Cellular Automata

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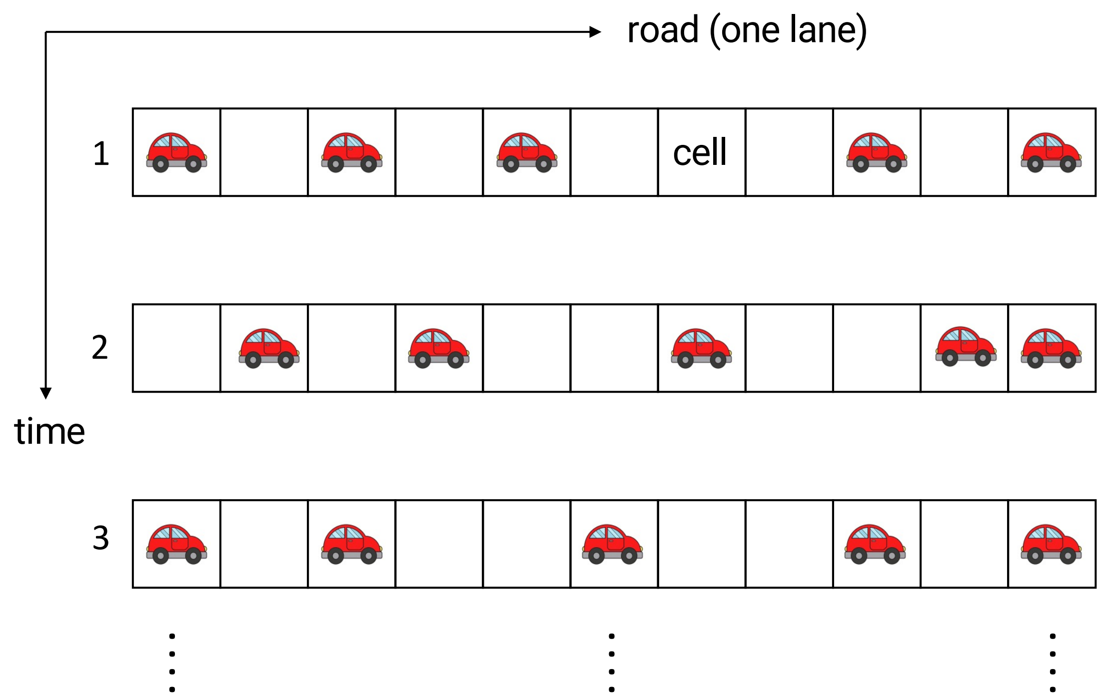
Glance

Cellular Automata in Traffic

- Road is divided into cells
- Vehicles are in cells (position)
- Update vehicle positions
  time by time
  according to **rules**

⬇

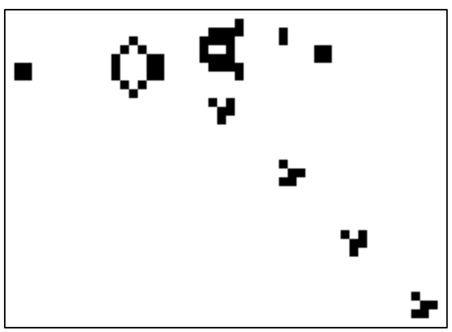
Traffic Dynamics



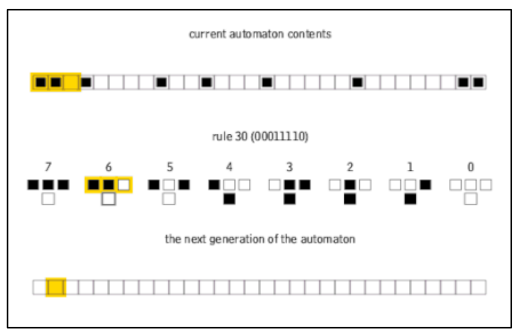
History

Cellular Automata

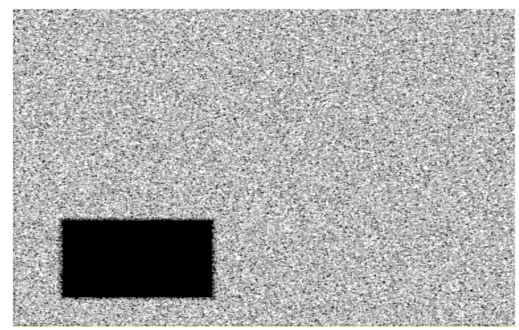
- 1940s, Cellular Automata (CA) was first proposed by **John von Neumann**
- 1970s, a two-state, two-dimensional CA, named, **The Game of Life**, became popular (Video)
- 1983, elementary CA was investigated by **Stephen Wolfman**.
  - **One-dimensional** string of cells
  - Each cell has only two states: “**0** and **1**”
  - A cell only interacts with **itself** and its two **adjacent neighbors**



Conway's Game of Life*



1D CA: determining next generation*



2D CA: Simulating gas emission*

* wikipedia

History: Cellular Automata in Traffic

Rule 184

- Most generic traffic-related CA rule
- In each time step of the rule
  - Vehicle moves 1 cell to the right if the new cell is empty ---- **free traffic**
  - Otherwise, vehicle remains in its old cell ---- **congested traffic**
- Based on the rules, a group of 3 cells has 8 possible patterns in total – which 8 patterns?

Current pattern	111	110	101	100	011	010	001	000
New state of center cell	**1**	**0**	**1**	**1**	**1**	**0**	**0**	**0**

binary number: **10111000**

decimal number: **184**

longitudinal movement

Nagel-Schrechenberg (NS/NaSch) Model

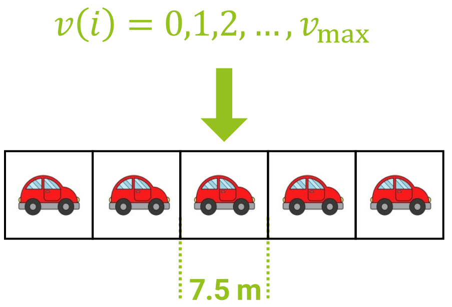
- Proposed by two German researchers K. Nagel and M. Schrechenberg in 1992
- Simplest and most generic/popular representative of traffic-related CA models

Reference

- *A cellular automation model for freeway traffic. Journal de Physique I, 1992, 2, 2221–2229.*

NaSch Model: Setting

- A road is first divided into cells of length **7.5 m** ?
- Each cell can be either **empty** or **occupied** by **exactly 1 vehicle**
- Each vehicle is characterized by its current velocity $v(i) = 0,1,2, \ldots, v_{\max}$ **(unit: cell)**
  $v_{\max}$ corresponds to a **speed limit** and is therefore the same for all vehicles (in the simplest case)
- The NaSch model simply consists of **4 Steps:**
  Acceleration, Safety, Randomization, Driving



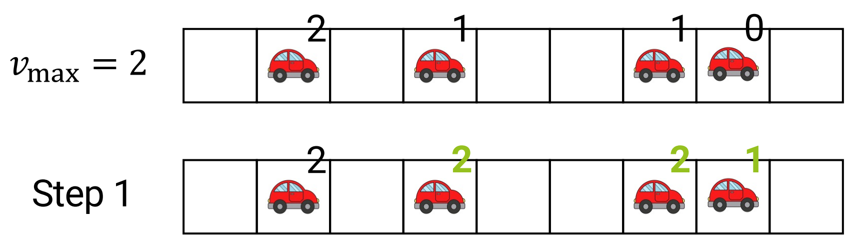
= vehicle length + [bumper] spacing in standstill
minimal space

NaSch Model: Steps

Step-1: Acceleration

- Vehicle (i), which has not reached the maximal velocity $v_{\max}$, accelerates by one cell

$$v(i) \;\rightarrow\; \min\{\, v(i) + 1\,,\, v_{\max} \}$$



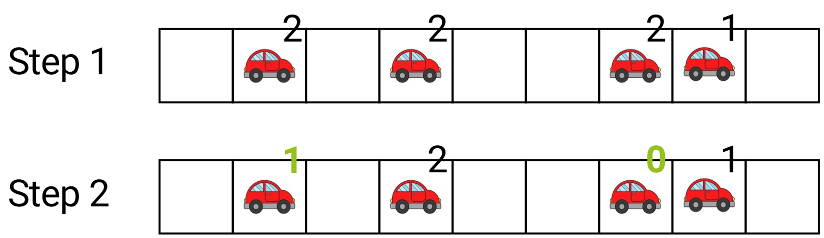
- It describes **drivers' desire to drive as fast as possible** if allowed

NaSch Model: Steps

Step-2: Safety

- If vehicle i has $s(i)$ empty cells ahead and its velocity $v(i)$ (after Step 1) is larger than $s(i)$, it reduces the velocity to $s(i)$

$$v(i) \;\rightarrow\; \min\{\, v(i)\,, s(i)\}$$



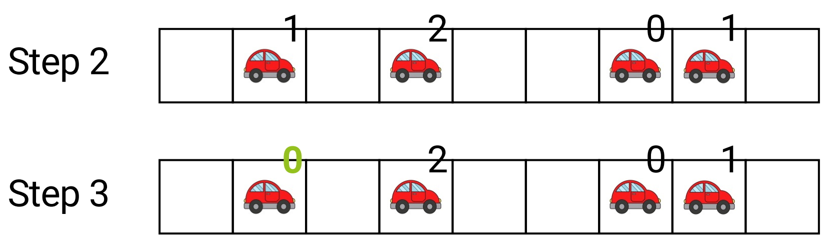
- It encodes the **interaction between vehicles**. In this simple model, interactions only occur to avoid accidents (accident-free model)

NaSch Model: Steps

Step-3: Randomization

- With slowdown probability p (around 0.25 usually), the velocity is reduced by one cell

$$v(i) \;\rightarrow\; \max\{\, v(i) - 1, 0\} \text{ with } \textbf{slowdown probability } \boldsymbol{p}$$



- It reflects **imperfect driving behavior**, and the simple microscopic setting results in many complex real-world macroscopic effects, such as traffic waves and **phantom traffic jams***

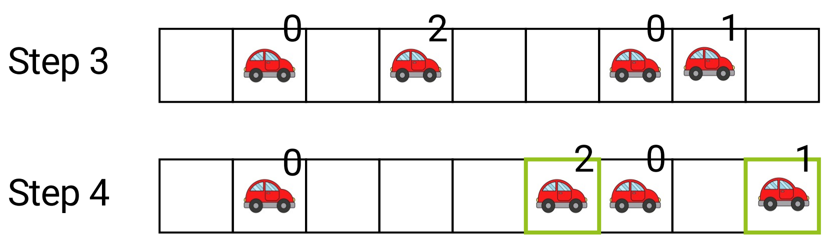
** Please go to YouTube*

NaSch Model: Steps

Step-4: Driving

- Physically move vehicles forward to new cells according to the new velocity $v(i)$ and last-time position $x(i)$

$$x(i) \rightarrow x(i) + v(i)$$



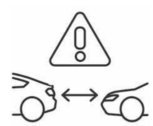
- Although we process it one-by-one, the actual movements are **PARALLEL**, since all velocities have been previously determined

Summary

Minimal Model: leaving out *[one of the 4 steps]* no longer leads to a realistic behavior

- Update Speed – No vehicle movement

Step 1
Driver desire



Step 2
Safety distance

Step 3
Imperfect behavior

Essential Parts

- Update Position – Step 4 – Only step that we move vehicles

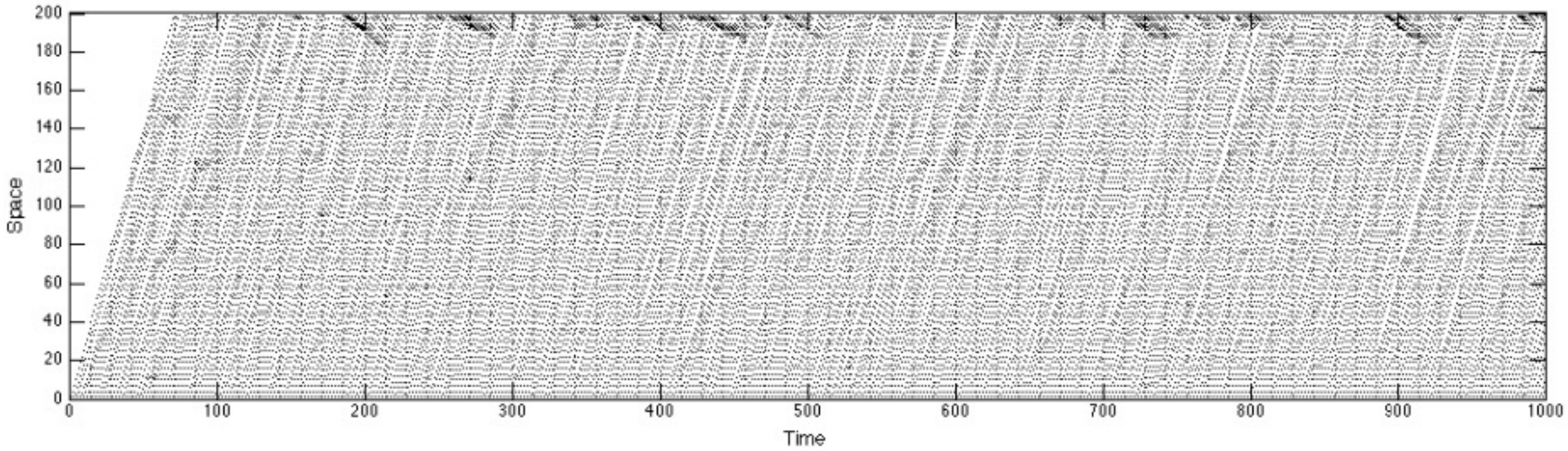
Simulation: Single/Lane Scenario

Setting

- Open boundary: a straight lane
- Total number of cells: 200
- Total simulation time: 1000 sec
- Maximum speed: $v_{\max} = 3$ cell/sec
- Entry boundary: loading a new vehicle every 2 seconds
- Exit boundary: blocking the last cell with a probability of $p = 0.1$

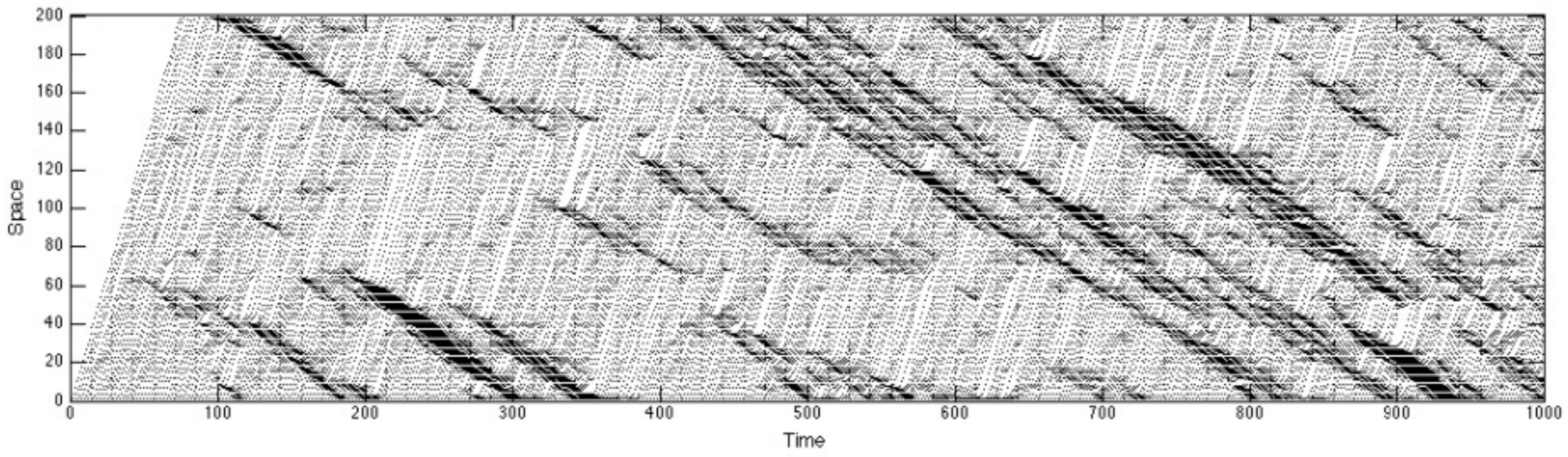
Simulation: Single/Lane Scenario

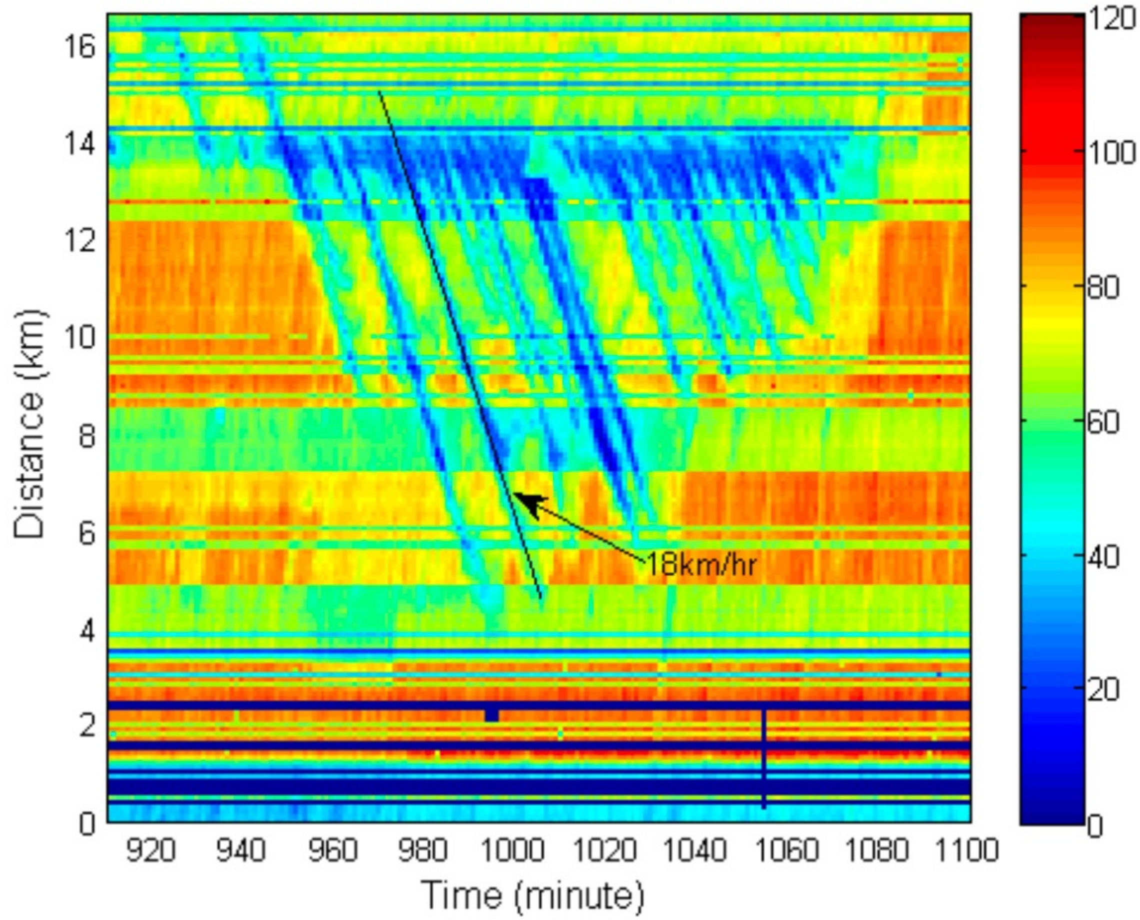
Results: Slowdown probability = 0.1



Simulation: Single/Lane Scenario

Results: Slowdown probability = 0.3





Distance (km)
Time (minute)
18km/hr
0
2
4
6
8
10
12
14
16
920
940
960
980
1000
1020
1040
1060
1080
1100
120
100
80
60
40
20
0

Velocity-Dependent-Randomization (VDR) Model

- In practice, the slowdown probability *p* is dependent on the vehicle velocity. While *p* in the NaSch model is constant.
- The Velocity-Dependent-Randomization (VDR) model incorporates the dependency by introducing a velocity dependent *p(v)*.

VDR Model: Setting

Step-0: Determination of the randomization parameter *p(v)*

- For standing vehicles $p(v = 0) = p_2$
- For moving vehicles $p(v > 0) = p_1$
- Typically, $p_1 \ll p_2$, such as

$$p_1 = 0.01 \quad p_2 = 0.5$$

lateral movement

Lane-changing Model

Reference

- *Two lane traffic simulations using cellular automata. Physica A, 1996 4367(95).*

Lane-changing

Step-1: Motivation (Acceleration)

Step-2: Feasibility (Safety)

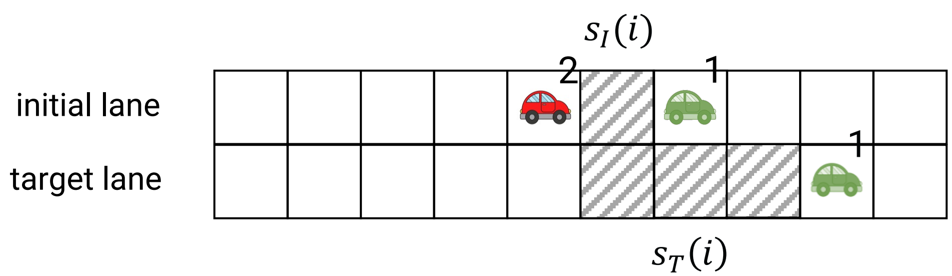
Step-3: Randomization

Step-4: Execution (Driving)

Lane-changing

Step-1: Motivation (Acceleration)

- A vehicle can drive faster by changing lanes
  - Being blocked by its front vehicle : $v(i) > s_I(i)$, $s_I(i)$ – distance to front vehicle, initial lane
  - More space on the target lane : $s_I(i) < s_T(i)$, $s_T(i)$ – distance to front vehicle, target lane

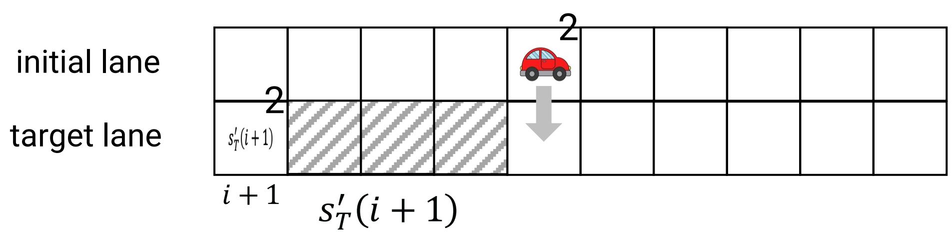


Lane-changing

Step-2: Feasibility (Safety)

- No rear-end collision if changing lanes

$$s'_T(i+1) > v_T(i+1)$$



Lane-changing

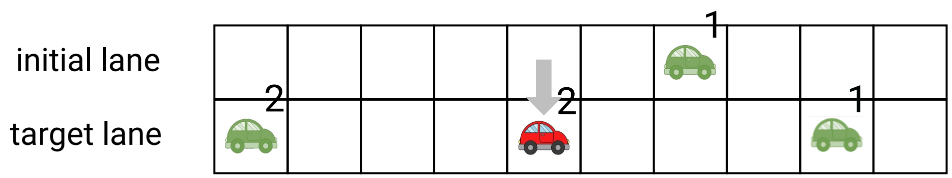
Step-3: Randomization

- A vehicle is not necessary to change lanes even if the motivation and feasibility exist at the same time

If changing lanes or not, with a possibility

Step-4: Execution (Driving)

- Physically move the vehicle to the target lane

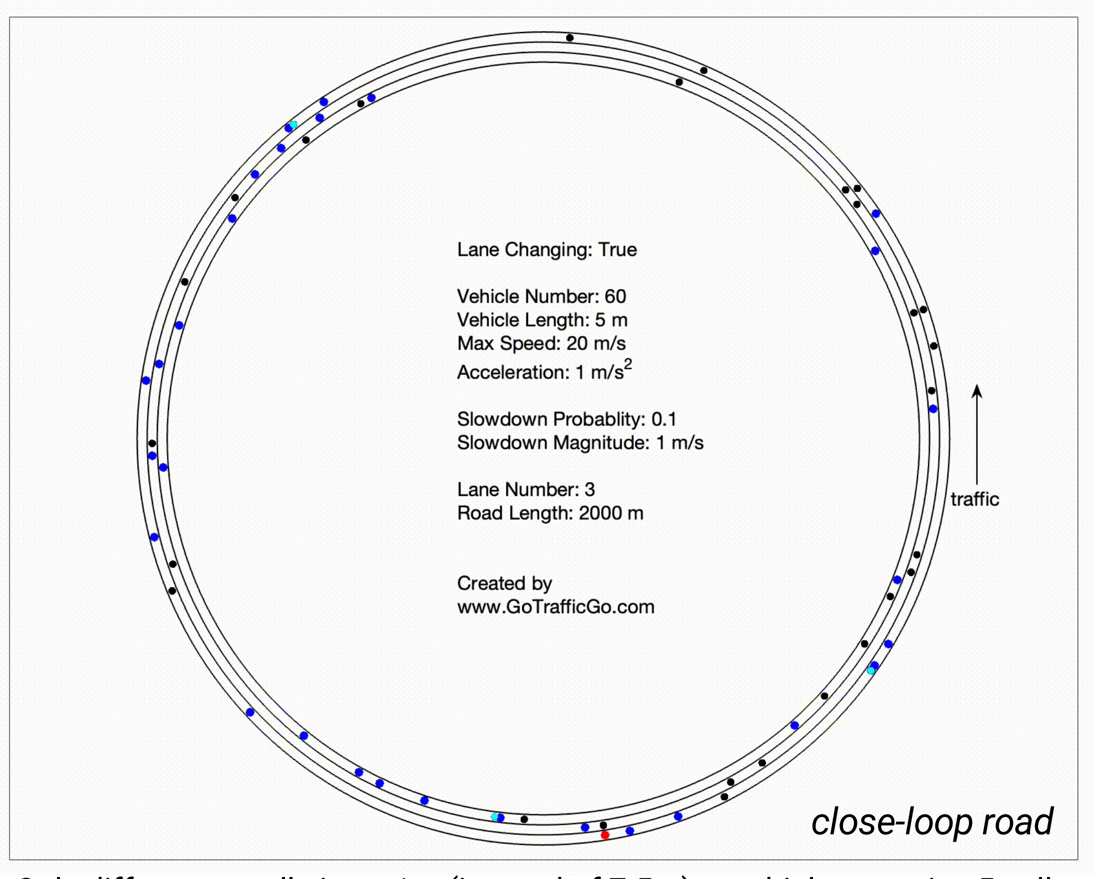


Application in Traffic Simulation

My On-going Research: Contagion of Speeding Behavior

Traffic Simulation

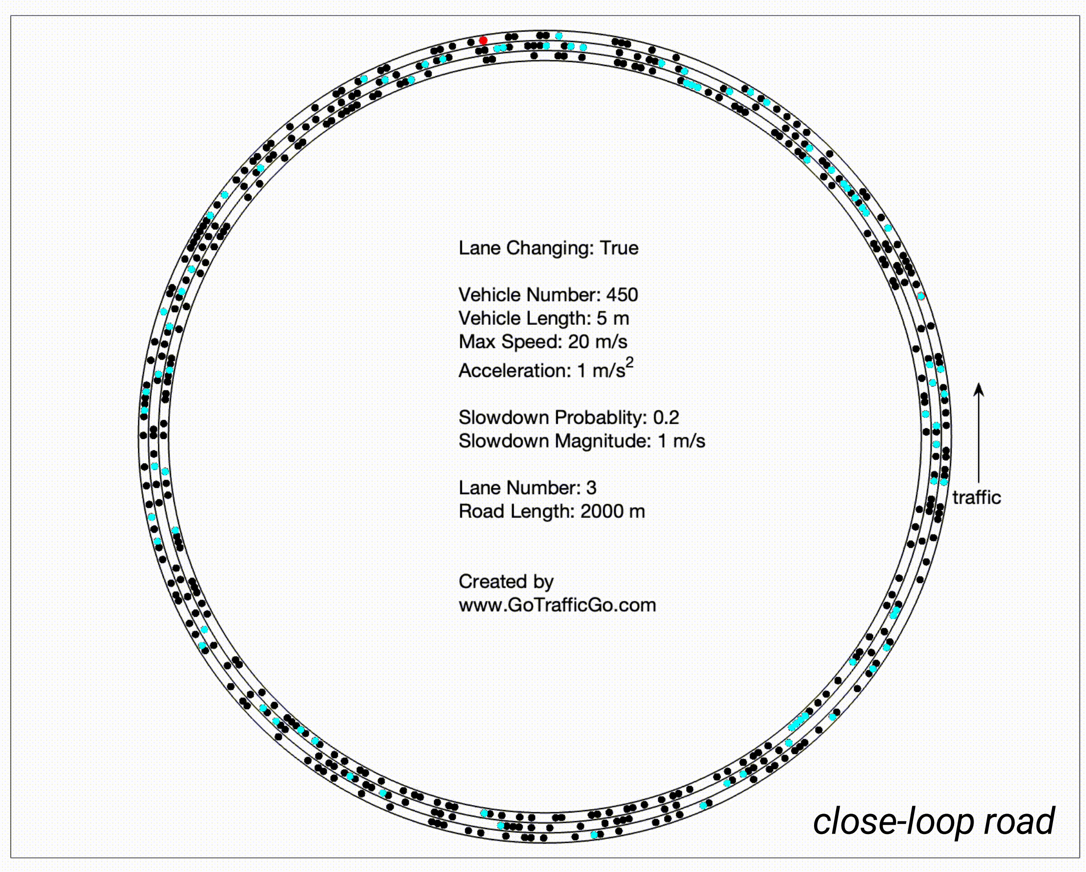
Free Flowing



Only difference: cell size = 1m (instead of 7.5m); a vehicle occupies 5 cells

Traffic Simulation

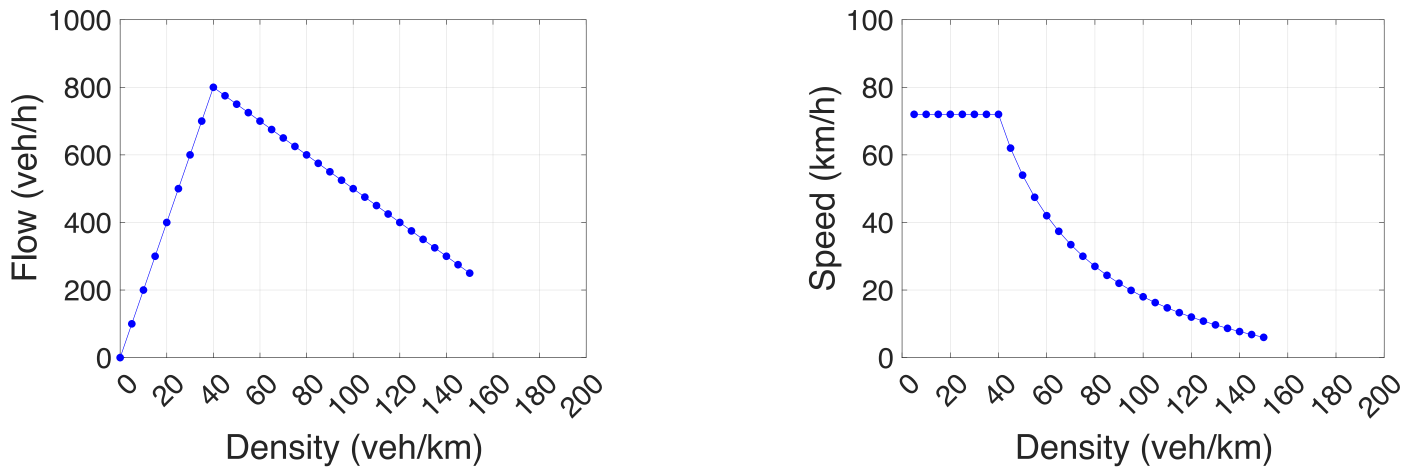
Congestion



Only difference: cell size = 1m (instead of 7.5m); a vehicle occupies 5 cells

Traffic Simulation

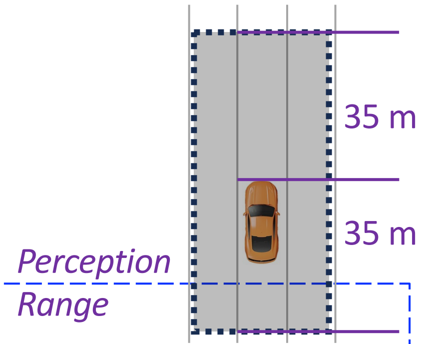
Fundamental Diagrams



Contagion of Speeding Behavior

Dividing Drivers into 3 Categories

- Aggressive: Always speed
- Neutral: Not speed initiatively, unless others speeding
- Timid: Never speed



Microscopic (Car-level) Mechanism

- **Stimulus**: one of the surrounding vehicles (j) moves faster than its max speed (v_i^*)

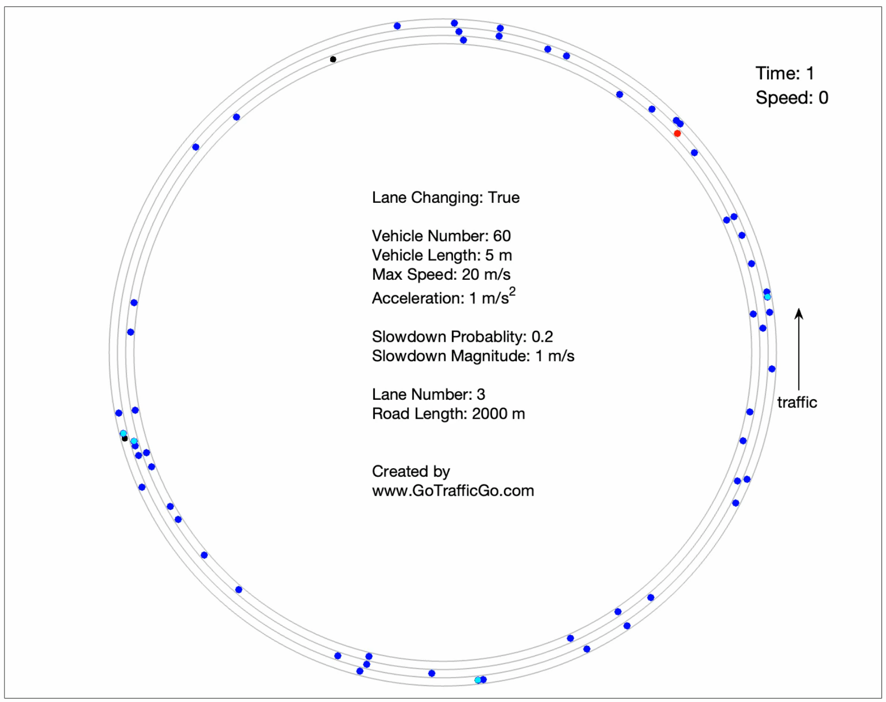
$$v_j > v_i^*$$

- **Response**: changing its max speed to the observed speed (v_j)

$$v_i^* = v_j$$

- **Duration**: maintaining the state for period τ (= 10 s)

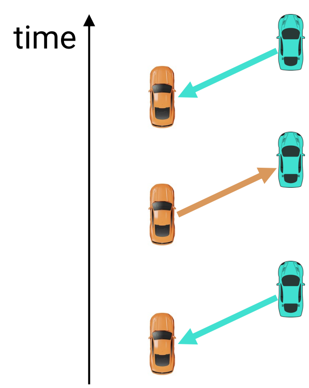
Contagion of Speeding Behavior



Aggressive 25m/s · Neutral 20m/s · Timid 20m/s · Lane changing · Speeding

Macroscopic (Road-level) Observation

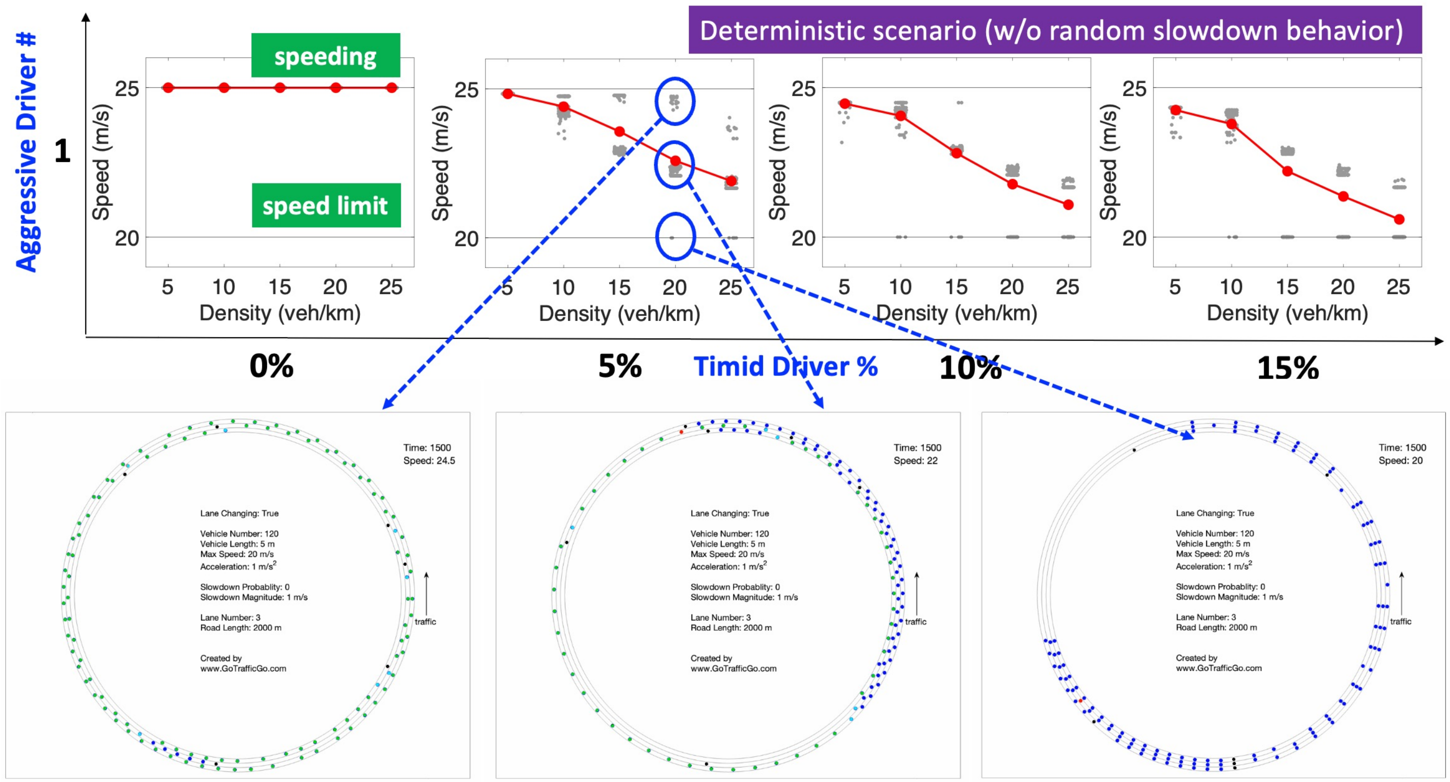
- Only 1 aggressive driver could result in collective behavior of speeding
- The collective behavior of speeding lasts forever



Emergence

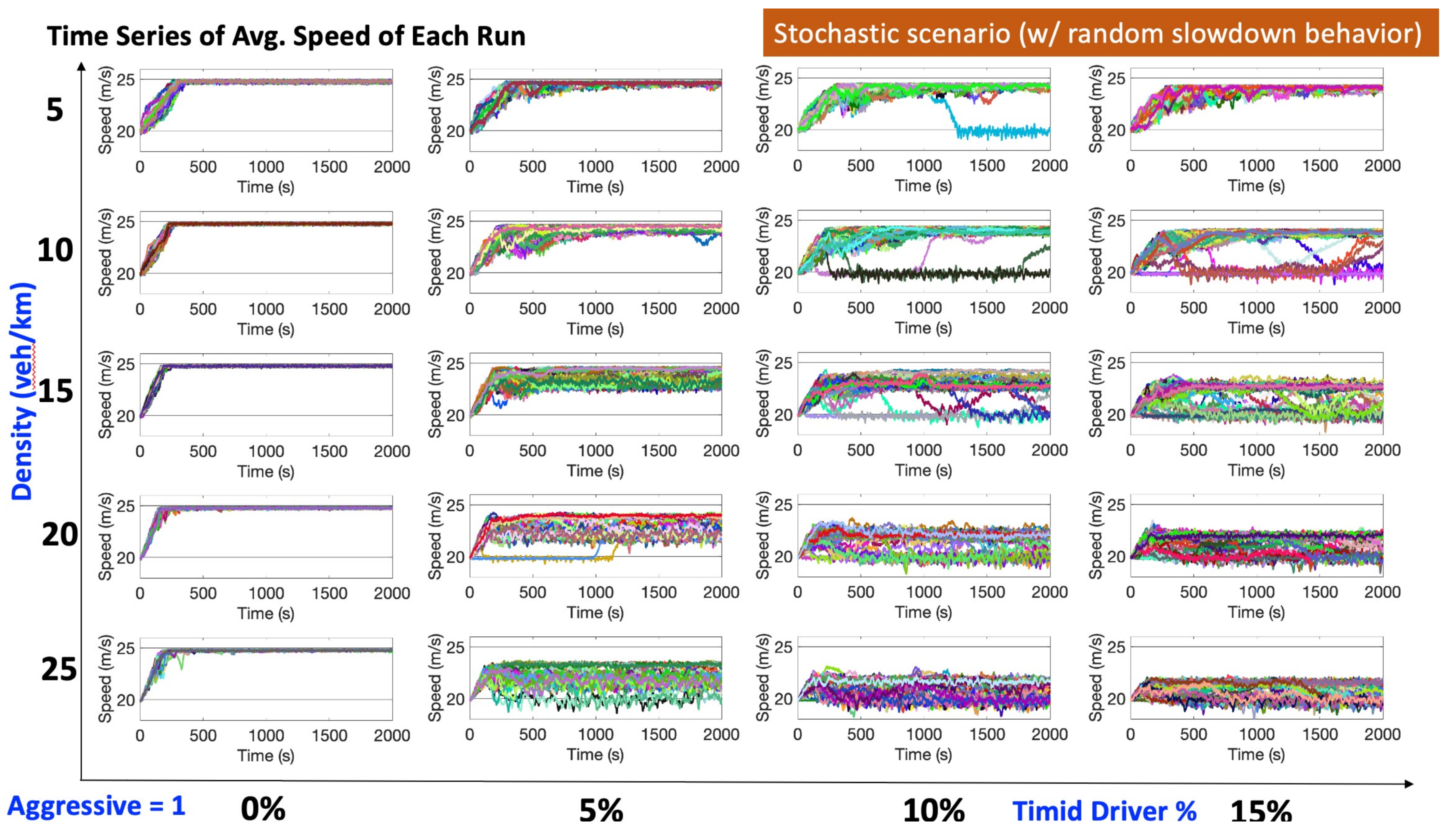
1+1>2

More Details



Completely passing "moving bottleneck" | Partially blocked by "moving bottleneck" | Completely blocked by "moving bottleneck"

More Details



Conclusion

- General and History
- Longitudinal Model
- Lateral Model
- Demonstration of Traffic Simulation