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Traffic flow with bicycle lanes and bike boxes: A cellular automaton

Class Report for
Complex Social Systems: Modeling Agents, Learning, and Games

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December 2022

Abstract

In this class report, we evaluate the influence of advanced stop lines (also called bike boxes) on urban traffic, using the established Nagel Schreckenberg model to simulate traffic. With this, we get quantitative results on the traffic flow and average speed which can be leveraged in the discussion of safe cycling in cities and city planning.

Agreement for free-download

We hereby agree to make our source code for this project freely available for download here. Furthermore, we assure that all source code is written by ourselves and is not violating any copyright restrictions.

- Louis Bettens
- Manuel Dublanc
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1 Introduction

Living in most European cities, where car traffic is still prioritized over safe bicycle traffic, makes one think about the possibilities in city planning to protect individuals on bikes. As research has shown, the implementation of bicycle lanes, to separate cyclists from motorized traffic has the biggest effect on safety and preference to use the bike [1, 2, 3]). In this report, we focus one further measure to increase the safety of cyclists especially at signaled intersections: the implementation of advanced stop lines (ASL) or so called bike boxes (American name).

These have been incorporated in multiple cities across the United States [4, 5] and Northern Europe like the Netherlands, Denmark and Great Britain [6], one of them being the city of Zürich [7]. Like the name would suggest, an advanced stop line in front of the traffic light, creates a special box for cyclists, such that they can stop in front of cars or busses when the signal is red. These boxes can be entered by the bike lane on the right side of the road. The aim of these ASLs is to increase the visibility and safety of cyclists by allowing them to cross the intersection in advance of other vehicles. Specifically, if a vehicle turns right, then it is harder to overlook cyclists. An example from Switzerland can be found in Figure 1.

Having a comprehensive understanding of how traffic safety can be insured in city infrastructure needs to be prioritized in city planning. As research has shown, countries with good cycling infrastructure support more trips done by bike [8] - and this has a major effect on personal health and the environment. Furthermore, improving safety for cycling infrastructure not only enables safe cycling overall, but has an even bigger effect on female cyclists, who explicitly state and show a preference for safe commuting [9], e.g. a large degree of separation from motorized traffic [10].

With this report, we aim to simulate a simple model of such a signaled intersection with bicycle lane and advanced stop line compared to an intersection of a shared road, to model the traffic flow for cars and bicycles. Furthermore, we explore the possibilities of cellular automata models used for traffic modelling and based on previous research done in this field, adapt the common Nagel Schreckenberg model to this specific case of bicycle lanes together with ASLs. By leveraging the results of the simulation, we manage to compare these two traffic concepts, based on parameters like average speed and traffic flow.
The aspect of how (at least perceived) safety can be ensured for cyclists has been studies in mulitple research papers [11], also with a focus on advanced stop lines [4, 5]. With this project, we hope to contribute to the thorough understanding of the influence of ASLs and the ways in which this influences traffic not only for aspects

of safety and potential crashes, but also for the traffic flow and the priority of cycling.

Figure 1: An example of an advanced stop line at a signaled intersection in Aarau
Source: self-taken

2 Related Work

The idea of using cellular automata for simulating real-life traffic flow and phenomena (traffic cellular automata - TCA) was first introduced by Nagel and Schreckenberg in their 1992 paper 'A cellular automaton model for freeway traffic' [12]. With this they took inspiration from statistical physics to model the microscopic behaviour of cars to reproduce macroscopic behaviour (e.g. the occurrence of spontaneous traffic jams). The idea is to model the overall behaviour of vehicles based on very simple rules for each vehicle. The great strength of a TCA model like that of Nagel and Schreckenberg is that they are very computationally efficient, whilst reproducing real-life traffic phenomena reasonably well [13].
In particular the Nagel Schreckenberg model (NaSchr model) is a one dimensional cellular automata (i.e. the vehicles travel only in one direction). Furthermore, due to the introduction of a stochastic term, it is not fully deterministic and allows for the emergence of spontaneous traffic jams. The four basic rules of the NaSchr model are the following:

1. **Acceleration**: If the velocity v of a vehicle is slower than its max velocity and the gap to the next vehicle is larger than $v+1$, its speed is updated to $v+1$

2. **Slowing down**: If the distance to the next vehicle is j and $j < v$, the vehicle's speed is updated to $j - 1$

3. **Randomization**: With given probability p (called the slow down probability) the vehicle decreases its velocity by 1

4. **Vehicle motion**: All vehicles are advanced v sites (according to their updated velocity of steps 1-3)

The steps 1-3 are evaluated for each vehicle separately before all locations are updated in parallel by step 4. It is due to the parallel updating, that the TCA is computationally efficient. Other models which have been in practice before the conception of this stochastic TCA, were entirely deterministic models, implying that the emergence of traffic jams is solely dependent on the initial conditions, see the original TCA by Wolfram from 1982 [14] or the so called car-following models [15].

As the NaSchr model only takes into account homogeneous vehicles (taking up one cell, i.e. a single-cell model) moving in one dimension, there has been further developments to account for heterogeneous vehicles (taking up multiple cells - multi-cell model - with different max speeds) from Helbing and Schreckenberg [16]. A deterministic model, developed around the same time as the NaSchr-model, was the first to introduce a 2-dimensional TCA [17]. That means, that the agents live on a lattice and move either from north to south or from west to east, generating intersections. This has been further developed to account for randomization effects, like the stochastic TCA of NaSchr on a lattice [18].

A further application of the NaSchr model which will be relevant for our approach, is the model for a road with a bicycle-lane by Vasic [19], where she applied a multi-cell model and introduced lateral interactions between cars and bikes to authentically model the traffic behaviour in a city. If cars and bikes share a road in the NaSchr model, we can expect the effect of platooning [20], where the speed of a vehicle with a slower max speed, creates a bulk of vehicles behind (in a model where overtaking is not possible).

3 Aims

After this brief introduction to Advanced Stop Lines and the Traffic Cellular Automata and their history, we state again our aims for this project. We hope to contribute to the application of Cellular Automata for traffic behaviour, by implementing a basic model which exhibits the basic interactions between cars and bicycles on a shared road with no bicycle lane. Furthermore, we want to incorporate a bicycle lane together with ASLs to have a more thorough understanding of how this might influence the traffic flow of cars and bicycles respectively.

As far as our research goes, the topic of modelling traffic with ASLs has not been explored in research yet, however we deem this necessary, as simulations of traffic flow are an important and recognized tool in decision making for urban traffic planning. Furthermore, increasing safety and visibility of bikes needs to be prioritized in city planning to make the bike more attractive [10].

4 Materials and Methods

We start off with the general assumptions imposed on our traffic model, before we describe in detail, the three TCAs - first off the model where cars and bikes share a common road and then the model with bike lanes and ASLs implemented.

4.1 General Assumptions

We implement the four basic rules of the Nagel Schreckenberg model as presented in Section 2, consisting of steps for acceleration, slowing down, randomization and vehicle motion, all updated in parallel. The traffic model is a 2 dimensional lattice with a total of 5×5 intersections and with size of 424×424 cells. Each cell is modelling a 3.5×3.5 metre strip of road. When with bike lanes our model consists of 24'540 road cells, without bike lanes there are 16'560. The lattice has open boundary conditions, to simulate real life traffic (it may be noted that more general claims about traffic flow can be made when looking at a closed system). See Figure 2 for the visualization of the empty lattice.

Vehicles move in one compass direction only (so not allowing for turns on intersections). Furthermore, we implement a heterogeneous version of the NaSchr model, with two different vehicle types: cars and bikes. They differ in their dimensions (the number of cells they take up on the street) and their maximum speed:

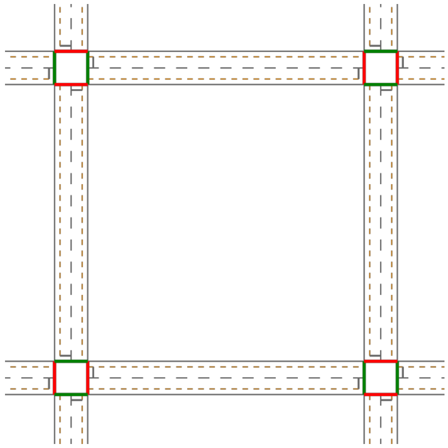
- **Cars**: occupancy of 2×2 cells with a max speed of 5 cells per time step
- **Bicycles**: occupancy of 1 single cell with a max speed of 3 cells per time step

Comparison to Real Life Traffic

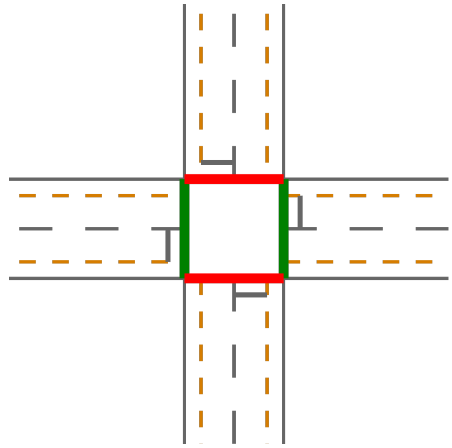
Setting one simulation step to equal 1 second, allows for scaling these settings to real life traffic: we have a maximum speed of $1s \cdot 5\frac{\text{cell}}{\text{s}} \cdot 3.5\frac{\text{m}}{\text{cell}} = 17.5\frac{\text{m}}{s} = 48.6\frac{\text{km}}{\text{h}}$ for

Figure 2

(a) Empty intersections with traffic lights



(b) Single intersection with bike lanes and ASLs



cars and about $29.2\frac{\text{km}}{\text{h}}$ for bikes. Having a time step of about 1 second resembles the reaction time of drivers and an occupancy of 7 metres for cars is close to the actual space a car occupies in a real life traffic jam [12]. This also makes one section between intersections about 175 metres when with bike lane.

Open Boundary Conditions

The open boundary conditions in the model are implemented as follows: each street spanning either from North to South or from West to East is assigned a probability of generating new agents at either end. This probability is fixed throughout the course of the simulation. Another parameter determines the ratio of cars to bikes which are generated throughout each time step of the simulation as a whole. Through parameter tuning, we can make this match the real life case as closely as desired.

Traffic Lights

Each intersection has traffic lights to have an ordered crossing. These traffic lights toggle their allowed direction after a fixed number of steps. Its state is represented by a Boolean value. If its value is 1, then traffic from East to West and vice versa is allowed to cross while agents in the vertical directions must wait. Otherwise when its value is 0, then traffic in the North-South direction can move. The state of the traffic lights are initialized in alternating order. See Figure 2a for a more detailed look on the signaled intersection.

Visualization

At last, the simulation is interactive with a few tuning parameters which can be scaled individually. These parameters include: the probability that a new agent is generated per street (0.3), the slow down probability for the third rule in NaSchr (see Section 2) (0.2), the length of the traffic light phase (20 time steps) and the ratio of new cars to new bikes (0.5). The baseline values are given in the parentheses. One slider allows to select whether the model includes bike lanes and/or ASLs.

4.2 Shared Roads

We start off with the baseline NaSchr model of a city road network for cars and bicycles which are supposed to share a road. This is for example the case for small lanes in cities, where the streets are narrow and don't allow for cars overtaking.

What becomes apparent when running the simulation, is that naturally the slower speed of the bikes acts as the limiting factor of the traffic flow, as cars will move in a bulk behind them, unable to overturn. With this, our natural assumption is, that the traffic flow and the achieved average velocity for cars and bikes respectively is least optimal. See Section 5 for statistics on our findings. Additional to this restricted traffic flow comes the diminished safety of bikes, as there is no separation from fast moving traffic.

4.3 Bicycle lanes

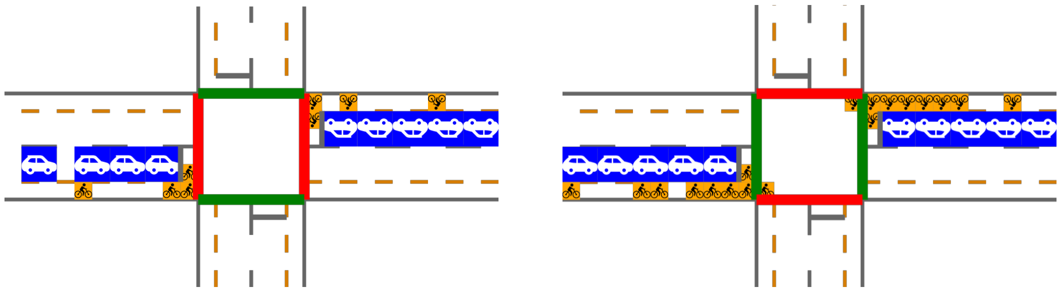
In a second phase we implemented bicycle lanes, as another lane next to the ones for cars, designated only for bicycles. This removes all interactions between bikes and cars. Cars can overtake bicycles in that sense without restriction and at the intersections there is no influence between the queue for cars and bikes.

Our expectation of the simulation runs of this configuration were that cars and bikes reach their maximum velocity respectively, because on the stretch between the intersections traffic can flow freely. Indeed this was the case, as will be presented in Section 5. The aspect of perceived safety increases, as now we have a separation between the vehicles. However, in the real-life case, the possible danger of right-turning vehicles overlooking bikes remains.

4.4 Advanced Stop Lines

In the last phase we finally added the Advanced Stop Lines (ASL). For this purpose, we have introduced three additional rules to our model.

Figure 3



(a) Filling up ASLs

(b) Emptying ASLs

1. Cars are not allowed to enter the ASL when the corresponding traffic light has turned red.

2. When a bicycle stands still in front of a red traffic light right behind another bicycle, it checks whether there is still an empty spot in the corresponding ASL. If there is one, it jumps to the empty spot. By doing so, the ASL is filled up one by one. An example of this transition is presented in Figure 3a.

3. When a bicycle is in an ASL and the traffic light turns green, the bicycles start to empty the ASL. First the left-most bicycle is allowed to move to the first cell on the intersection on the bike lane. As soon as this spot is empty again, the second bike enters this cell. After that, the ASL is empty and all cars and bikes can progress according to the rules of NaSchr. An example of this step is given in Figure 3b.

Our hypothesis for this third and final model with ASLs was, that traffic flow is again optimal for bikes, as they are still independent of cars. However, cars now have to wait a little longer at an intersection, until all bikes have left the ASL. Therefore, it is not an optimal scenario for cars. However, the deprioritization of speed for cars and the increased safety for bikes have to be weighed against each other. More detailed results can be found in Section 5.

4.5 Programming Framework

To realize our model we used a Python framework called Mesa. It provides an environment to run a model either directly in the browser with some visualization or in a Jupyter notebook. It allows for great flexibility when it comes to how to create a model. For example, Mesa contains a scheduler which stores a reference to all agents and calls their ‘step‘ function each round. So when the simulation runs in the browser, there is no need to worry on how to call our agents, gather all results and transfer the data to the browser.

5 Results

The main aspects, in which we compare these different configurations are average speed obtained by cars and bikes, the cell density and the traffic flow. We capture these statistics for each time point and for the complete overall system. They are calculated as follows (see [13] for details):

1. **Average speed**: calculated for cars and bikes respectively, we average over the current speed of the vehicles within the simulation.
2. **Cell density**: we take ratio of number of cells occupied at each time step against the total number of cells in the simulation.
3. **Traffic flow**: as traffic flow we denote the number of vehicles moving in the system and it is the product of average speed of all vehicles and cell density.

The plots generated over time will start at the time step 200, as after multiple runs we observed that this eliminates the 'burn-in' period. Like this vehicles are evenly distributed across the lattice and exhibit the stable patterns, we want to make claims about.

We keep most of our parameters (slow down probability 0.2, ratio of cars and bikes 0.5 and probability of creating a new agent 0.5) fixed for a general analysis as we lay our focus on the patterns we observe through the bike lanes and ASLs and not necessarily the emergence of spontaneous traffic jams etc. However, as we found from running the simulation, the length of the traffic light phase has an unintentional side effect, being that bikes tend to get a green wave if the traffic light length is set at 20 time steps. In order to eliminate this effect for our analysis, we vary the traffic light phase over multiple simulation runs in Section 5.1 and 5.2.
Furthermore, we examine the effect of the probability that new agents are generated with regards to flow and density in Section 5.3. As this parameter controls the open boundary conditions, we do a sensitivity analysis on the impact it has on our simulation.

5.1 Average speed comparison

The first aspect through which we want to gain an understanding of the effect of bike lanes and ASLs is the aspect of average speed. The statistics are gathered over the course of 80 simulation runs for each configuration (shared road, bike lanes, bike lanes and ASLs). As mentioned previously, we want to eliminate the effect of traffic light length and a possible green wave, therefore with each iteration we cycle through the traffic light length between 20 and 55 in time steps of length 5 (the length being constant throughout one iteration).

Running the simulation for a fixed traffic light length, gives a very stable pattern for the average speed of cars and bikes, with very little deviations throughout multiple runs. Therefore, the plots of Figure 4 generate meaningful insight into the patterns, irregardless of the specific length of the traffic light cycle. One can however still observe a wave pattern in all three plots, this is the effect of slowing down and waiting for the traffic light to turn green again.
In Figure 4a, we can clearly observe, what we already expected: on a shared road, where cars are not allowed to overturn bikes, the average speed obtained is almost the same for cars and bikes. The mean average speed in this system is 1.17 cells/step for cars and therefore only slightly higher as 1.15 cells/step for bikes.
If we compare this to Figure 4b and 4c, we can observe a clear difference in average speeds throughout the simulation runs. Moreover, the average speeds are clearly also higher than in the case of the shared road. Specifically we have a mean average speed of 2.02 against 1.73 cells/step in the case of bike lanes and 1.61 against 1.58 cells/step for the bike lanes and ASLs. This makes also clear, that the ASLs slow all vehicles down slightly, with an even bigger effect on cars. Furthermore, we notice a slight decline in average speed over the simulation run in Figure 4c, this might be because of congested roads.

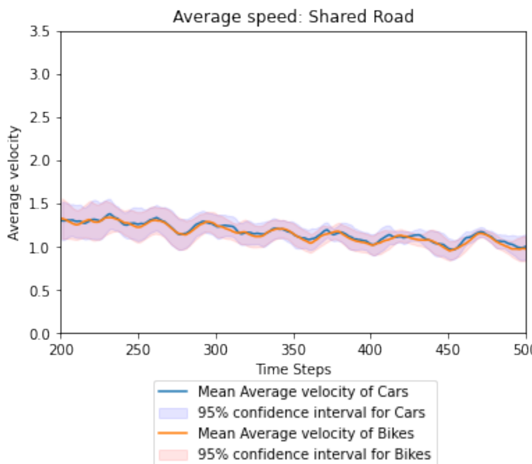
5.2 Traffic flow

Another important aspect, that was already visible in the analysis of average speed, is the achieved cell density and the resulting traffic flow. For the analysis of cell density it has to be noted, that in the case of bike lanes and ASLs, we have one more lane of cells present. This makes the plot of shared roads less comparable to the others, as we have a different underlying space. The plots in Figure 5 are based on the same iterations as the ones in Section 5.1.

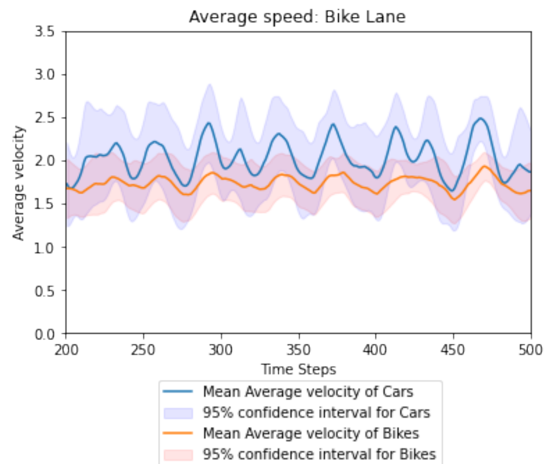
In the plot of Figure 5a we can still see that the system is not really free flowing, as the cell density is high and the average flow remains constant and the amplitude of the waves is not that high.
Looking at the plots in Figure 5b and 5c, we observe that the flow of the system is higher and also the wave's amplitudes are bigger. Again, the flow in the case of ASLs and bike lanes is slightly lower than in the case of just bike lanes. Furthermore, as

Figure 4: Average speed

(a) Shared



(b) Bike lane



(c) ASL & Bike Lane

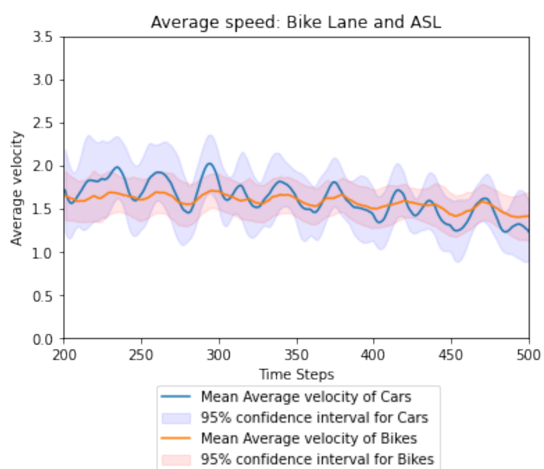
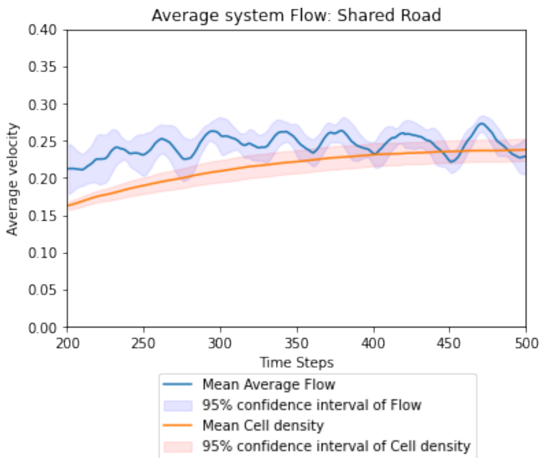
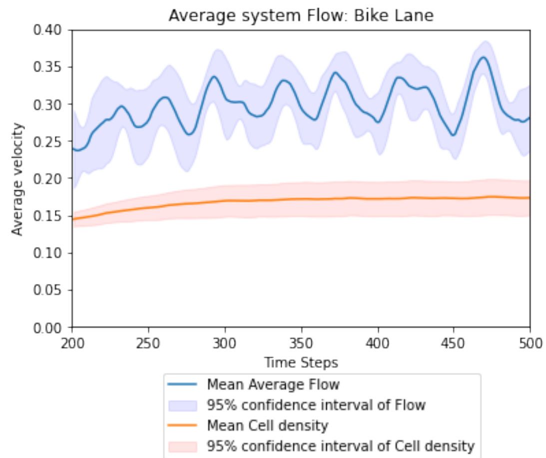


Figure 5: Average Flow and Cell occupancy

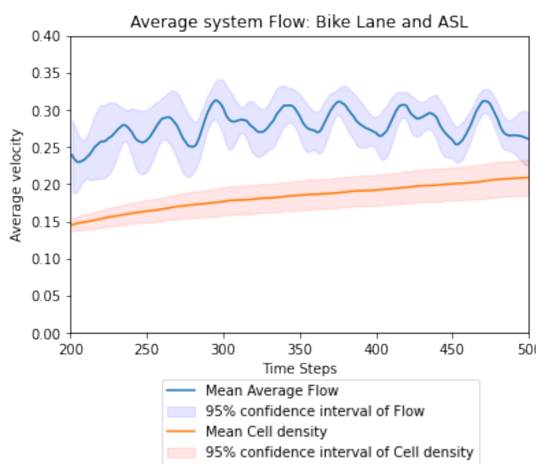
(a) Shared



(b) Bike lane



(c) ASL & Bike Lane



already noted in Section 5.1, we see an increase in the density in the case of ASLs, we assume this is because the system becomes more congested, as cars have to wait even longer at red lights and therefore are in a queue for longer.

5.3 Flow/density plots

We further compare the flow-density plots for various values (0.05 up to 1.00 in steps of 0.05) of the probability of new agents at each end a road per step. We run the model 50 times and calculated the average flow and density between steps 101 and 300. We observed that when the probability is small then there are fewer agents on the road. Hence, the density is smaller. When we increase the probability more agents are in the system and we observe a higher density. We can use this observation to make a statement about how much density the system can handle.

When we compare the red data points in Figure 6 for the system without bike lanes, we see that it reaches its maximum flow at a value of 0.24 agents per cell per time step for a capacity of 0.14 agents per cell when we run the model with the probability of new agents set to 0.4. When we add even more agents, the capacity further increases while the flow slightly declines.

For the configurations of bike lanes (blue) and of bike lanes together with ASLs (green) we observe a similar behaviour for small densities up to 0.12 agents per cell (see Figure 6). But when the density further increases, the model with bike lanes and ASLs reaches its total maximum flow of around 0.3 agents per cell per time step. The model without ASLs can handle even more traffic and attains its maximum flow at 0.34 agents per cell per time step. However, the settings of our model do not allow for densities higher than 0.25, therefore we didn't manage to observe any further convergences.

6 Discussion

The goal of our modelling process was, to get quantitative data on the implementation of bike lanes and ASLs in a city. We succeed at quantifying the influence this has on a simple traffic system with intersections. However, our model is based on the simplistic rules of the original Nagel Schreckenberg model and traffic behaviour within a city can be more intricate than a few simple rules. See for example the paper from Vasic [19] where lateral interactions between cars and bikes are introduced. Furthermore, we simplify our model in assuming that overtaking is not possible and there is no turning on intersections. These assumptions are far off the real-life case.

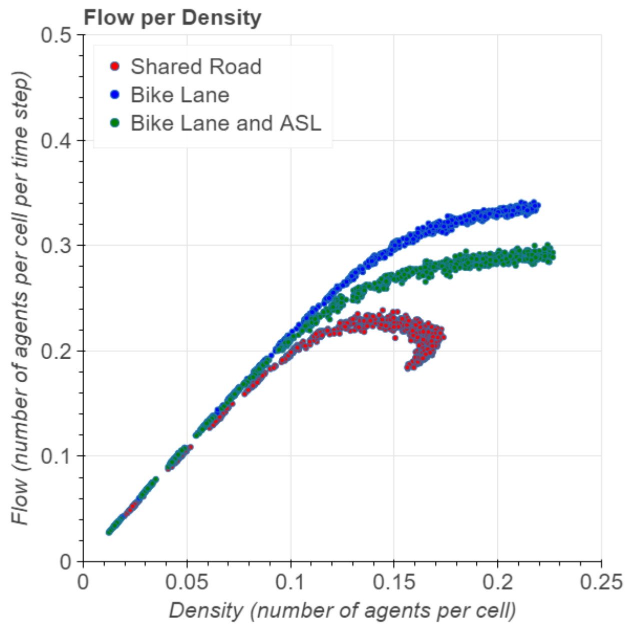


Figure 6: Flow-density plots

The idea of safety in these different configurations of city traffic is not a parameter which is incorporated in the model. However, we use results from literature to compare the safety aspects of the different configurations. One further step for our model could therefore be, to develop an inherent safety parameter (based on findings in research) in the model, to also get quantitative and comparable results based on this parameter.

The different models we present in this report show a first insight into the prioritization of bicycles in city traffic and the resulting influence on traffic. By comparing parameters like average speed, flow and density, we can observe, that the concept of a shared road is the worst case for traffic as a whole. The results for a traffic model with a bicycle lane shows that completely separated traffic results in the best case scenario, in terms of speed and flow, for cars and bikes respectively. Taking ASLs into account, we get a non-optimal state for cars (slower average speed) and an almost optimal state for bikes.

Regarding these results by itself, would suggest that for an optimal traffic system, bike lanes are the best choice. However, to change city traffic to be more bike oriented, we have to take the aspects of safety into account. And as research has shown, visibility and perceived safety for cyclists is increased if there is an ASL present [4, 5] (the reduced risk in accidents is hard to measure in real-life studies). Furthermore, in order to prioritize cyclists in cities, cities may take the next step to deprioritize cars in order to make cycling more attractive. The establishment of ASLs at signaled intersections, might help in exactly that: prioritizing the safety of cyclists and nudging people to use the bike.

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Contributions

We finalized the project in a group of three people. However, at the beginning we were four. So to make clear who worked on which part of the project we list the contributions of all team members.

Carolin Heinzler

- Report writing: all sections
- Literature review for ASLs (bike boxes)
- Generating statistics for average speed and flow
- Preparation of presentation slides

Louis Bettens

- Implement agents
- Implement traffic lights
- Implement data collection
- Document installation methods
- Preparation of presentation slides

Manuel Dublanc

- Implementation of traffic visualization in JavaScript
- Implementation of NaSchr rules
- Implementation of ASLs (bike boxes)
- Adding parameters to the model
- Generating flow-capacity plots
- Part of Report sections 4 and 5
- Photography

Leo Konzett (dropped out)

- Brainstorming of the potential project idea

ETH

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