Highway traffic flow with parallel cellular automata

Computational Models for Complex Systems
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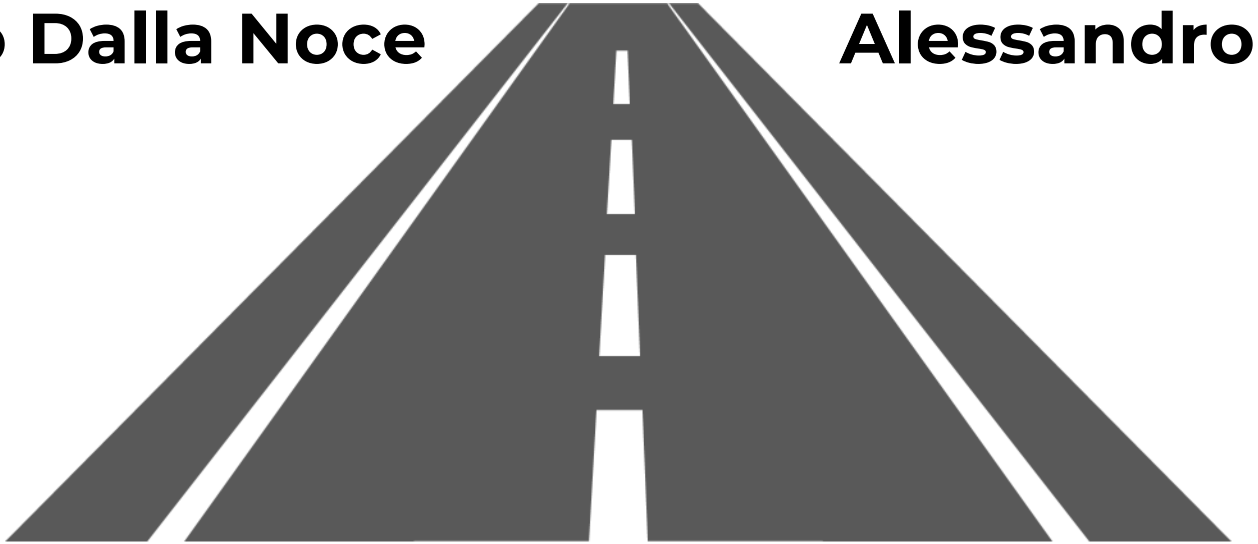


Presentation Roadmap

Traffic Automata

How to integrate cellular automata within a traffic context

Implementation

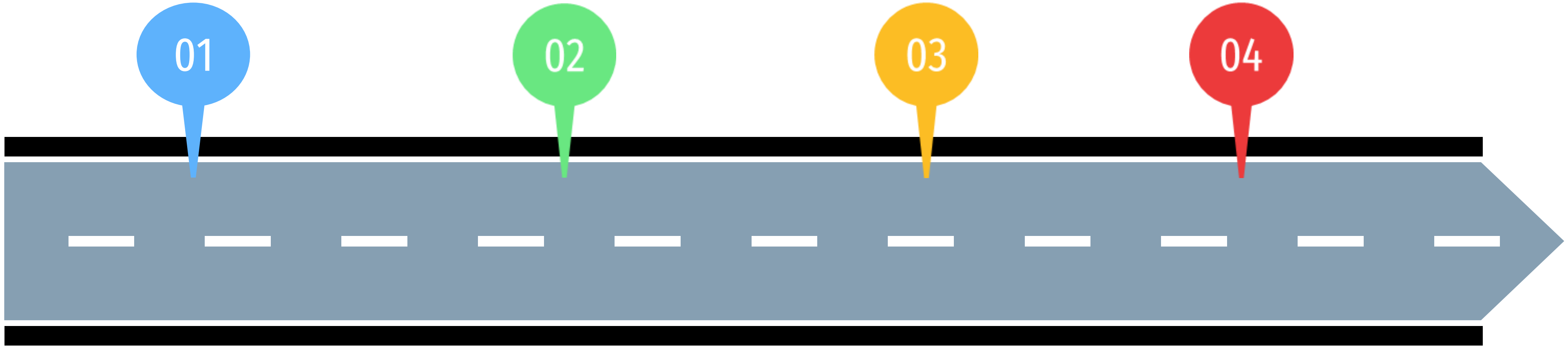
How the approach has been implemented

Results

How the system performed, with a case study under consideration

Demo

We will show three different scenarios

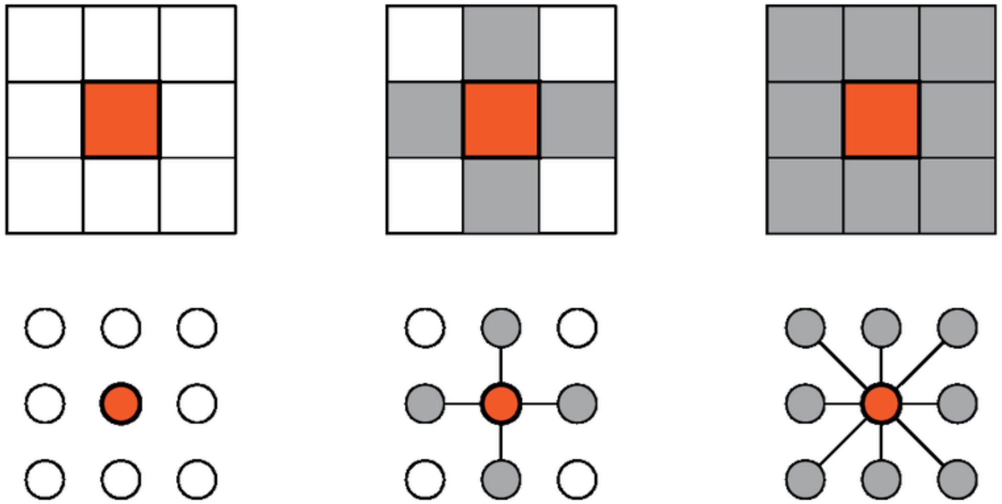


Traffic Automata

Cellular Automata, a quick introduction

Recall what the professor said during lesson:

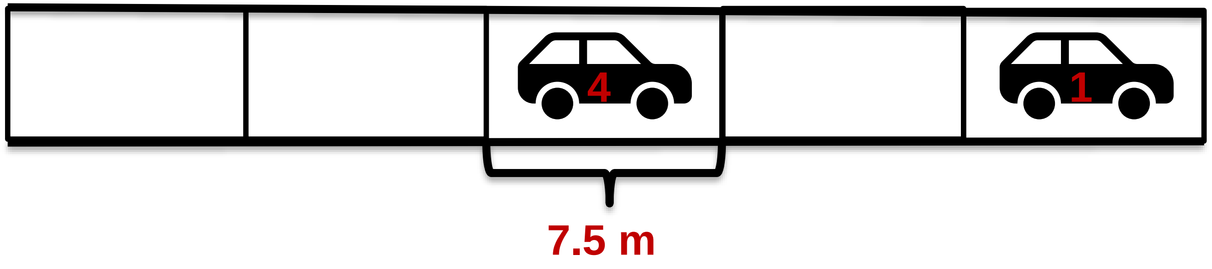
- Cellular Automata (CA) allows describing **1D, 2D or 3D environments**;
- The environment consists of a **matrix of cells**;
- Each cell has its **own state** that can evolve by means of **rules;**
- Each cell knows its **neighborhood.**



Cellular automata in highway traffic

We can implement cellular automata in a **highway traffic environment** by following simple rules:

- Each **cell corresponds to 7.5 meters** and it's occupied by only one vehicle;
- The interval between each **time step is 1 second**;
- The **vehicle's speed is an integer** that tells how many cells the **vehicle can move forward**;
- The cell neighborhood is **determined by the maximum allowed speed**;
- The **rules depends on the scenario** you want to implement (this will be seen in a few slides).



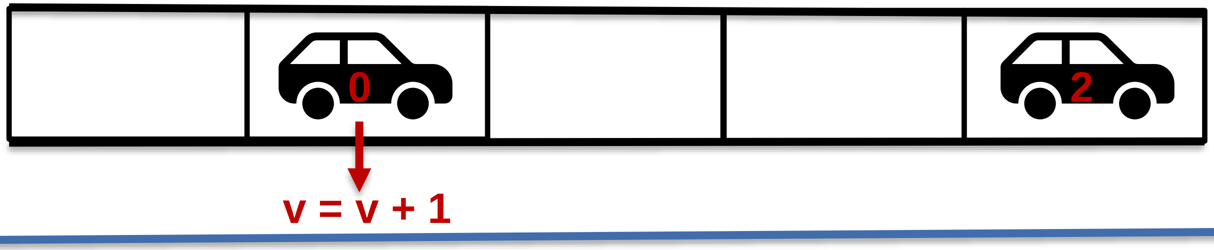
The **maximum allowed speed is 5**, which corresponds to

37.5 m/s = 135 km/h

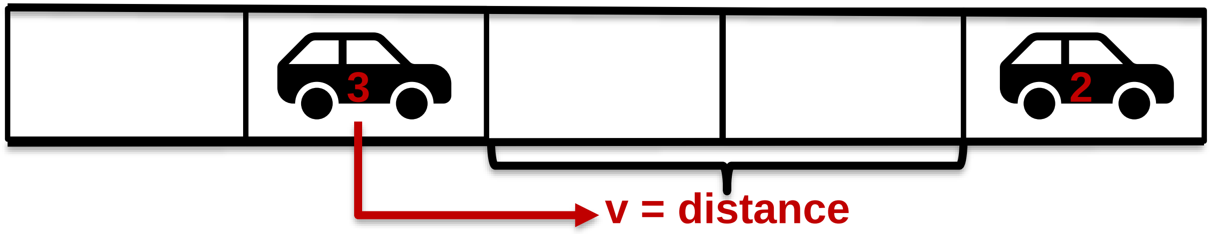
One lane traffic model

The **Nagel-Schreckenberg model** defines the rules for the speed update.

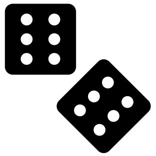
Acceleration: increase the vehicle's speed if the distance to cover is bigger than its actual speed, and it has not reached the maximum.



Deceleration (due to other cars): if the distance between the vehicle and the one that precedes it is lower than its speed, then set vehicle speed to such distance.



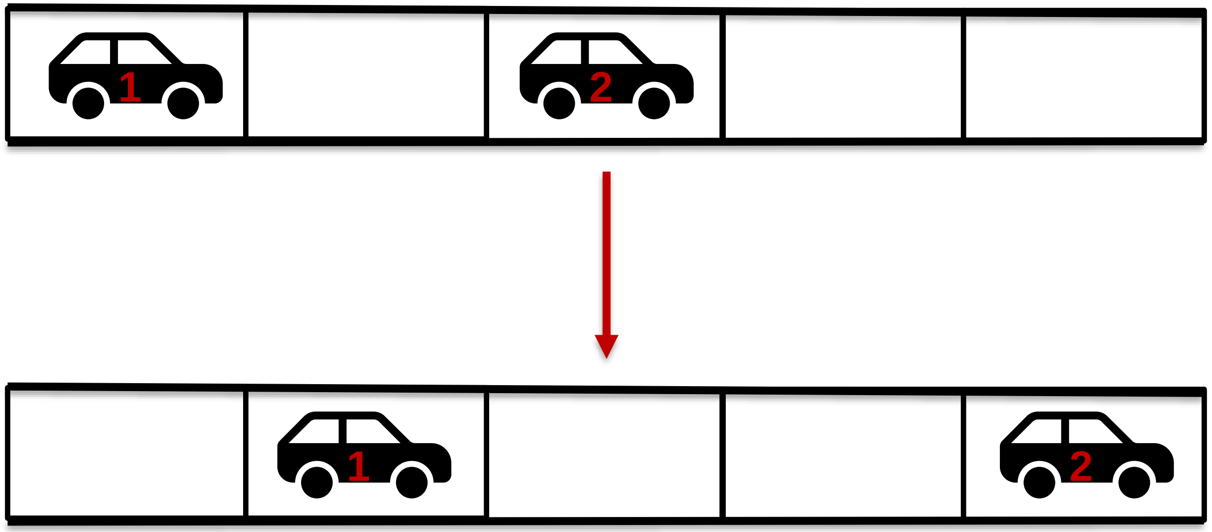
Random deceleration: if the vehicle's speed is higher than 0, than reduce its speed with probability *p*.



random(0, 1) <= *p* → **v = v - 1**

Move the cars

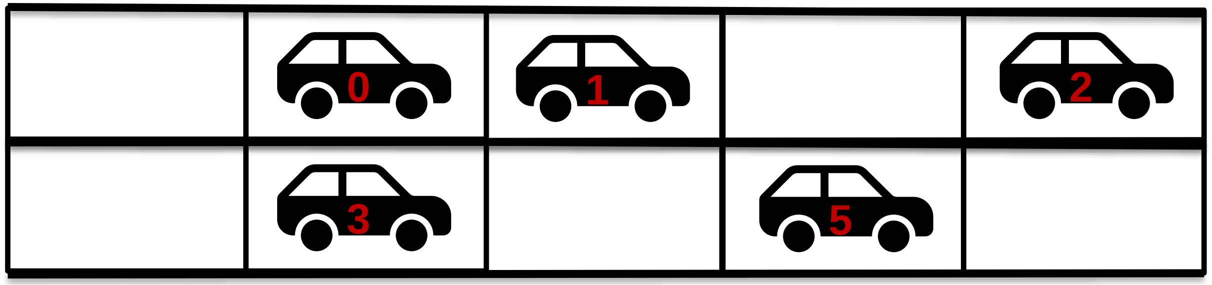
After the speed update, it's time to do the same with the road matrix. Each **vehicle "moves" forward** as many cells as its speed.



The **single lane model it's extremely easy**, what if we have more lanes?

Two (or more) lane traffic model

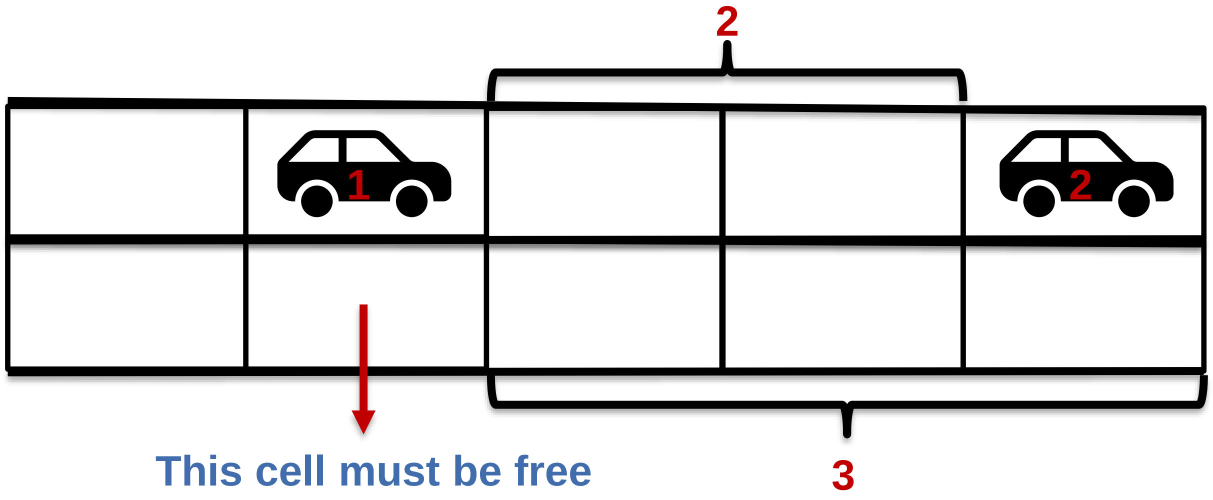
The **Nagel-Schreckenberg model was updated** in a following paper considering a **scenario in which vehicles can change lane**. It was proposed only for two-lanes roads, **we decided to extend it to more lanes**.



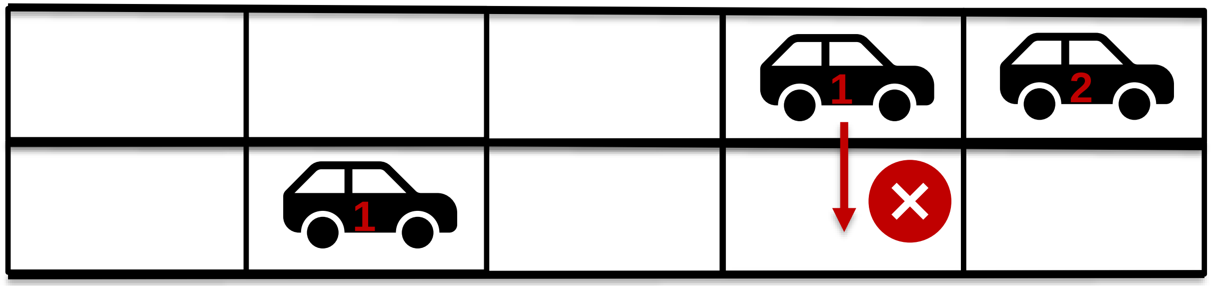
The **speed and road updates still hold** as before, then, when does a vehicle change lane?

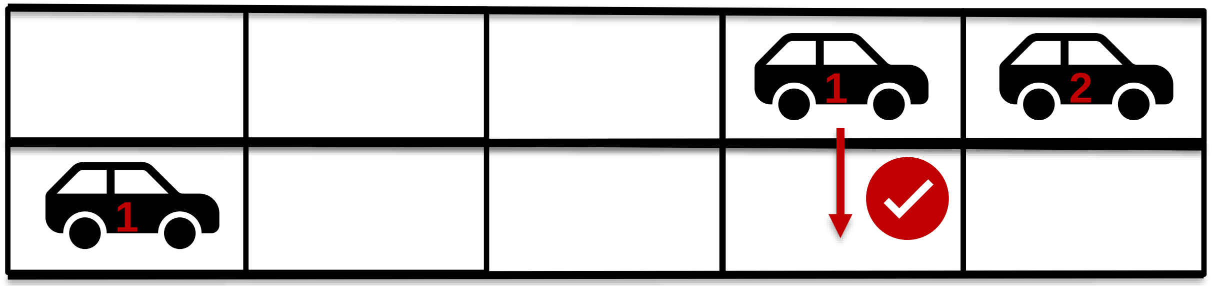
Rules for changing lane

Moving forward is convenient: the drivable distance in the other lane should be higher than the one in the current lane.

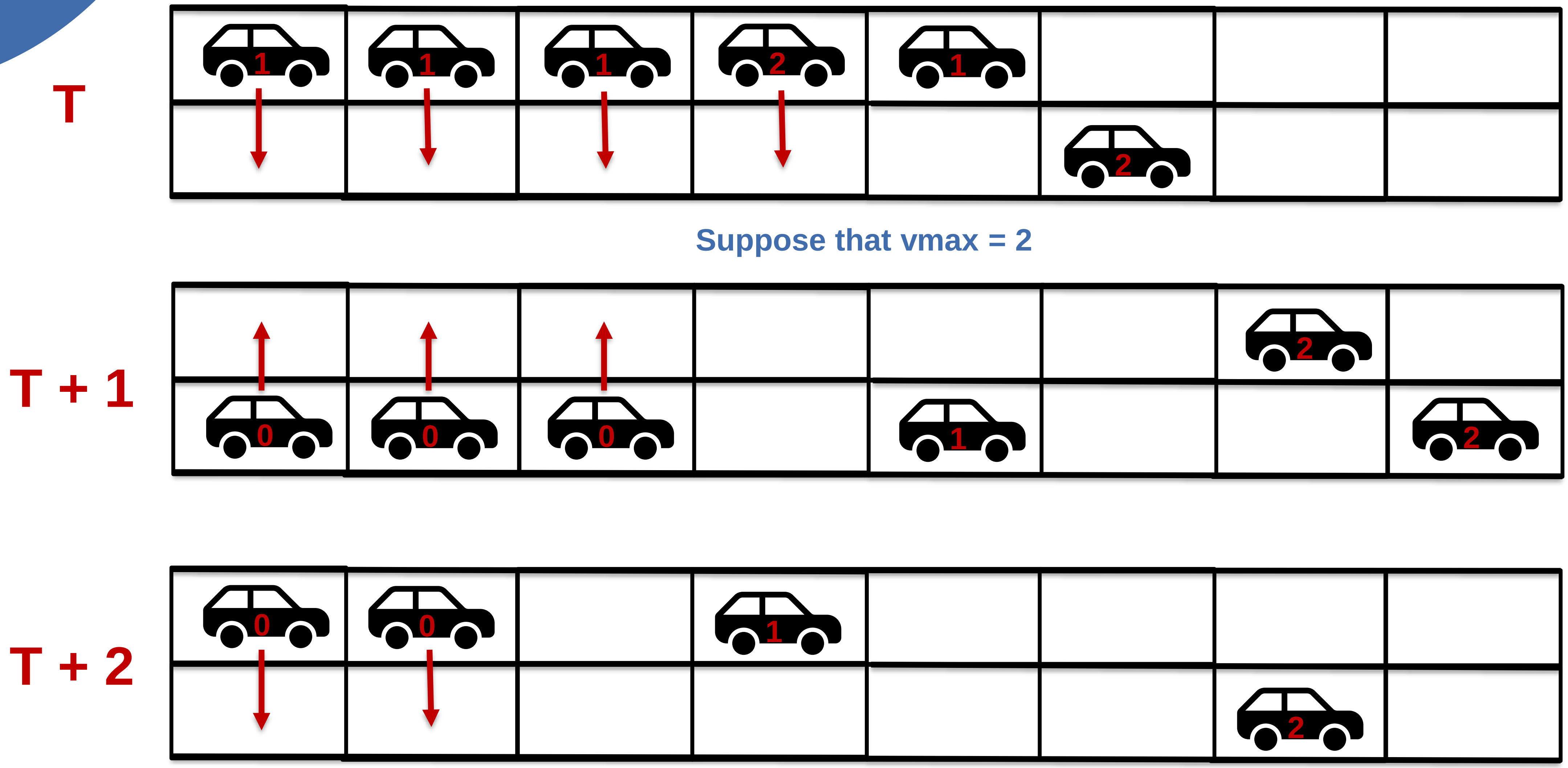


No vehicle is coming from behind in the other lane: the distance between the adjacent cell and the following vehicle is at least the maximum allowed speed, as an example let's suppose that the latter is 2.



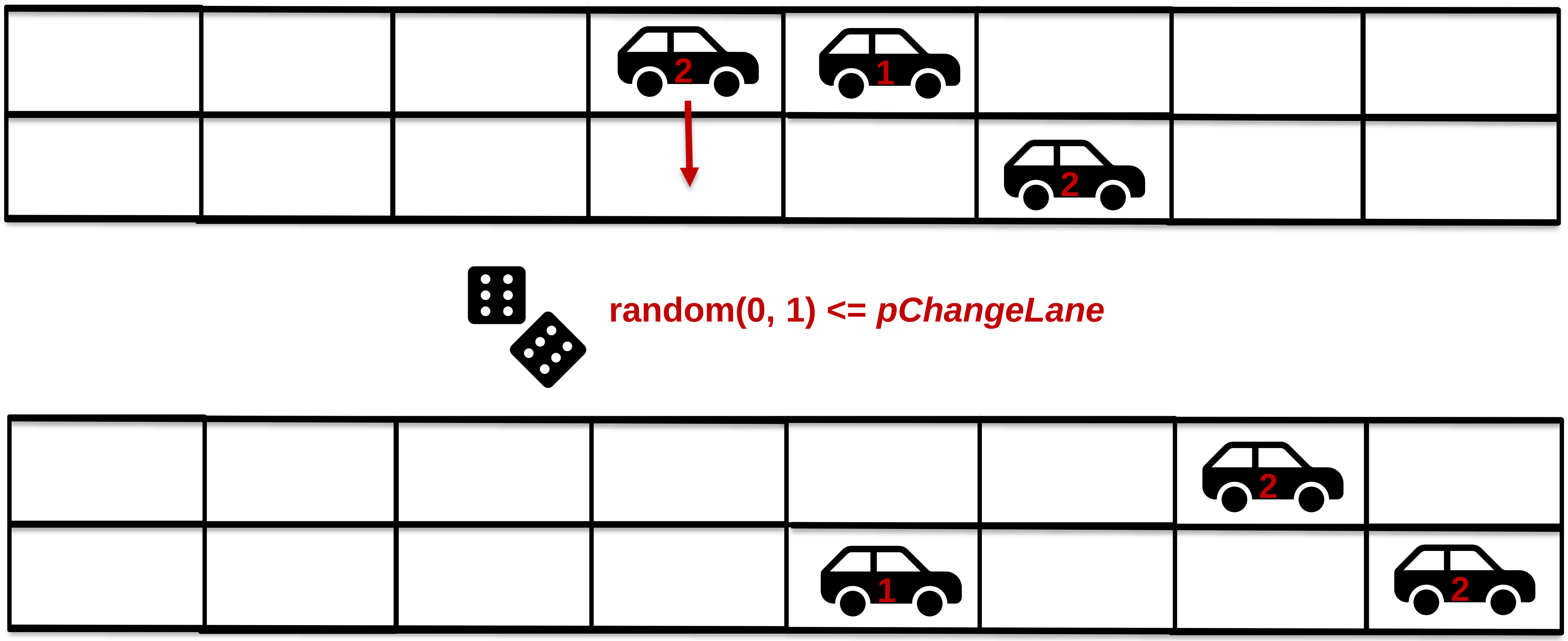


Issue: the ping pong movement



Solution: randomness

If a vehicle can move in the other lane, then change its position with probability *pChangeLane.*



Summary of traffic automata

Schedule and its rules

Change lane

- **Moving forward is convenient;**
- **No vehicle is coming from behind in the other lane;**
- **Move with probability pChangeLane**

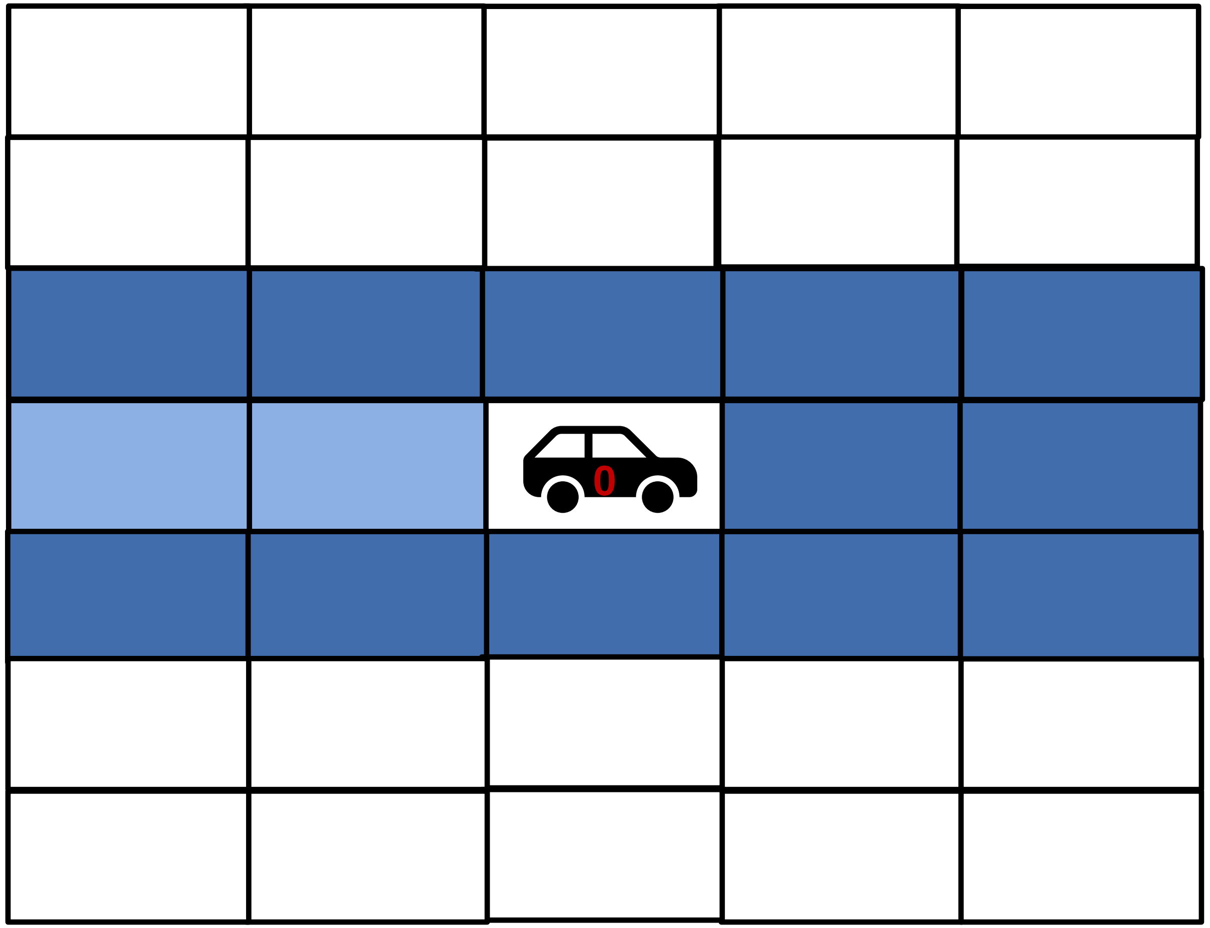
Update speeds

- **Acceleration;**
- **Deceleration (due to other cars);**
- **Random deceleration.**

Update road

- **Move cars.**

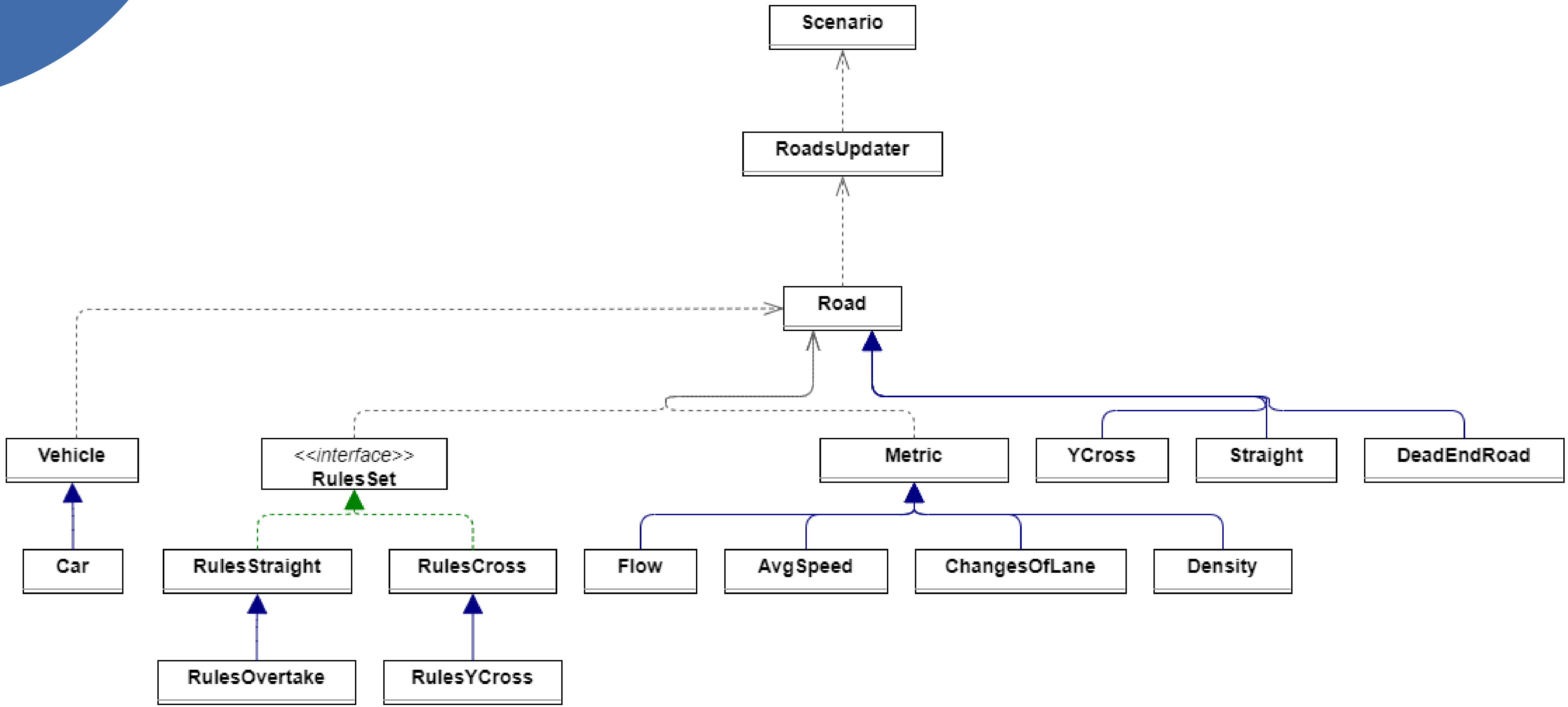
Neighborhood



Neighborhood with vmax = 2

Implementation

Class diagramm

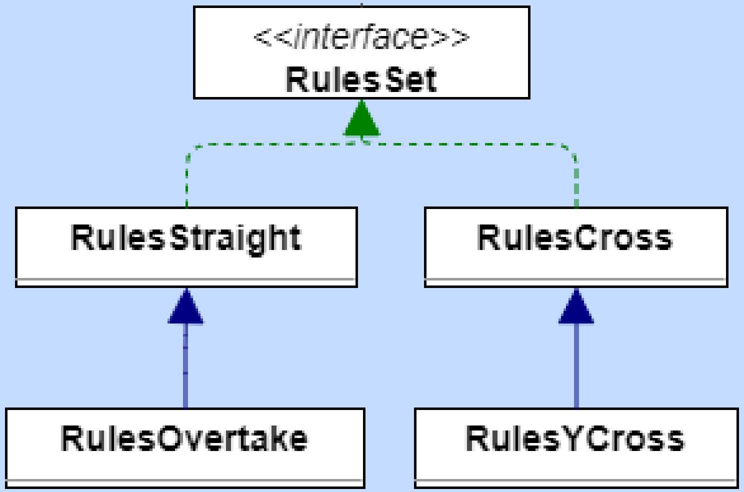


Rules

The **rules define how a vehicle moves** within a road:

- We implemented two different kinds of roads: **Straight** and **Ycross**;
- Each kind of road should implement its own rule set;
- Generally, a **rule set in a straight road defines the neighborhood** of a cellular automata.
- A **rule set of a cross defines how the vehicles move from an incoming road to an outgoing road**.

Road **Rule set**



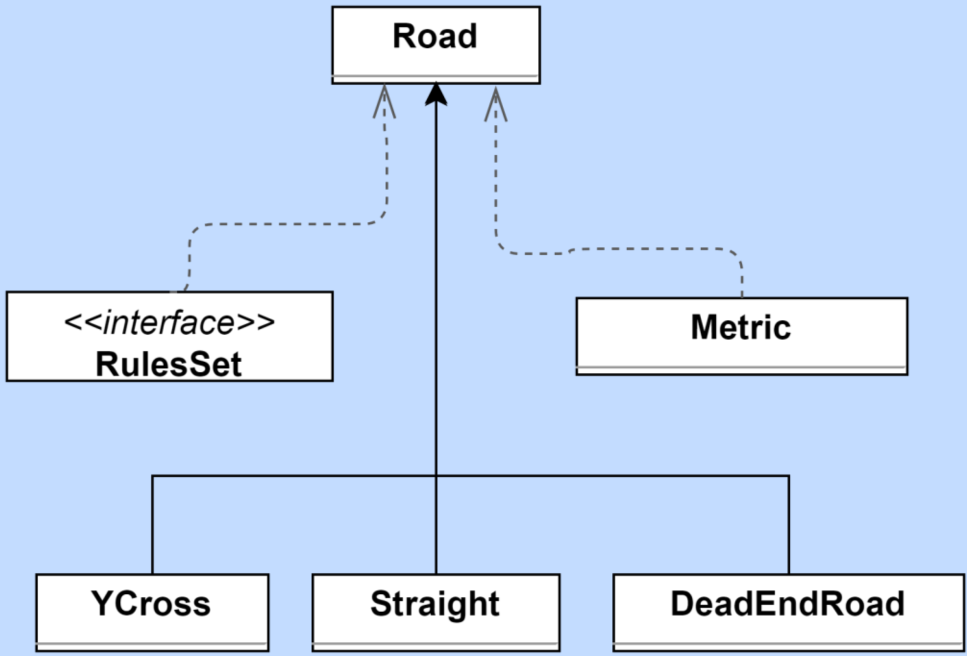
Rules: code snippets

```java
public class RulesOvertake extends RulesStraight {

   public RulesOvertake(double pDecreaseSpeed, int direction,
                        double pChangeLane) {
      super(pDecreaseSpeed, direction);
      this.pChangeLane = pChangeLane;
   }

@Override
public void apply(Straight road) {
   //Change lanes if possible
   if (road.nLanes()>1) {
      changeLane(road);
   }
   //Update the cars' speeds and the road state
   super.apply(road);
}
```

```java
public class RulesYCross extends RulesCross {
   @Override
   public void apply(YCross road) {
      Road outgoing = road.nextRoad();
      BlockingDeque<Vehicle> queue = road.vehiclesQueue();
      var accepted = true;
      while (accepted && queue.size()>0){
         accepted = outgoing.acceptVehicle(queue.element());
         if (accepted) queue.removeFirst();
      }
   }
}
```

Roads

- Any “concrete” new **road should extend the abstract class Road**. We did it for the **Ycross**, **Straight** and **DeadEndRoad** classes.
- The **DeadEndRoad** can be set as an outgoing road to indicate that a road has no next road.
- Optionally, a **Road can exploit some Metrics to monitor the behavior** of the vehicles inside of it.



Roads: code snippets

```java
public abstract class Road {
   public Road(Road outgoing, RulesSet rules) {
      this.outgoing = outgoing;
      this.rules = rules;
      this.roadId = seq;
      seq++;
   }

public void runStep() {
   rules.apply(this);
}
```

```java
public class Straight extends Road {

   public Straight(int lanes, int length, double density, int maxSpeed,
RulesSet<Straight> rules, Road outgoing, List<Metric<Straight, Double>> metrics) {
      super(outgoing, rules);
      this.lanes = lanes;
      this.length = length;
      this.density = density;
      this.maxSpeed = maxSpeed;
      initializeMetrics(metrics);
      buildRoad();
   }

   @Override
   public void computeMetrics(int step) {
      for (var metric : metrics.keySet()) {
         var ris = metric.compute(this, step);
         ris.ifPresent(aDouble -> metrics.get(metric).add(aDouble));
      }
   }
```

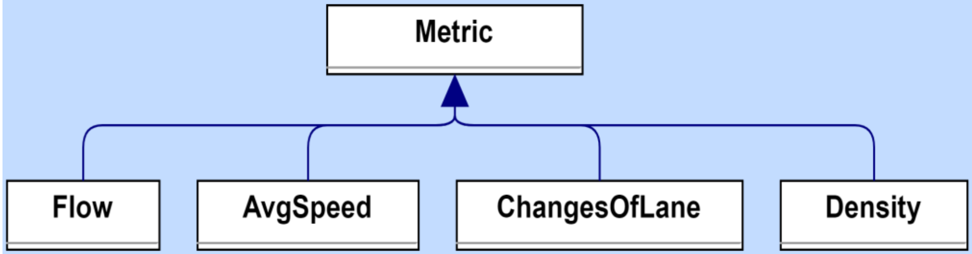
Roads: code snippets

```
public class YCross extends Road {

   private BlockingDeque<Vehicle> queue;
   private final int capacity;

   public YCross(int capacity, Road outgoing, RulesSet<YCross> rules) {
      super(outgoing, rules);
      this.capacity = capacity;
      this.queue = new LinkedBlockingDeque<>(capacity);
   }

@Override
public boolean acceptVehicle(Vehicle vehicle) {
   boolean acceptedVehicle = queue.offer(vehicle);
   if (acceptedVehicle) {
      vehicle.setSpeed(1);
   }
   return acceptedVehicle;
}
```

```
@Override
public void runStep() {
   var accepted = true;
   while (accepted && queue.size()>0){
      accepted = outgoing.acceptVehicle(queue.element());
      if (accepted) queue.removeFirst();
   }
}
```

Metrics

- It is possible to **create new metrics by simply extending the Metric class**.
- For our purposes, we implemented the **traffic flow metric**, the **average speed** of the vehicles, the total number of **lane changes** and the **density** of a Road.



Metrics: code snippets

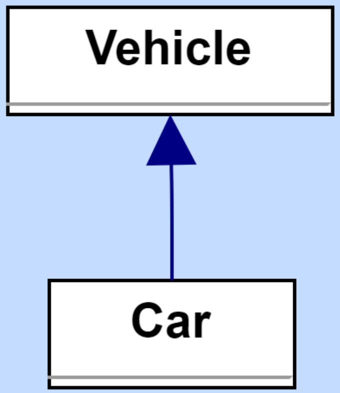
```java
public abstract class Metric<T extends Road, K extends Number> {
    protected int intervalOfRecording;

    protected Metric(int intervalOfRecording){
        this.intervalOfRecording = intervalOfRecording;
    }

    public Optional<K> compute(T road, int step){
        Optional<K> metric = Optional.empty();
        if (step % intervalOfRecording == 0){
            metric = Optional.of(getRecord(road));
        }
        return metric;
    }

    public abstract K getRecord(T road);
}
```

```java
public class AvgSpeed extends Metric<Straight, Double> {

    public AvgSpeed(int intervalOfRecording) {
        super(intervalOfRecording);
    }
    @Override
    public Double getRecord(Straight road) {
        return road.averageSpeed();
    }
}
```

```java
public class Density extends Metric<Straight, Double> {
    public Density(int intervalOfRecording) {
        super(intervalOfRecording);
    }
    @Override
    public Double getRecord(Straight road) {
        return road.density();
    }
}
```

Vehicles

- Every **Class** that **extends Vehicle** can be **placed inside** a **road**;
- It can be useful if there is the necessity to **simulate traffic** with vehicles that are larger than a car, for example **bus** or **trucks**.



Vehicles: code snippets

```
public abstract class Vehicle {
   private final int ID;
   private static int seq;
   private int speed;
   private final int size;

public Vehicle(int speed, int size) {
      this.ID = seq++;
      this.speed = speed;
      this.size = size;
   }

public int getSpeed() {
   return speed;
}
public void setSpeed(int speed) {
   this.speed = speed;
}
public int getSize() {
   return size;
}
```

```
public class Car extends Vehicle {

   public Car() {
      super(1,1);
   }

   public Car(int speed) {
      super(speed,1);
   }
}
```

Multithreading

Managing the concurrency: problems

- The **transfer of vehicles from one road to another is the most critical** operation;
- It could happen that a **thread managing a road allows a vehicle to move** towards the next road while **another thread updates the status** of that road.
- **Threads having less roads/vehicle to update could run faster than the others**, causing desynchronized updates at different time steps.

Managing the concurrency: solutions

- Every time a **thread updates** the **roads** assigned, it **reaches** a **barrier** and **waits** for the **other threads** to **join**.

```
public class RoadsUpdater implements Runnable{
   private final List<Road> roads;
   private static int seq;
   private final int ID;

   public void setFinished(boolean finished) {
      this.finished = finished;
   }

@Override
public void run() {
   while (!finished) {
      for (var road : roads) {
         road.runStep();
      }
      try {
         barrier.await();
      } catch (InterruptedException | BrokenBarrierException e) {
         throw new RuntimeException(e);
      }
   }
}
```

Managing the concurrency: solutions

- **Any straight should be followed by a cross**;
- **A thread updates a Cross and then a Straight**. It must follow this order.
- Also, following this "structural" rule, **we avoid some useless synchronizations between threads**.

```java
public class YCross extends Road {
/*some code*/
@Override
public boolean acceptVehicle(Vehicle vehicle) {
   boolean acceptedVehicle = queue.offer(vehicle);
   if (acceptedVehicle) {
      vehicle.setSpeed(1);
   }
   return acceptedVehicle;
}
}
```

```java
public class Straight extends Road {
/*some code*/
@Override
public boolean acceptVehicle(Vehicle vehicle) {
   List<Integer> freeLanes = new ArrayList<>();
   for (int i = 0; i < lanes; i++) {
      if (!road[i][0]) {
         freeLanes.add(i);
      }
   }
   if (freeLanes.size() > 0) {
      Collections.shuffle(freeLanes);
      int chosenLane = freeLanes.get(0);
      road[chosenLane][0] = true;
      vehiclePositions.put(vehicle, new Position(chosenLane, 0));
      return true;
   } else {
      return false;
   }
}
```

Putting all together: Scenario

The **Scenario** class lets the **program start** running.

- It **defines** the **time step**;
- **Assignes** the **roads** to the **threads** in the **order specified** before;
- **Updates** the **metrics**;
- **Defines** a **barrier**.

```java
public class Scenario {
    private List<Thread> threadUpdater;
    private CyclicBarrier barrier;
    private List<RoadsUpdater> roadsUpdaters;
    private int step;

    private boolean verbose;
    private List<Road> roads;

private void setup(int numOfWorkers) {
    this.roadsUpdaters = setupThreadsWorkload(numOfWorkers);
    this.barrier = new CyclicBarrier(numOfWorkers + 1, this::endOfAStep);
    this.threadUpdater = new ArrayList<>(numOfWorkers);

    for (var upd : roadsUpdaters) {
        roads.addAll(upd.getRoads());
        upd.setBarrier(barrier);
        Thread thr = new Thread(upd);
        threadUpdater.add(thr);
    }
}
```

Results

Metrics

Density: indicates the fullness of the road.

$$\frac{\#vehicles}{lanes \, * \, laneLength}$$

Average speed: average speed of all the vehicles inside the road.

$$\frac{\sum_{vehicle} vehicle(speed)}{\#vehicles}$$

Traffic flow: the product of the two previous metrics.

$$Density \, * \, Average\ speed = \frac{\sum_{vehicle} vehicle(speed)}{lanes \, * \, laneLength}$$

Lane changes

Average lane changes over **1000 steps**, with ***pChangeLane* = 0.5**, lanes of **length 50**, **maximum speed = 5** and **one loop road** (the vehicle re-enters at the start, so the density stays the same). The **values are averaged over 5 runs** for each configuration.

Lane changes		Densities			
		0.1	0.3	0.5	0.8
Lanes	2	0.198	0.118	0.018	0
	3	0.3638	0.236	0.047	0.004
	4	0.5896	0.3623	0.0662	0.006
	5	0.7734	0.4871	0.1017	0.0032

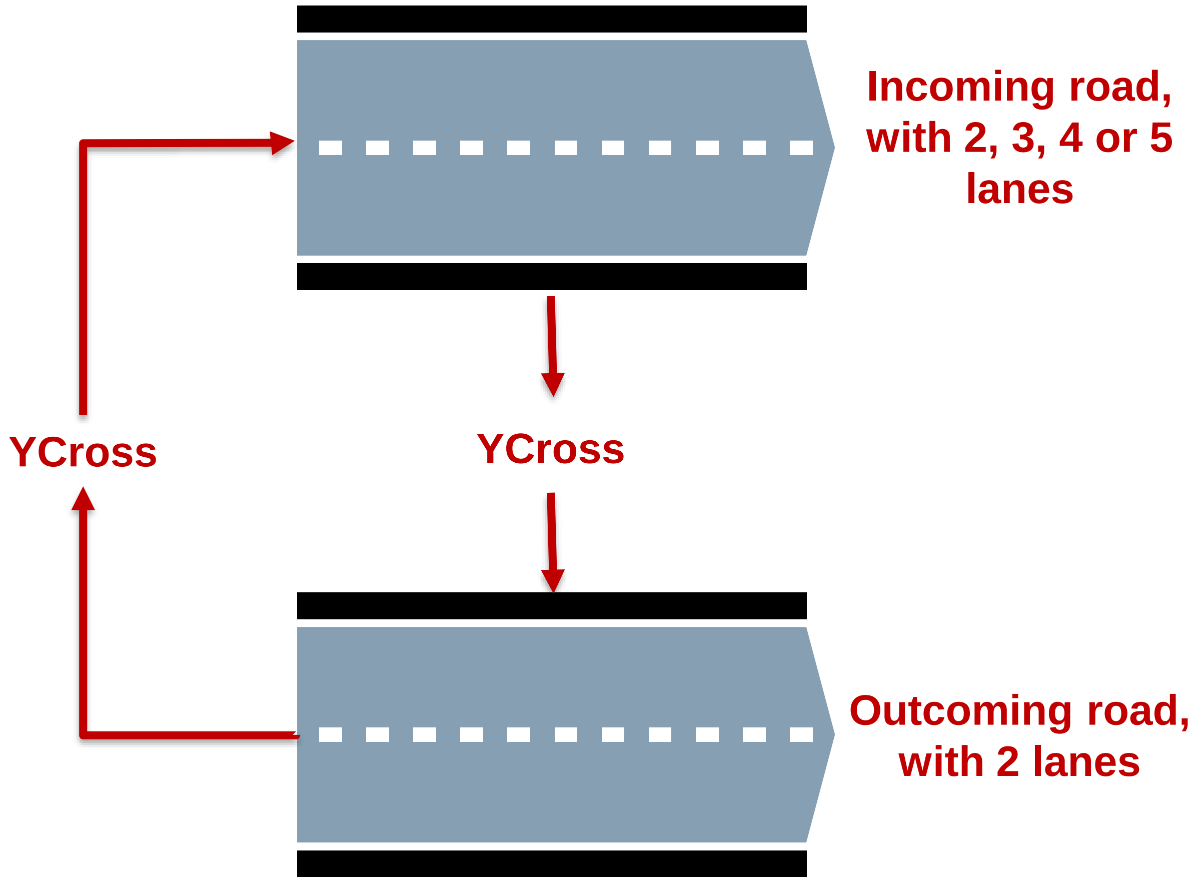
As expected, **more lanes and less density increase the number of lane changes**.

Case study: traffic bottleneck

What happens when the **incoming road has more lanes than the outcoming one**?

Traffic bottleneck: setup

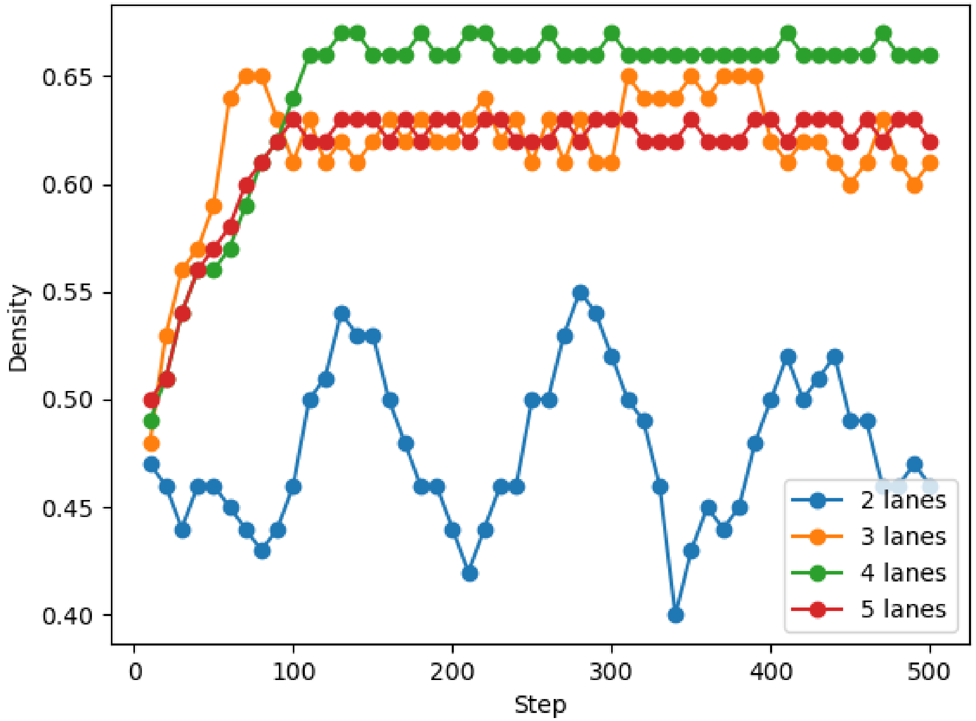
Scenario structure



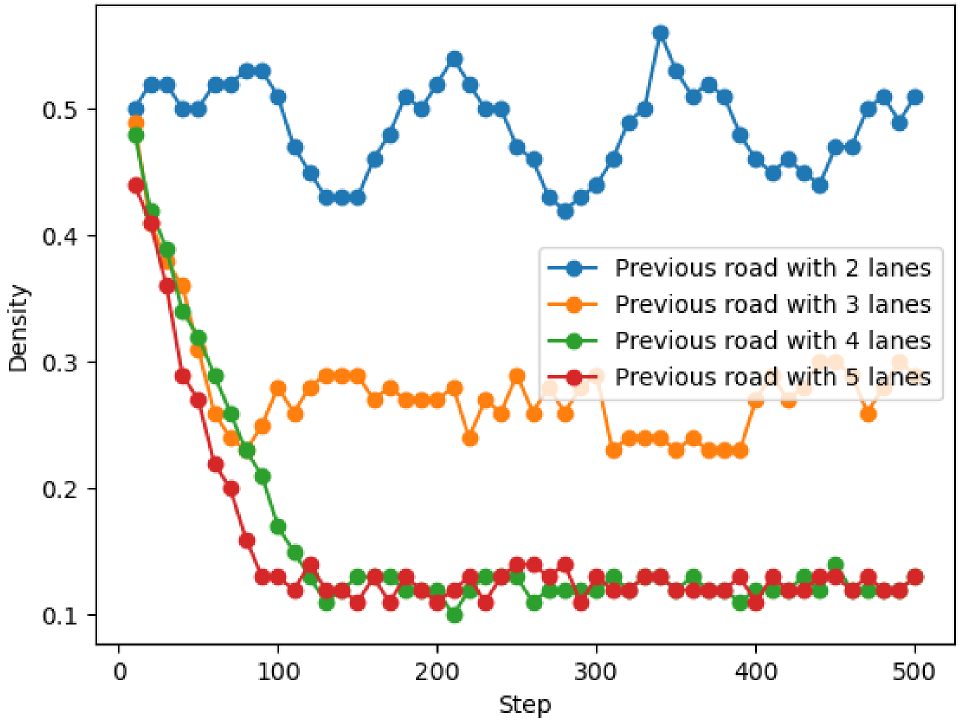
Parameters

- **Lane length** = 50;
- **Starting density** = 0.5;
- **Maximum speed** = 5;
- **pDecreaseSpeed** = 0.1;
- **pChangeLane** = 0.5.

Traffic bottleneck: density



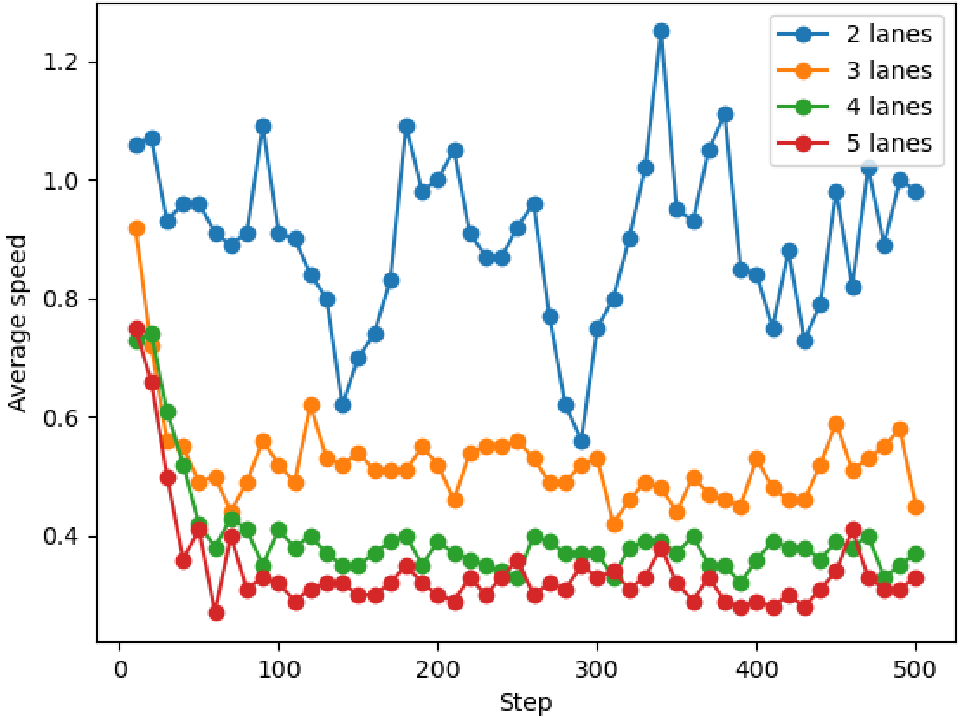
Density for the incoming road



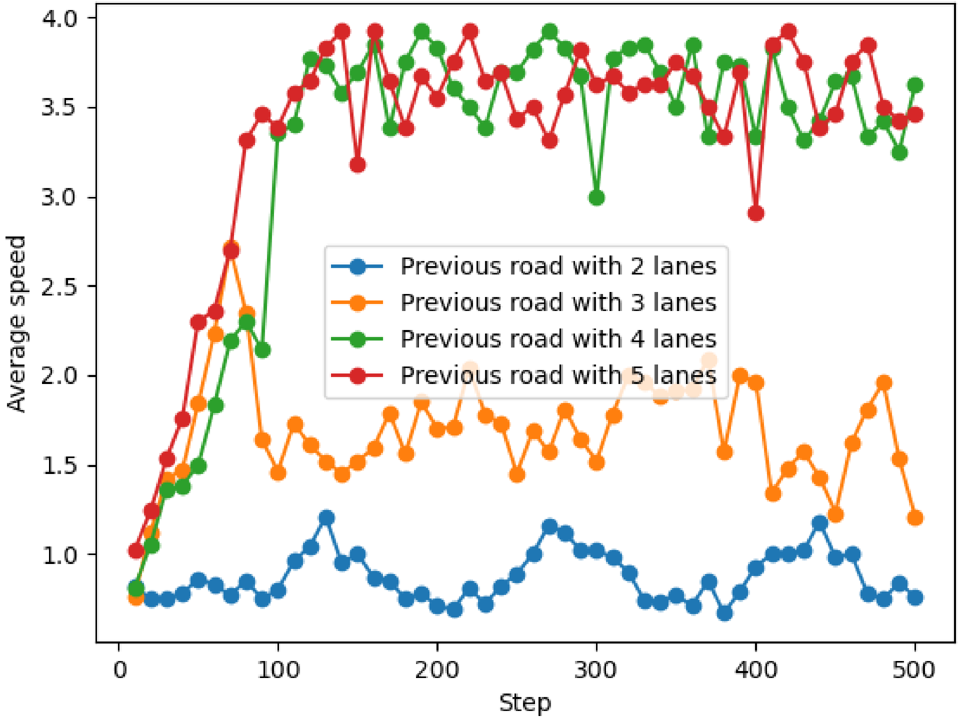
Density for the outcoming road

The **density for the incoming road increases** as the number of lanes grows, meanwhile **it drastically drops for the outcoming road**.

Traffic bottleneck: average speed



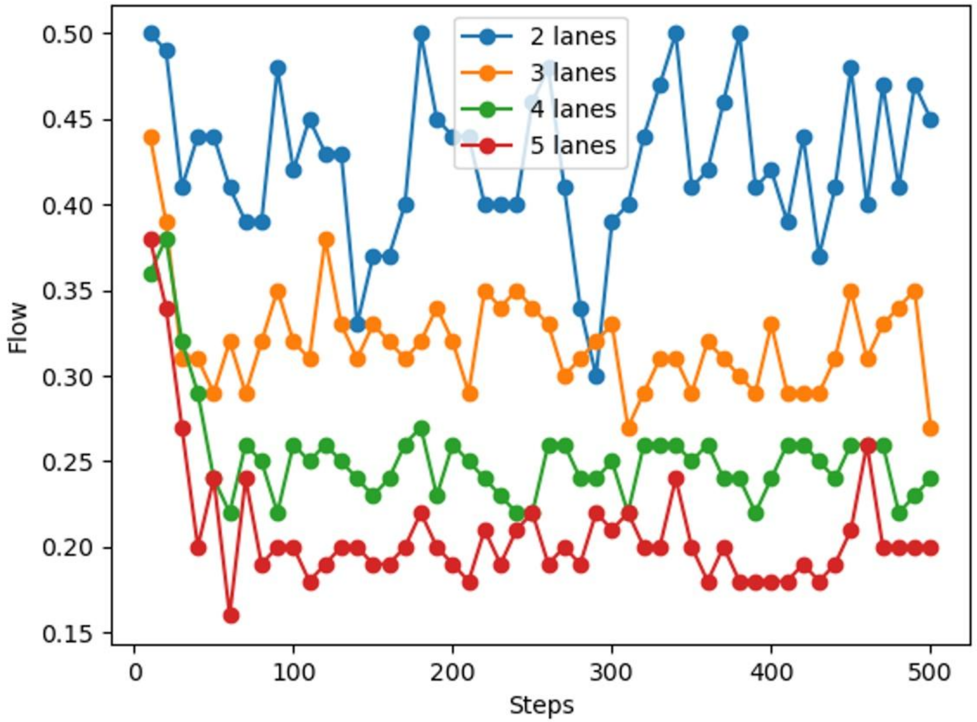
Average speed for the incoming road



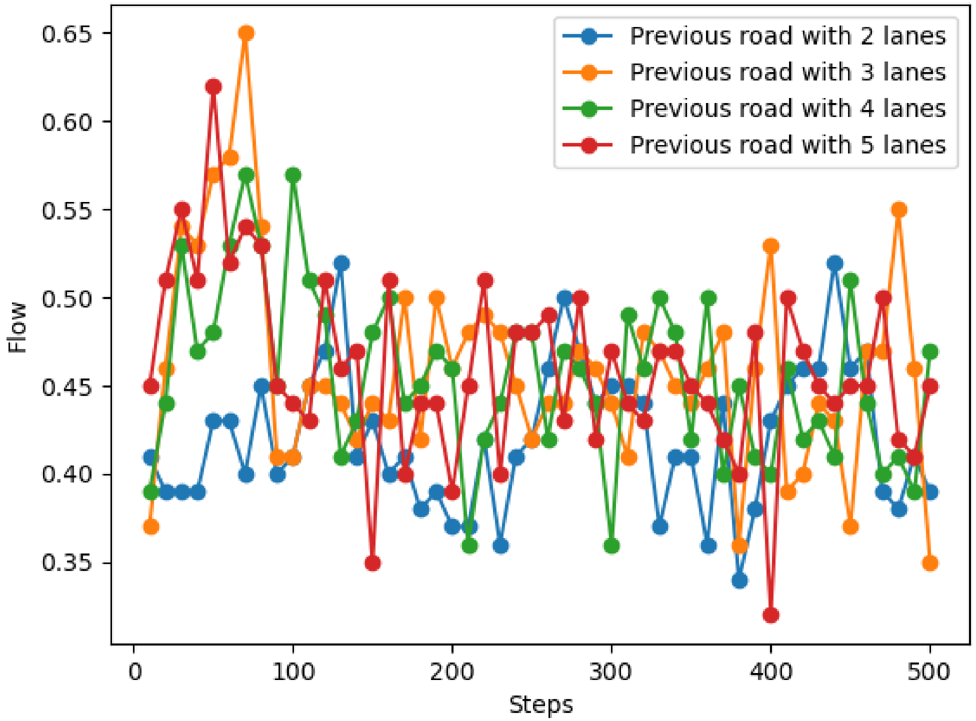
Average speed for the outcoming road

The **average speed for the incoming road decreases** as the number of lanes grows, meanwhile **it increases for the outcoming road**.

Traffic bottleneck: flow



Traffic flow for the incoming road



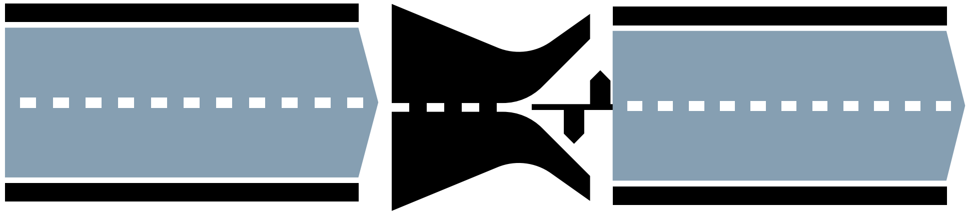
Traffic flow for the outcoming road

The **flow for the incoming road decreases** as the number of lanes grows, meanwhile **it stays somewhat the same for the outcoming road**.

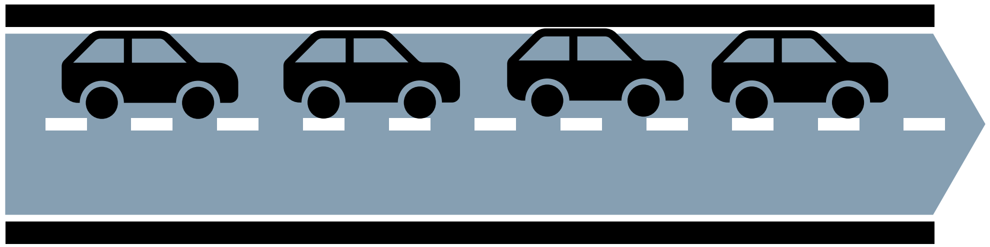
Demo

Three scenarios

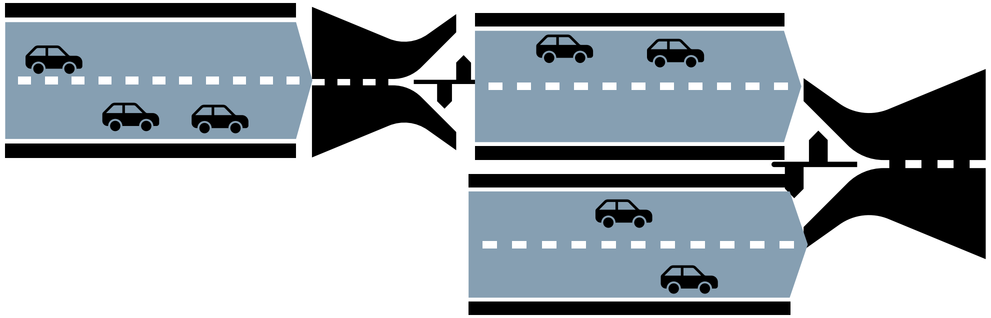
Overtake and road change: we will show an example of how to solve the issue of a vehicle changing road while there is an overtake in the outcoming road.



Ping pong movement: we will show how the ping pong movement works and when it happens.



Random scenario: at last, we will run a random scenario with an incoming road with more lanes than the outcoming one. Moreover, we will also show how two roads converge into one.



References

Nagel, K., & Schreckenberg, M. (1992). A cellular automaton model for freeway traffic. *Journal de physique I*, *2*(12), 2221-2229.

Rickert, M., Nagel, K., Schreckenberg, M., & Latour, A. (1996). Two lane traffic simulations using cellular automata. *Physica A: Statistical Mechanics and its Applications*, *231*(4), 534-550.

GitHub

https://github.com/nikodallanoce/TrafficAutomata