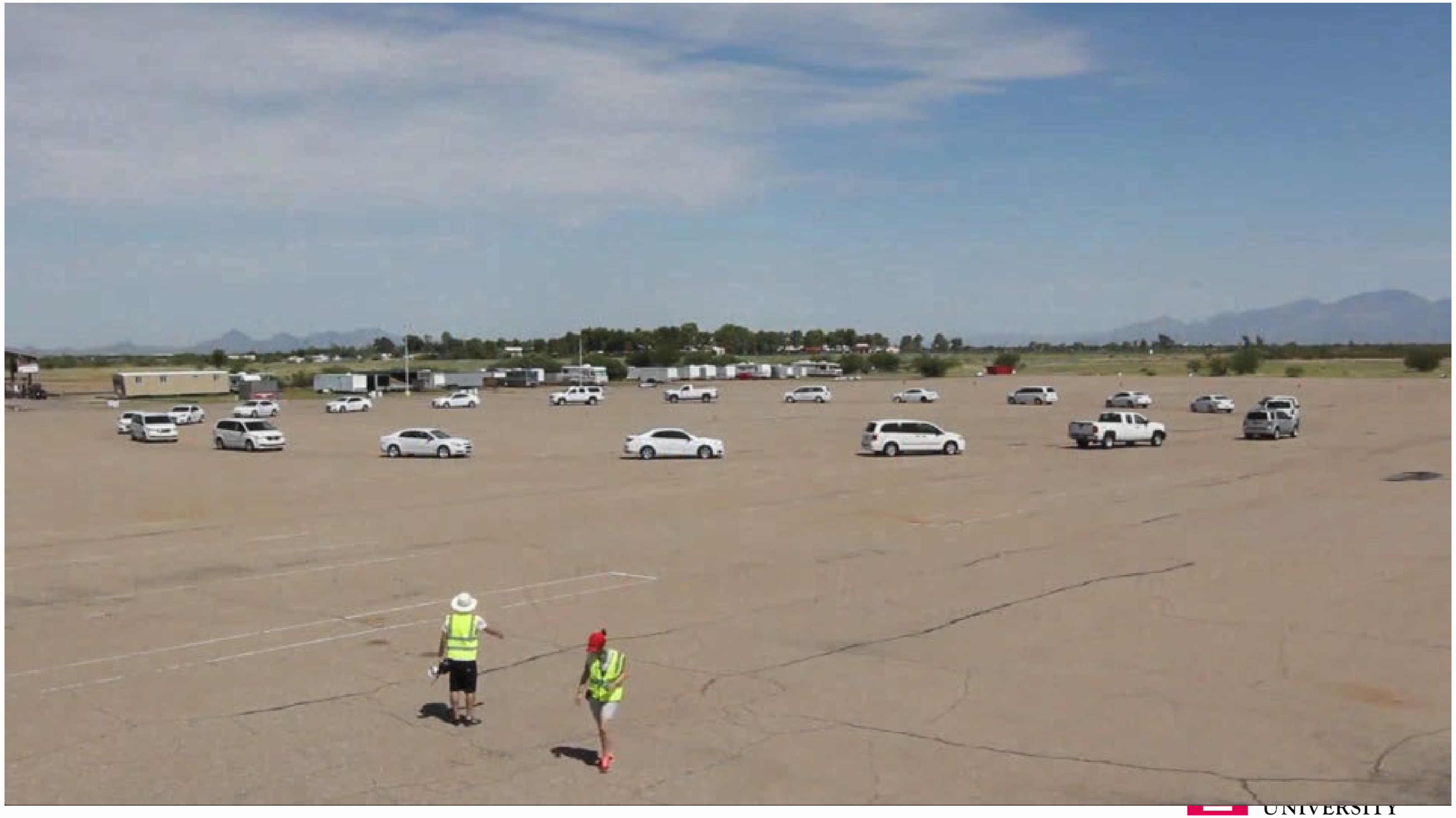
I-24 into downtown Nashville during morning rush hour.

Experimental Proof of Concept of Flow Smoothing

- Can a few connected & automated vehicles, if properly controlled, smooth traffic flow so that the energy consumed *of all vehicles* is reduced?
- Societally relevant global swarm performance metric!
- Why could it work? Dynamic instabilities can yield unsteady flow and traffic waves, which are energy-inefficient.

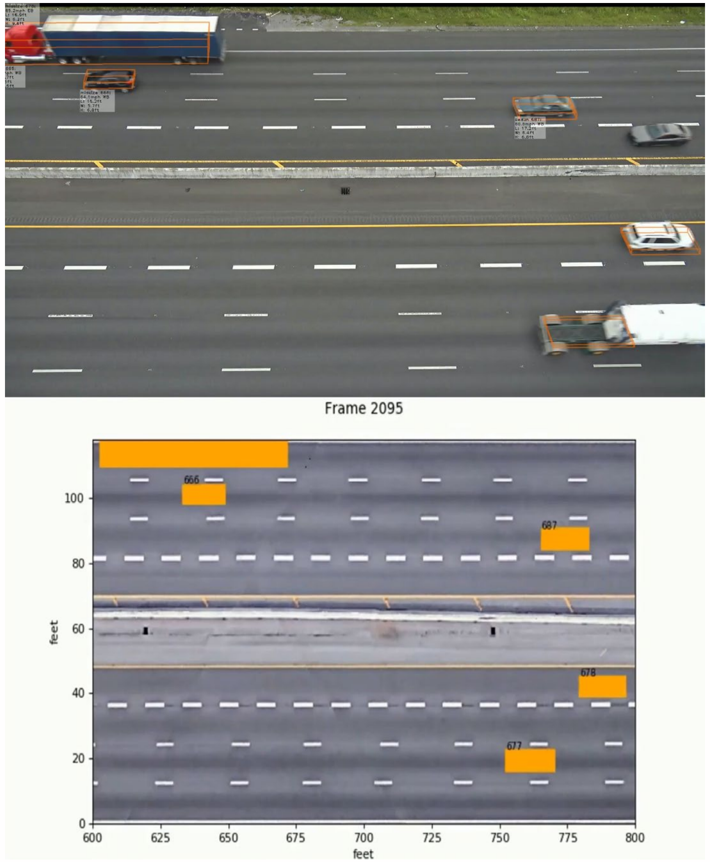
2016 experiment: One control vehicle can dampen waves.

IPAM program "New Directions in Mathematical Approaches for Traffic Flow Management" (Fall 2015) was instrumental in enabling this.



CIRCLES Project (2021-2024)

- Scope: Upscale ring road experiment to a real highway.
- Ingredients:
  - 100+ consumer vehicles with ACC
  - Scalable (x100) tech to safely overwrite stock ACC
  - Many controllers (AI- & theory-based), simulation, software
  - Experimental design and organization
  - I-24 MOTION: produce trajectory of every vehicle on I-24
  - Energy models compatible with simulations, RL, I-24 MOTION
- MegaVanderTest (November 2022)
  - Deploy 100 CAVs, driven by hired humans; test many controllers



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IPAM program "Mathematical Challenges and Opportunities for Autonomous Vehicles" (Fall 2020) was instrumental in enabling this.

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MegaVanderTest

arxiv.org/abs/2310.18151

arxiv.org/abs/2310.18776

dl.acm.org/doi/abs/10.1145/3576914.3587711

doi.org/10.1145/3459609.3460530

doi.org/10.1109/CDC49753.2023.10383810

doi.org/10.1016/j.ifacol.2023.01.107

doi.org/10.1109/ICRA46639.2022.9811912

Look out for results of the MegaVanderTest in the near future.

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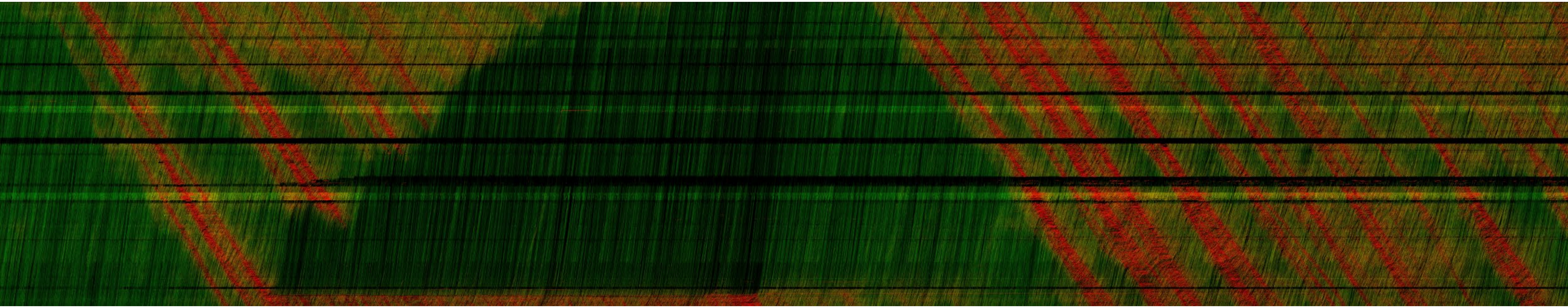
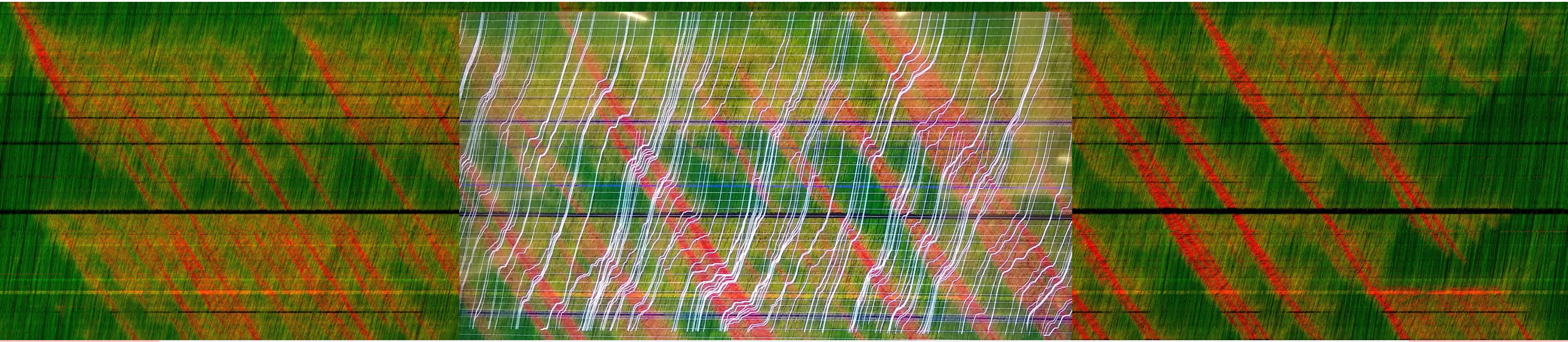
MegaVanderTest: Large Scale Plots of Data

Thursday Nov 10, 2022: No AVs; traffic with accident. Fantastic confirmation of macroscopic traffic models.



Monday Nov 14, 2022: AVs running stock ACC. Middle part: GPS traces of AVs overlaid onto I-24 MOTION trajectories



Accurate yet Simple Vehicle Energy Models

Autonomie
Detailed engine, power train, environment, driver model

virtual chassis dyno

Data
Gear-by-gear fuel rate vs. speed vs. torque

run Autonomie on established drive cycles

Semi-principled model
Fit dyno data; include in principled vehicle/engine model, using: gear shifting, fuel cut, etc.

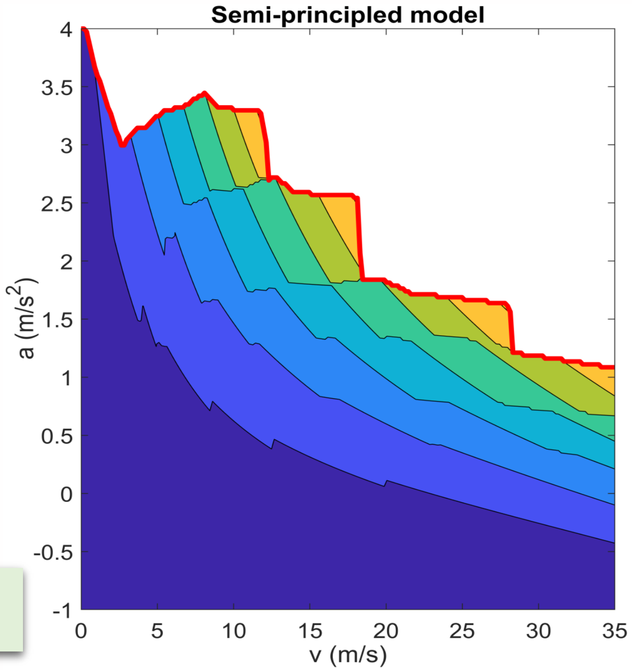
Simplified model
Fit piecewise polynomial functions; fast to implement & evaluate

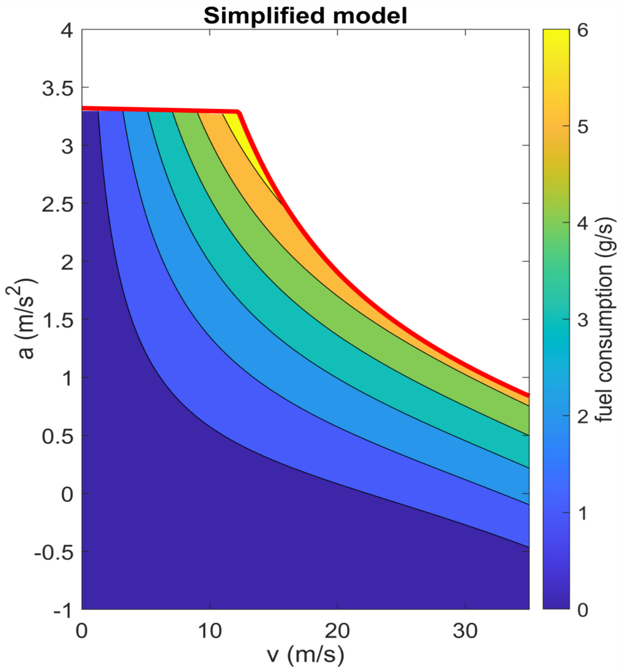
$v(t), a(t), \theta(t) \rightarrow P(t)$

AUTONOMIE

$P(v, a, \theta)$ with jumps
v =speed; a =accel.; θ =grade

$P(v, a, \theta)$ (piecewise) smooth & convex





Simplified models (here for flat road, $\theta = 0$):

$$P(v,a) = \max((c_0 + c_1 v + c_2 v^2 + c_3 v^3) + (p_0 + p_1 v + p_2 v^2)a + (q_0 + q_1 v)a_+^2, \beta)$$

Generalizes basic physics power demand:

$$P(v,a) = \max((c_0 + c_1 v + c_2 v^2 + c_3 v^3) + mva, 0)$$

arxiv.org/abs/2310.06297

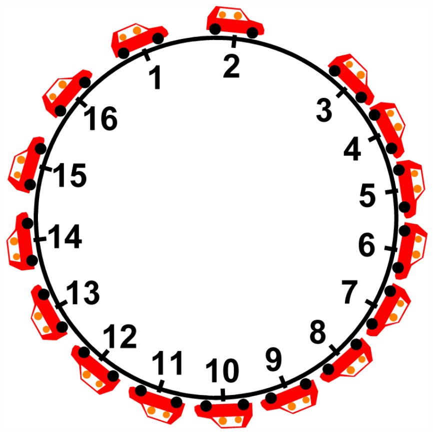
Validated **within 4% error**.

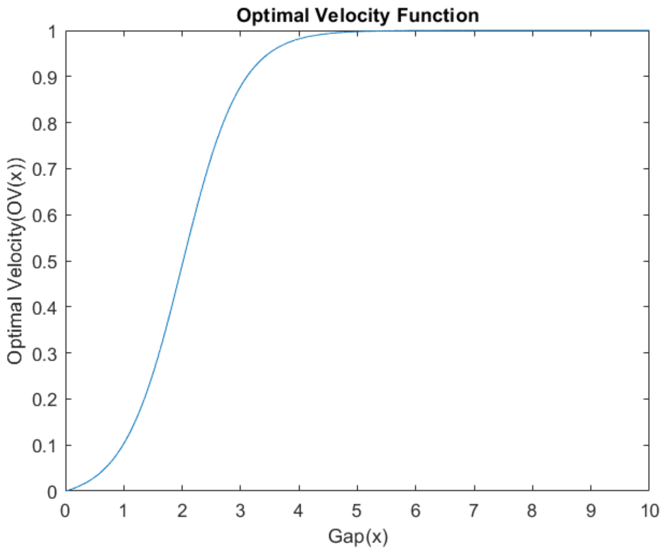
A Simple Traffic Model with Dynamic Instability

Optimal Velocity Model (OVM)

$$\ddot{x}_j = a(V(s_j) - \dot{x}_j)$$

where x_j position of j-th vehicle and gap ahead $s_j = x_{j+1} - x_j - \ell$.





Special case of second-order dynamics $\ddot{x}_j = f(s_j, \dot{s}_j, \dot{x}_j)$.

Stability analysis: Linearization around equilibrium $x_j^{\mathrm{eq}} = d^{eq} j + v^{eq} t$, i.e., $x_j = x_j^{\mathrm{eq}} + y_j$,

yields $\ddot{y}_j = \alpha_1 (y_{j+1} - y_j) - \alpha_2 \dot{y}_j + \alpha_3 \dot{y}_{j+1}$ where $\alpha_1 = \frac{\partial f}{\partial s}$, $\alpha_2 = \frac{\partial f}{\partial \dot{s}} - \frac{\partial f}{\partial \dot{x}}$, $\alpha_3 = \frac{\partial f}{\partial \dot{s}}$.

Ansatz $y_j(t) = x_j e^{zt}$ yields I/O system with transfer function $F(\omega) = \frac{\alpha_1 + \alpha_3 z}{\alpha_1 + \alpha_2 z + z^2}$.

String stability, i.e., $|f(z)| \leq 1$ for all $z \in i\mathbb{R}$, if $\alpha_2^2 - \alpha_3^2 - 2\alpha_1 \geq 0$.

OVM stability: $a \geq 2V'(s^{eq})$.

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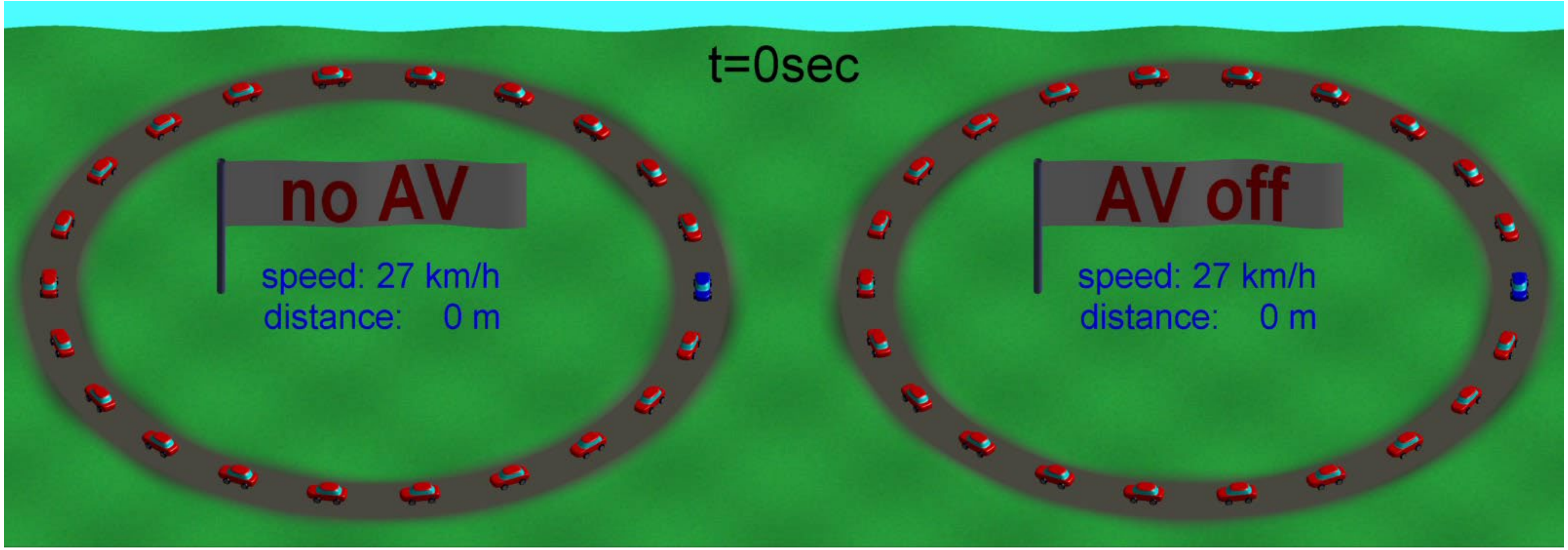
Other Microscopic Models with Instabilities

Delay models: $\dot{x}_j(t) = V(s_j(t-\tau))$

Follow-the-leader-OVM: $\ddot{x}_j = a\big(V(s_j) - \dot{x}_j\big) + b\,\frac{\dot{s}_j}{(s_j)^{\delta}}$

Intelligent driver model (IDM): $\ddot{x}_j = \mathrm{a}\left[1 - \left(\frac{\dot{x}_j}{v_0}\right)^{\delta} - \left(\frac{s_0 + \tau\dot{x}_j - \dot{x}_j\dot{s}_j/(2\sqrt{ab})}{s_j}\right)^2\right]$



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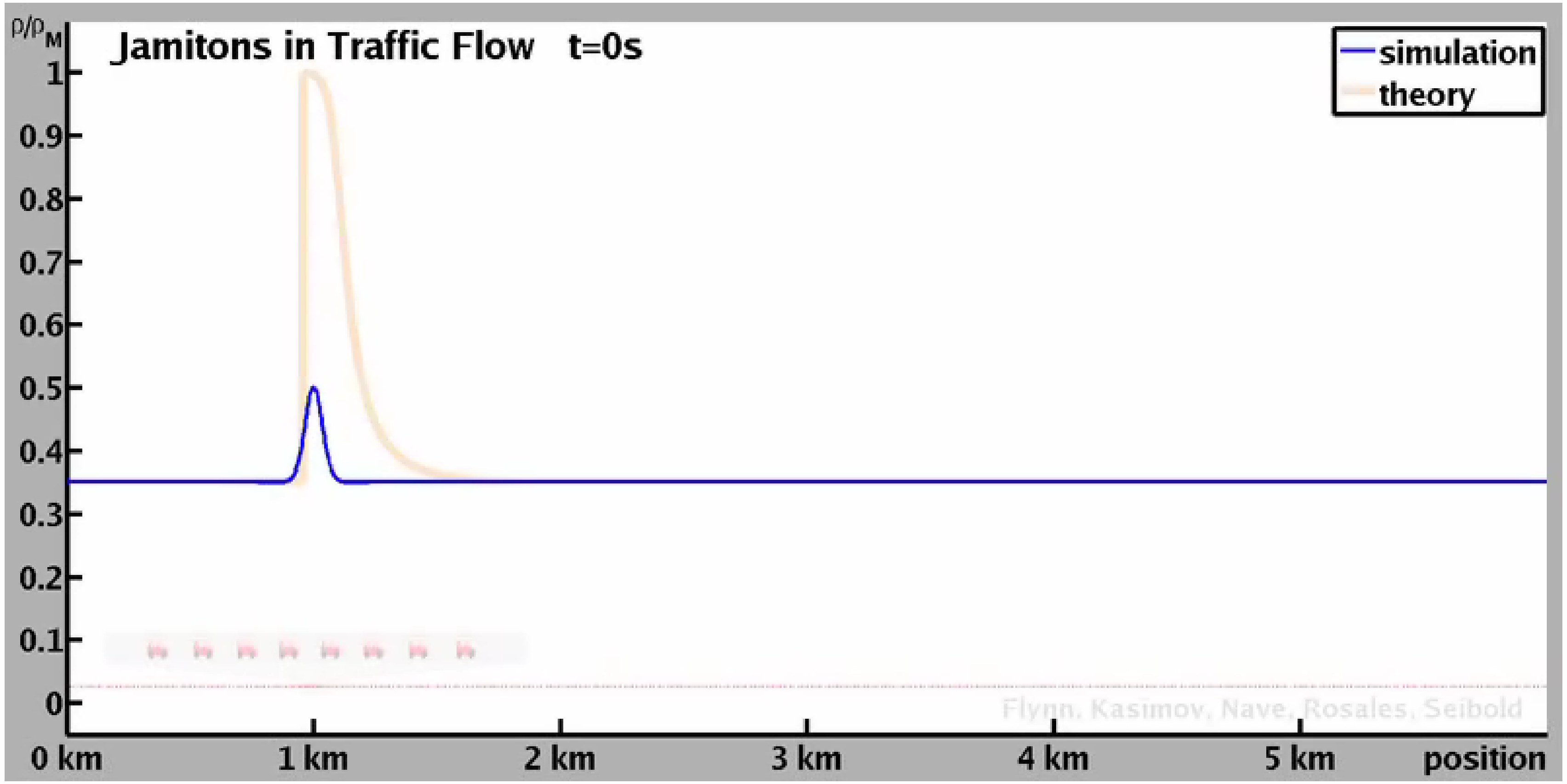
Macroscopic Traffic Models with Instabilities

The inhomogeneous Aw-Rascle-Zhang model

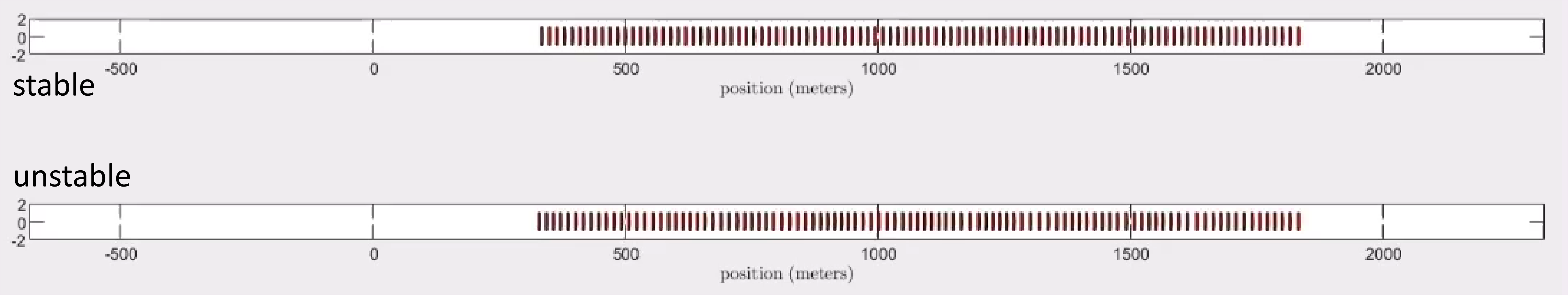
$$\rho + (\rho u)_x = 0$$
$$w_t + u w_x = \frac{1}{\tau}(U(\rho) - u)$$
$$w = u + h(\rho)$$

generates instabilities and traveling wave solutions whenever the sub-characteristic condition $h'(\rho) + U'(\rho) \geq 0$ is violated.



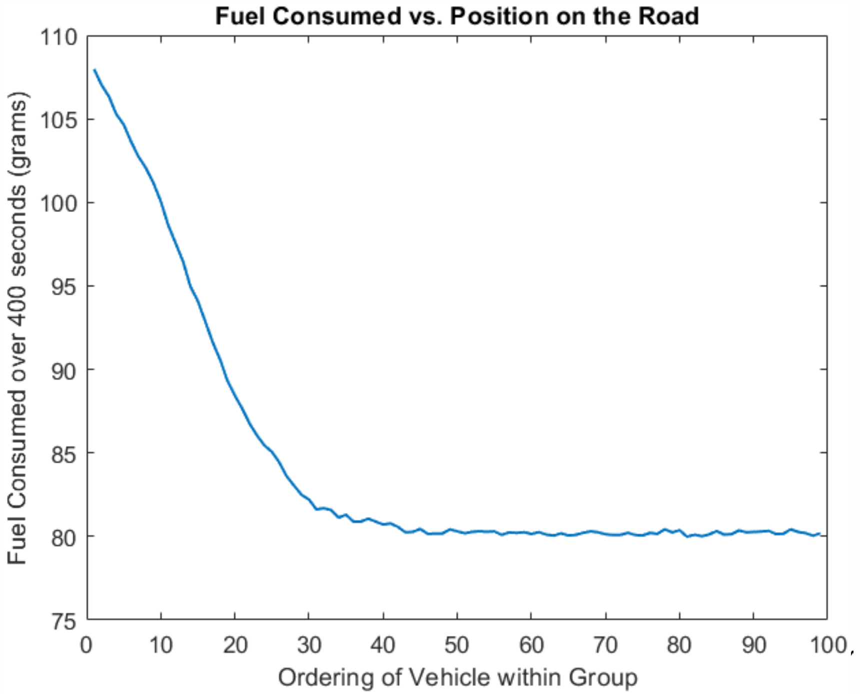
doi.org/10.1103/PhysRevE.79.056113
doi.org/10.3934/nhm.2013.8.745
doi.org/10.1007/978-3-030-66560-9_3

Convoy of Vehicles with Dynamic Instabilities



Agents in the back of the convey are in a different position but otherwise identical to ones in the front. Yet, an observation of the dynamics (strong oscillations) creates an impression that the agents in the back are less capable at driving.

Significant impact on operational range of convoy.



Traffic Waves in Morning Commute in US City

Fact:

- Flow-smoothing technology could significantly reduce local pollution, accident risk, wear-and-tear on materials and drivers, etc.

Fundamental concern:

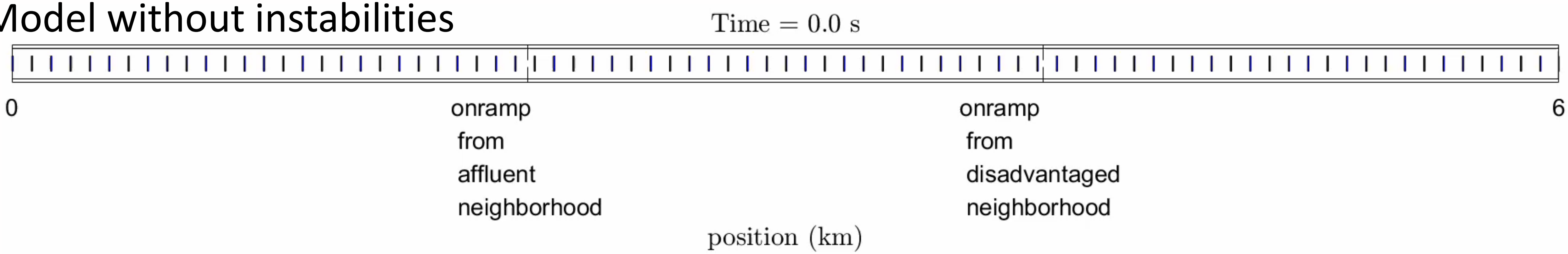
- If vehicles with flow-smoothing capabilities end up being accessible largely to affluent communities, will their benefit be restricted to those affluent neighborhoods?

Simple model setup:

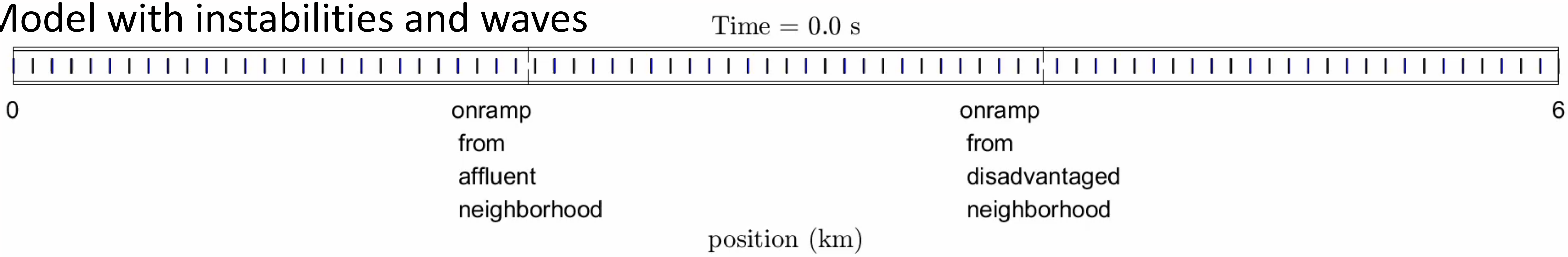
- Highway from suburbs to downtown area, with two on-ramps (first from affluent neighborhood, second from poor neighborhood) separating segments I, II, and III.
- Vehicles already on highway ("type 0") have no CAVs; vehicles from on-ramp 1 ("type 1") have 50% CAVs; vehicles from on-ramp 2 ("type 2") have only 10% CAVs.

Traffic Waves in Morning Commute in US City

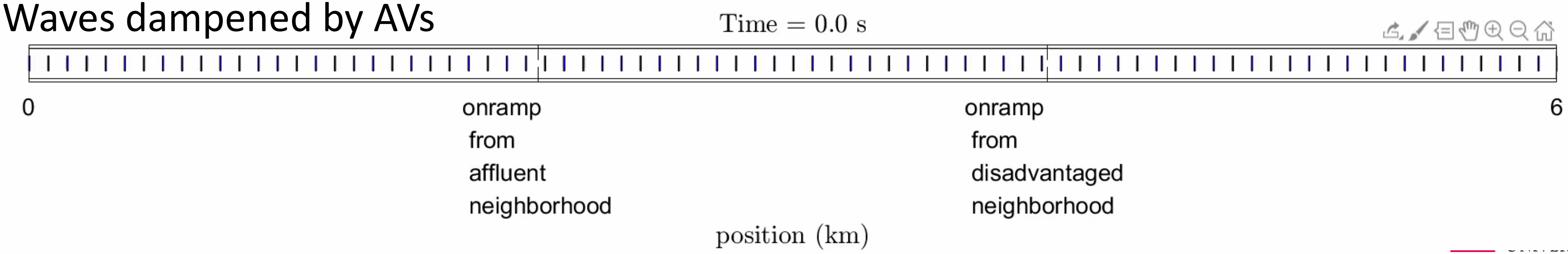
Model without instabilities



Model with instabilities and waves



Waves dampened by AVs



Traffic Waves in Morning Commute in US City

Total fuel consumed across all vehicles

Reference	Segment I	Segment II	Segment III
vehicle type 0	284 kg	311 kg	327 kg
vehicle type 1		131 kg	136 kg
vehicle type 2			5 kg

Waves	Segment I	Segment II	Segment III
vehicle type 0	6069 kg	5791 kg	5921 kg
vehicle type 1		2153 kg	2184 kg
vehicle type 2			318 kg

AV Control	Segment I	Segment II	Segment III
vehicle type 0	6069 kg	5901 kg	5855 kg
vehicle type 1		2441 kg	2411 kg
vehicle type 2			158 kg

Fuel consumed per distance traveled

Reference	Segment I	Segment II	Segment III
vehicle type 0	47 g/km	52 g/km	56 g/km
vehicle type 1		52 g/km	55 g/km
vehicle type 2			51 g/km

Waves	Segment I	Segment II	Segment III
vehicle type 0	55 g/km	94 g/km	70 g/km
vehicle type 1		95 g/km	70 g/km
vehicle type 2			61 g/km

AV Control	Segment I	Segment II	Segment III
vehicle type 0	53 g/km	61 g/km	58 g/km
vehicle type 1		62 g/km	59 g/km
vehicle type 2			52 g/km

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Sparse Flow Smoothing – Remarks

- Systems with intricate emergent phenomena could easily mislead observers into false conclusions about agents' capabilities.
- In typical US cities, CAV-based flow smoothing technology may actually be more equitable than it may appear at first glance.

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Example 2:
Swarm Travel by Swarming with “Car”-Following

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Bio-Inspired Swarming

Flocks of birds, schools of fish, swarms of bugs, etc. exhibit swarming behavior where individuals interact in a way that drives the collective group to form structures with complex emergent behavior despite having no clear leaders.

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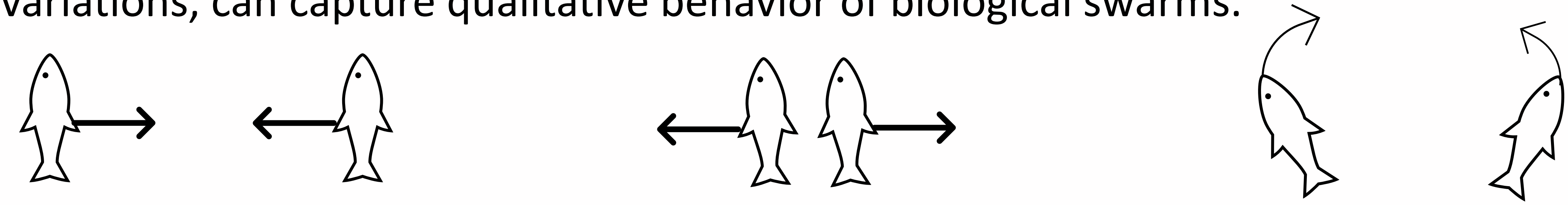
Existing 2D/3D Swarming Models

Reynolds' Boids model (SIGGRAPH '87), Cucker-Smale model (IEEE Autom. Control 2007), and many variations, can capture qualitative behavior of biological swarms.

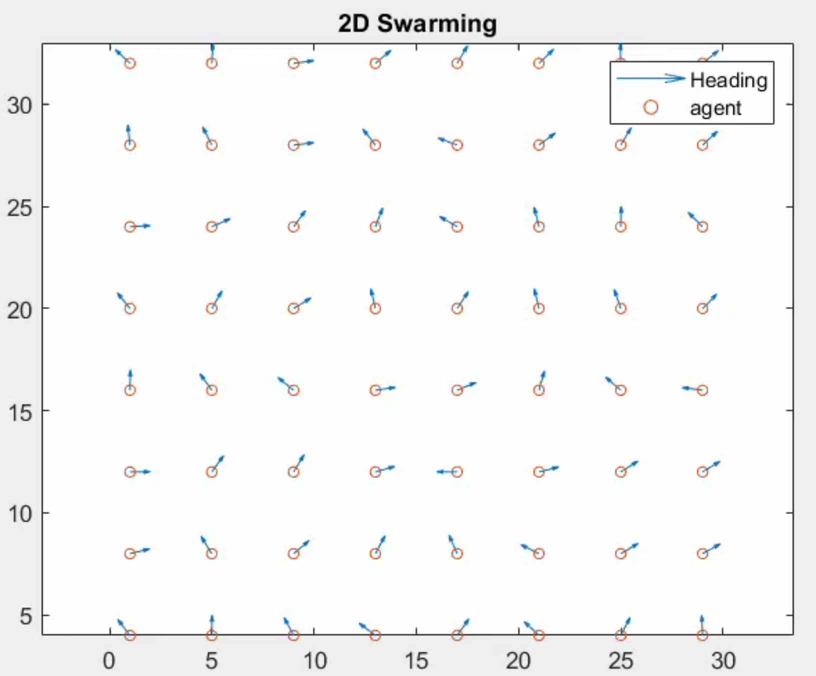


Attraction	Repulsion	Alignment

Important modification [Motsch, Tadmor, J Stat Phys 144, 923 (2011)].

Swarm forms directional consensus (models also used in opinion dynamics).

But swarm would not start moving when starting at rest.



New Combined Swarming Model

Model, using velocity v_i, speed $s_i = |v_i|$, direction $h_i = \frac{v_i}{s_i}$:

$$\dot{x}_i = v_i$$

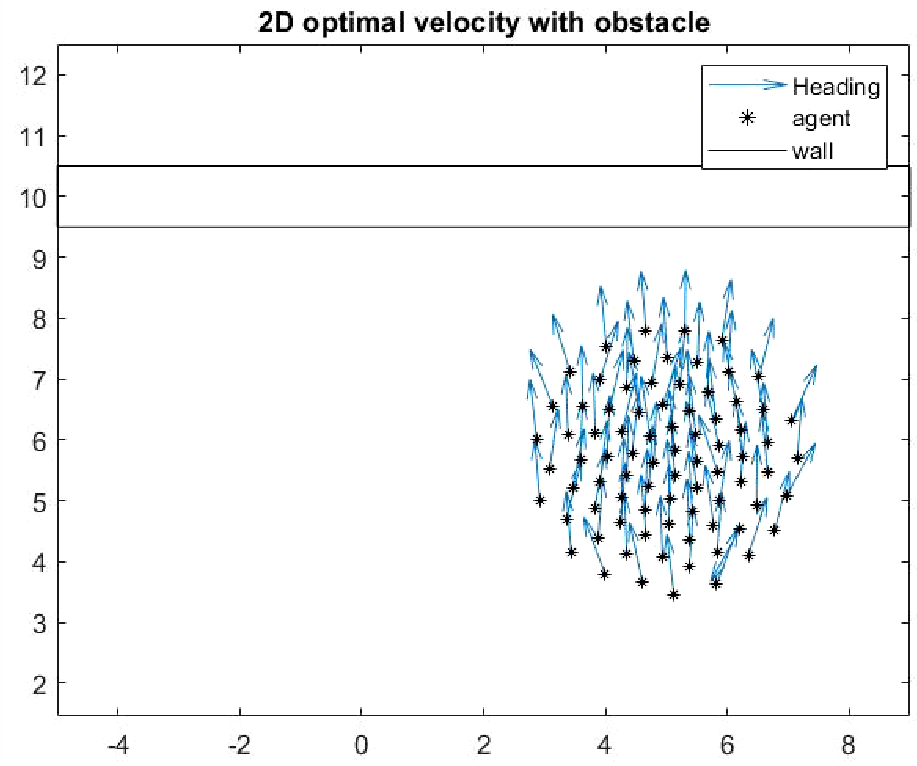
$$\dot{v}_i = \sum_{j \neq i} w_{ij} \left[F(|x_j - x_i|) \frac{x_j - x_i}{|x_j - x_i|} + R(|x_j - x_i|) P_i(h_j - h_i) + \overbrace{a(V(|x_j - x_i|) - s_i) h_i}^{\text{the new optimal velocity term}} \right]$$

$F(s)$ = attraction/repulsion force

$R(s)$ = alignment force

$V(s)$ = optimal velocity function

P_i = projection onto orthogonal complement of h_i



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Swarming Travel Simulation – Setup

- Initialize each simulation with agents arranged as steady state of attraction/repulsion term.
- Half the agents are able to travel fast (optimal velocity max speed 1); the other half of the agents can only travel half as fast.
- Agents may die to predation, with the probability of predation significantly increased with decreasing number of other agents nearby (e.g., sharks can sense and chase individual fish very well, but that ability fails when prey are part of a swarm).

Study: As a function of the attraction parameter magnitude…

- Show selected simulations and plots of (a) survival rates and (b) average speeds.
- Augment the travel phase by an egg laying phase and study which agent behavior leads – via the complex swarm dynamics – to the optimal reproductive value.

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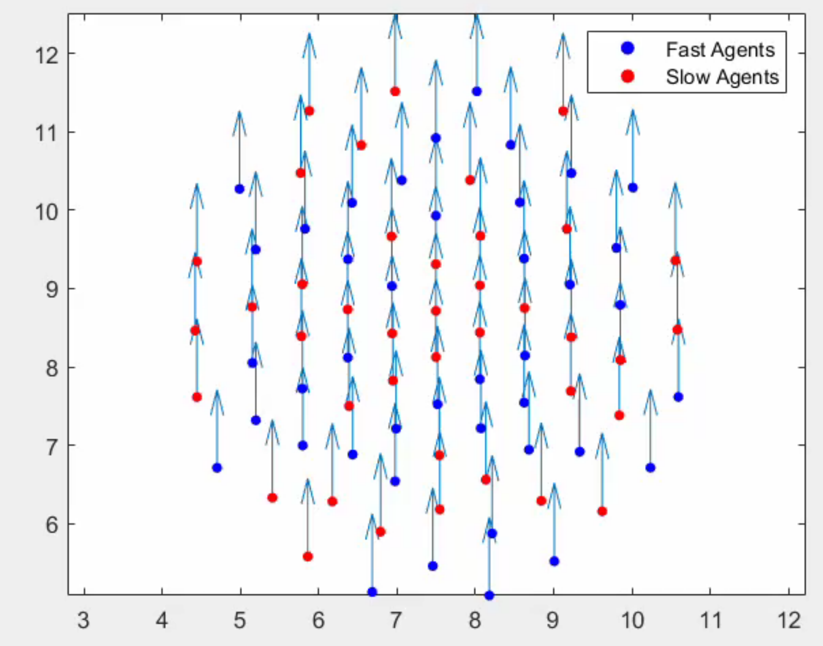
Swarming Travel Simulation – Dynamics

very strong attraction (20)

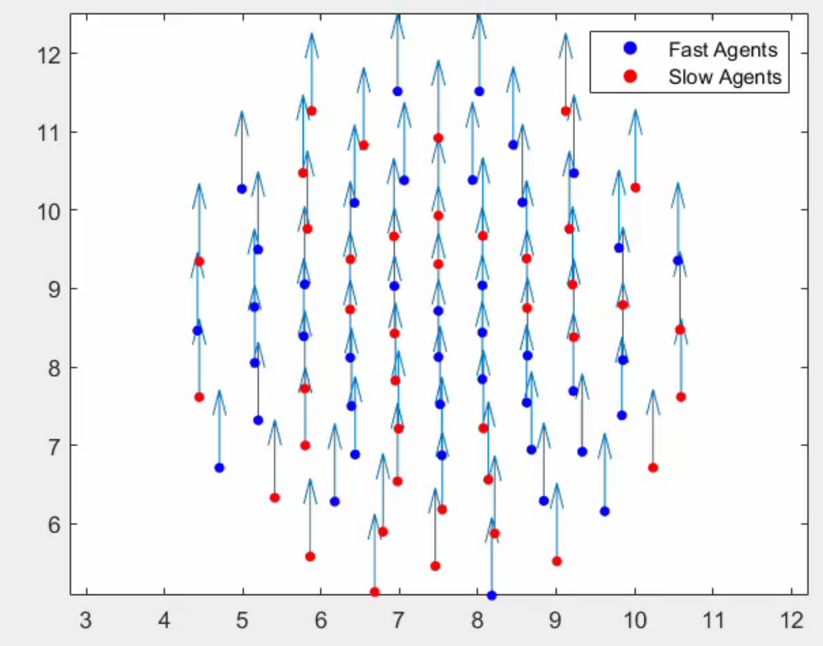


One mixed swarm with hardly any internal motion.

Joint avg. speed: 0.64

Survival rate: 100%

medium attraction (15)

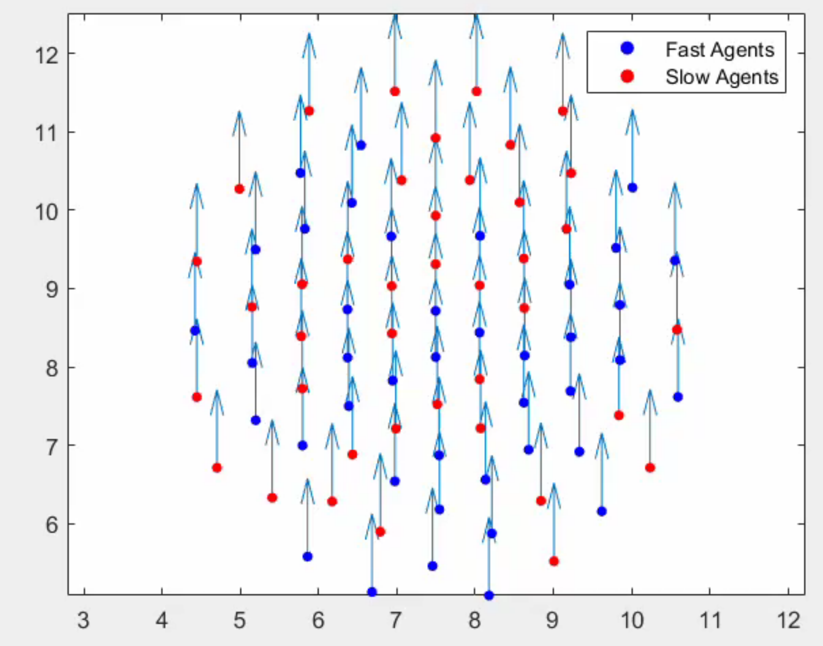


After some stratification of a single swarm, separation into two sub-swarms.

Avg. speeds: 0.69 and 0.53

Survival rates: 87% and 75%

Weak attraction (5)

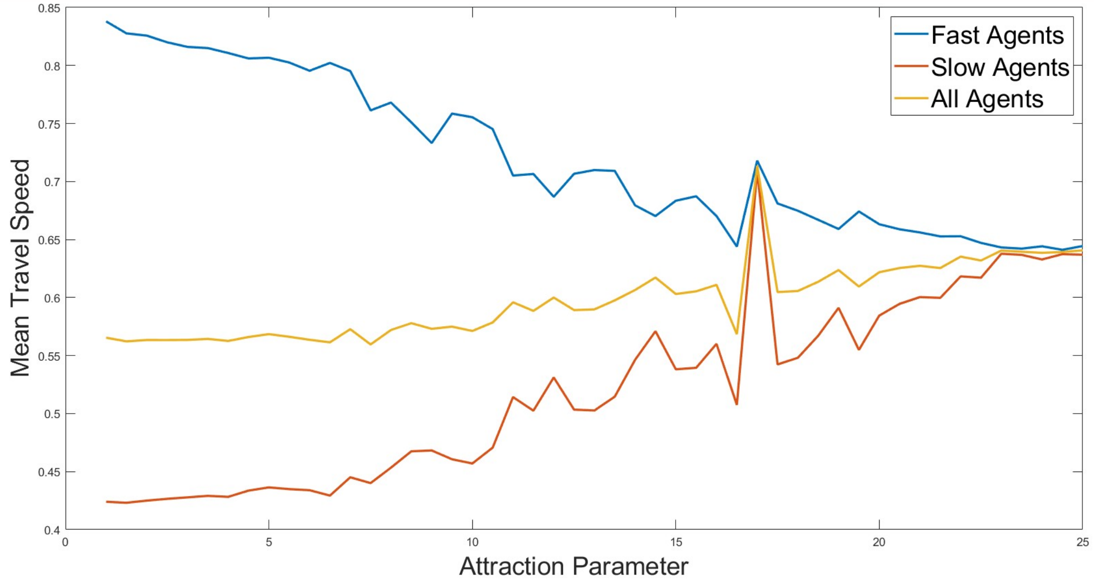


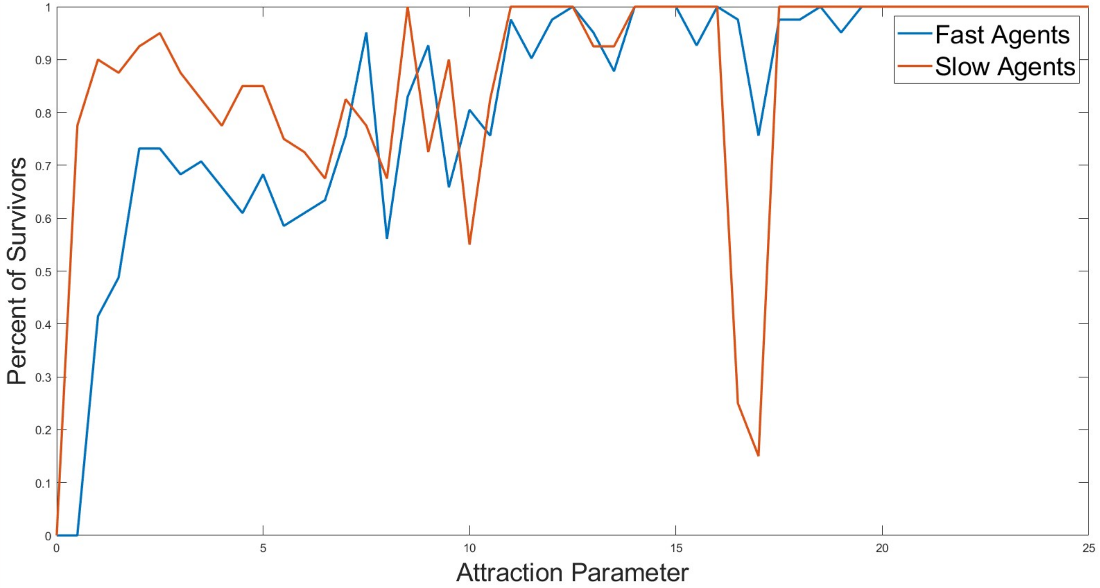
Quick separation into two sub-swarms that are loosely packed.

Avg. speeds: 0.80 and 0.44

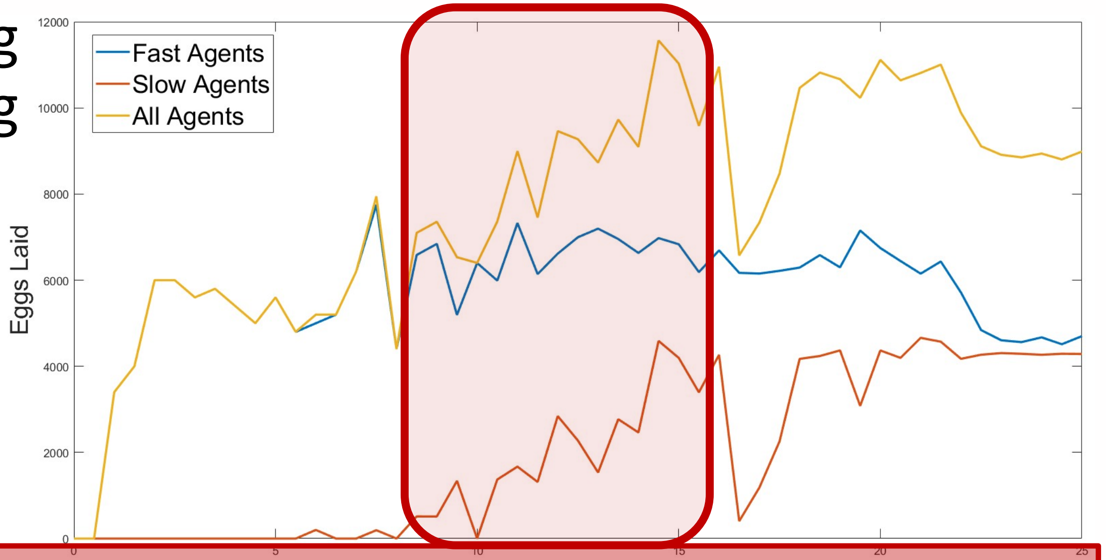
Survival rates: 58% and 82%

Swarming Travel Simulation – Parameter Study

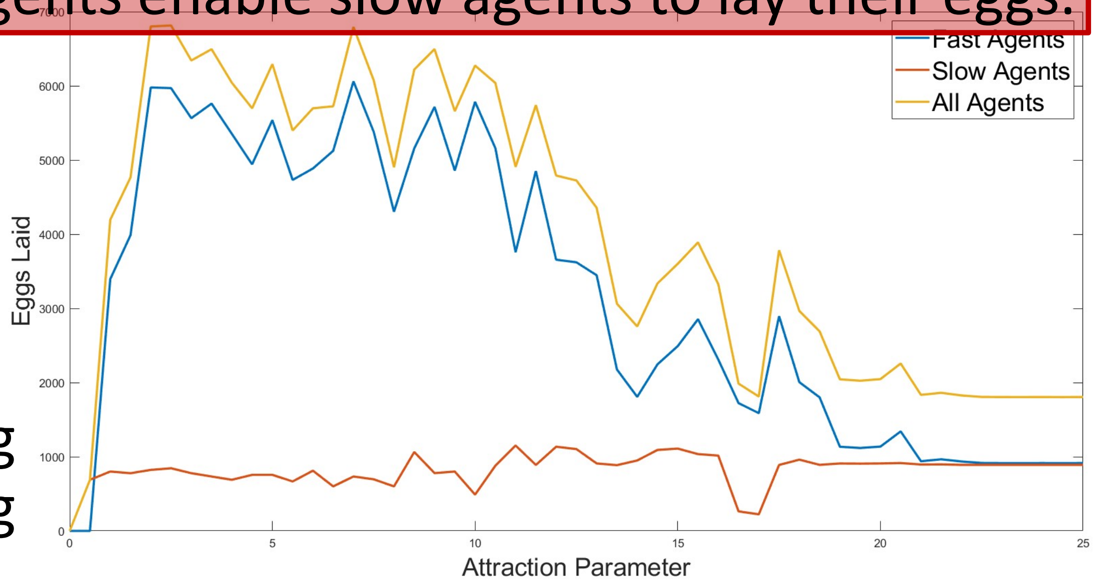




Slow egg laying



Fast agents enable slow agents to lay their eggs.



Rapid egg laying

Swarming Travel Simulation–Remarks and Thoughts

- No ethical/moral reasoning is needed to justify why the more capable agents may want to slow themselves down to assist the less capable agents. Under appropriate circumstances, such behavior can be rooted solely in the collective reproductive success.
- Depending on the circumstances, it could be advantageous for the swarm to stay together, or to segregate.
- The fewer agents are available, the more critical it becomes for the swarm to stay cohesive.

Thoughts:

- Analogy to education: optimal form/level of inclusion; milestones vs. growth.
- Analogy to transportation systems: ideas?

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Example 3:
Emperor Penguins

Emperor Penguins

Real-world observations:

- Emperor penguins form colonies to assist each other to survive the cold Antarctic winter.
- Penguins in the inside of the group are well-protected from the cold winds.
- Penguins continuously cycle their positions, taking turns who is at the edge, exposed to the cold winds.

Which agent behavior has evolution “generated” that yields an effective movement?

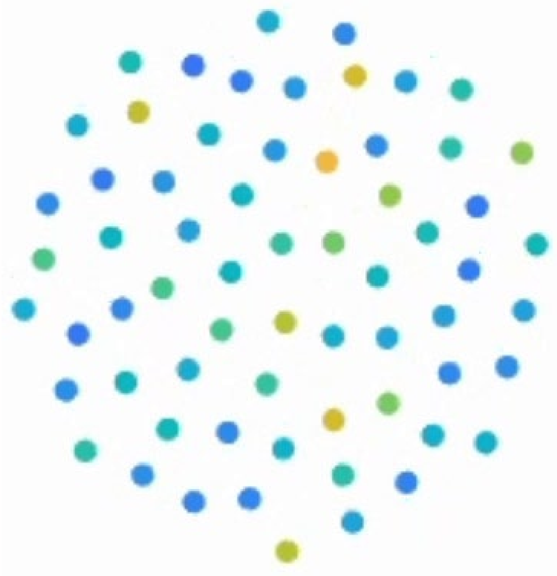
Agents inside the group must be willing to yield their advantageous position for the sake of the swarm performance.

Emperor Penguins – Mathematical Model

First-order motion with dynamic state “coldness”:

$$\dot{x}_i = (\alpha + \beta c_i)\underbrace{\frac{1}{n}\sum_{j=1}^{n}(x_j - x_i)}_{\text{move towards center}} - A\underbrace{\frac{1}{n}\sum_{j=1}^{n}\frac{x_j - x_i}{\left|x_j - x_i\right|^2}}_{\text{repulsion}}$$

$$\dot{c}_i = B\frac{1}{n_i} - Dc_i$$



x_i = position of agent i

c_i = coldness of agent i

n = total number of agents

n_i = number of agents nearby agent i

A, B, C = constants describing relative importance of effects

α = equality parameter; β = equity parameter $\rightarrow \gamma = {}^{\beta}/_{\alpha}$ = relative strength of equity

remove agent when $c_i > 1.05$ for a continuous duration of 100s

$\Delta = \max_{i,j}(T_i - T_j)$ = observed unfairness metric, where T_i = total time spent at coldness $c_i > 0.9$

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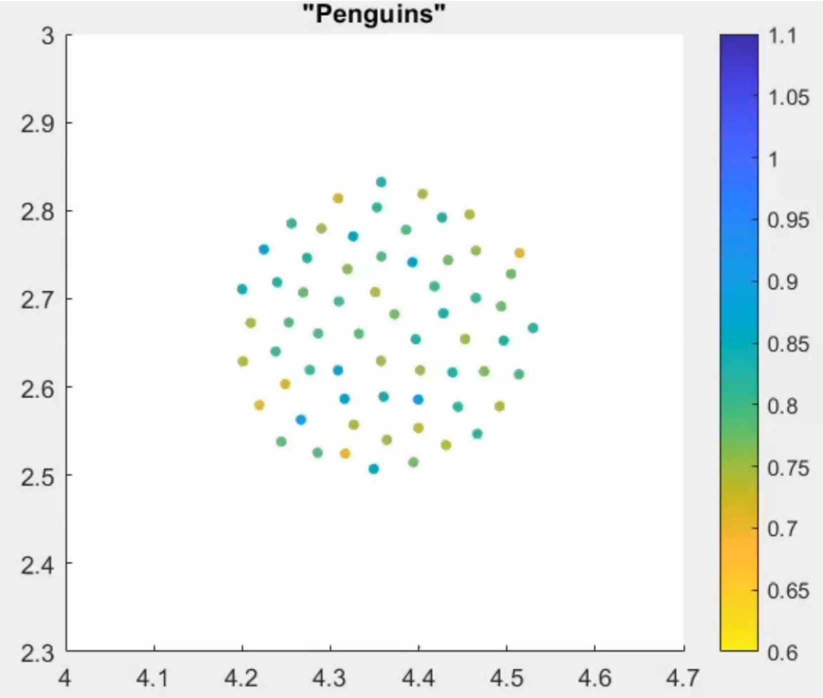
Emperor Penguins – Simulation Results

no equity ($\gamma = 0$)

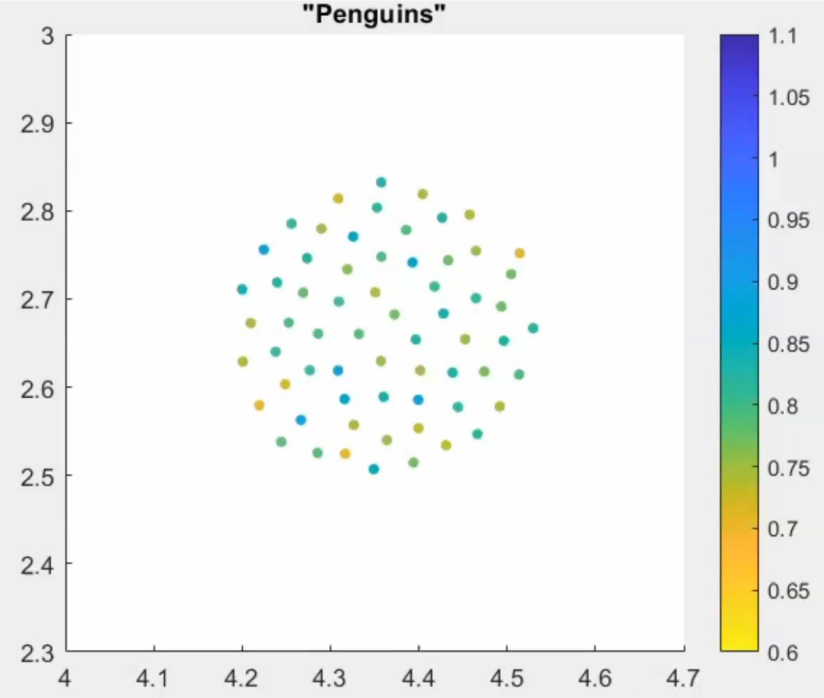


Disparity of circumstance (here: coldness) has no effect on mobility (here: strength of push to center vs. willingness to yield the center).

$\Delta = 796\text{s}$

Results in death of all agents.

balanced ($\gamma = 1$)

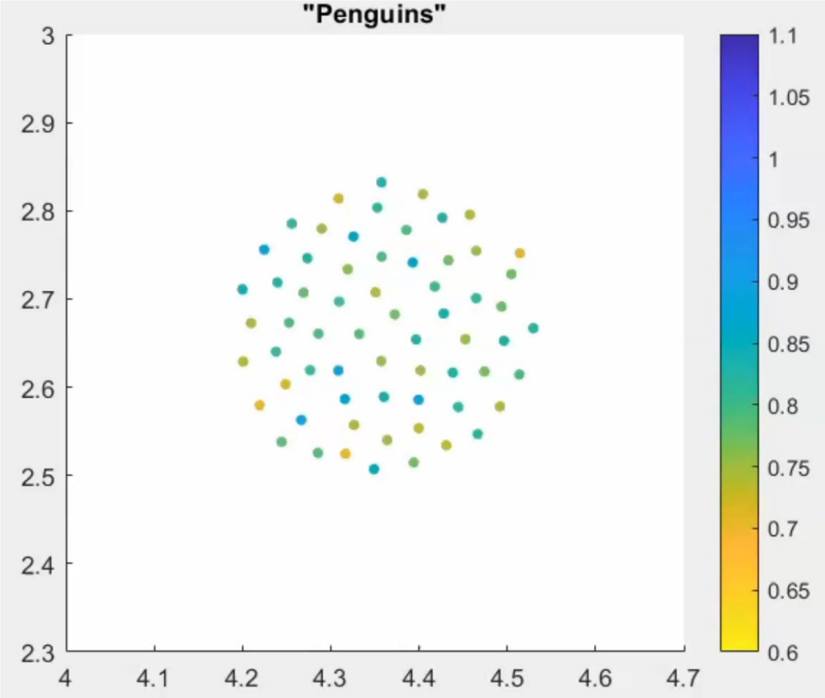


Some impact of circumstance on push strength towards center.

$\Delta = 327\text{s}$

No agent death; moderate motion.

highest equity ($\gamma = \infty$)



If coldness $c_i = 0$, agents have no push towards center and are maximally willing to yield center to agents with higher need).

$\Delta = 231\text{s}$

No agent death; lots of movement.

Emperor Penguins – Remarks and Thoughts

- If the mobility does not factor in the agents' circumstances, the status quo is maintained.
- Real-world Emperor penguins also must not become too hot (would diminish reproduction).
- Optimal situation would be a "milling" that, at minimal energy expense, gives every agent an acceptable temperature over a suitable time-average.

Thoughts:

- Analogy to transportation: Agents on the fringe of accessibility may become invisible as possible users of mobility, thus reducing the perceived need/demand and thus reducing public investment.
- Analogy to sports: "Belgian tourniquet" in cycling.
- Analogy to job market: Removal of agents from job market due to burnout or "giving up".

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Conclusions

- [Lots of interesting observations related to applications (vehicle automation, biology).]
- But related to equity: In complex systems, …
  - … purely “cut-throat” objective functions could nevertheless generate forms of “equity”.
  - … it is critical to distinguish (i) agents’ capability/circumstances, (ii) agents’ behavior, (iii) agents’ observed performance, and (iv) system performance. Uninformed observation may confuse them (e.g., observed oscillations).
- Which aspects of the “complex systems” shows here are present in transportation systems?
- Why does it matter from which principle equity results?
  a) fundamental cause-effect understanding
  b) political discourse

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