

2D Traffic Jam Simulation

Group 1

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1 Introduction

Traffic jams are an inevitable part of road networks and individual transportation. It is therefore interesting to investigate the dynamics of traffic jams, effects of various conditions and possible optimizations of those conditions. Many models have been proposed to replicate the behavior of traffic jams and aid in the endeavor of understanding and avoiding them. The aim of this exploratory project will be to investigate some of these models. More precisely, a 1-lane (1-dimensional) model will be replicated as a starting point. Then, the model will be expanded to accommodate 2 or more lanes (2-dimensional). Experiments will be carried out on both versions of the model to identify interesting behaviours, observe the changes caused by different parameters and find possible weaknesses of the model. The experiments will also be used to verify that the 2-dimensional extension is true to its 1-dimensional original simulation.

[Section 2](#) will provide a description of the model to be implemented, as well as the methodology used to approach this task. Research questions will also be enumerated.

[Section 3](#) will further detail the setup of the model and the simulations run on it. It will also list the simplifications made for the sake of implementation.

[Section 4](#) will provide descriptions and observations related to the experiments that were ran, and it will also contain visualisations of the gathered results.

[Section 5](#) and [Section 6](#) together will elaborate on the possible future improvements and the conclusions that were reached during the course of the realisation of this project.

2 Model and methodology

As a starting point for this project, a model will be built to imitate the one used by T. Nagatani as described in [\[1\]](#). This means that a 1-dimensional cellular automaton traffic simulation will be created. As a result, cars will be simplified to cells (points on a plot), the motion of which can be calculated and visualised.

For a more detailed list of the assumptions and simplifications of the model, see [Subsection 3.1](#).

2.1 Research Questions

Since the aim is exploration, some research questions have been identified. They are:

1. What are some observations that the model produces and do they mirror real-life phenomena?
2. What parameters of the model produce the biggest changes in the traffic jams that are created?
3. What is the best way to replicate the findings in [1]?
4. How can a 1-lane model such as the one proposed in [1] be extended to two or multiple lanes?

3 Simulation setup

3.1 The model

A computer simulation will be used to simulate traffic jam formation and phenomena associated with it. The simulation will be written in Python and run on a 2020 desktop computer. Multiple simplifications are made in order to make the simulation run faster as well as simplify it, namely:

- The road is continuous instead of being made of one car-length cells
- The cars themselves do not have a length. They are represented as points only by their location and speed.
- The cars are updated one at a time instead of in parallel
- All cars have identical acceleration, max speed and other characteristics
- The road is looped around. If a car reaches the end, it is put back at the beginning, maintaining its current speed. This simulates new incoming traffic without the need to generate new cars and discard ones going out of scope.
- The cars do not have a memory. They decide their actions based entirely on the current state of the simulation.
- TODO think of more?

The entire simulation code will be published on [the students' GitHub](#). The code is clearly documented and available for use for verification of the results presented in this paper as well as drawing new conclusions. In order to ensure reproducibility, the random number generator is seeded with a constant. All simulations are defined by the parameters used to define some part of the behaviour of the cars. These constants are usually kept the same, while only changing one or two in order to observe how that parameter affects the traffic jams that are produced. The baseline of the constants are shown in [Listing 1](#) with one exception being acceleration for which 0.05 and 0.2 are used commonly. For the purpose of reproducibility, the parameters used for every simulation that is mentioned and shown in this report have been added in the appendix of this document, found in [Section 7](#).

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constants = {
    "initial_density": 0.15,
    "initial_velocity": 0.3,
    "max_velocity": 1.0,
    "acceleration": 0.05,
    "safety_distance": 7,
    "max_distance": 300,
    "pattern": "random",
    "max_time": 500.0,
    "time_step": 1.0,
    "deceleration": 0.1,
    "dimensions": 1,
    "lane_change_max_speed": 0.0,
    "lane_change_method": "space-based",
    "random_slowdown_probability": 0.0
}
```

Listing 1: The default parameters of the model.

3.2 The 1D CA model implementation

Initially it was decided to implement the model proposed in [1] and explore the effects of various parameters. To achieve this, an implementation of the simulation proposed in the paper was made in Python. One small change had to be made to the model. The deceleration had to be set to twice the acceleration constant. This would mimic real car performance since braking performance is usually better than acceleration. This change allows a wider range of acceleration values to be tested without the cars crashing into each other due to relatively small safety distance and maximum speed. To verify that the created simulation was accurate, two experiments were run with the same parameters as shown in [1] to compare the resulting visualizations. The progress of traffic is shown in the visualizations by displaying the position of each car through time, where each car is represented by a single line in the graph. As shown in [Figure 1](#), the simulation replicates the paper accurately. The wave-like propagation of the traffic jams is clearly seen in both simulations. Knowing this, the simulation can be used with varying inputs to explore their effect on the resulting phenomena like the propagation of the traffic jam. After extending the simulation to two

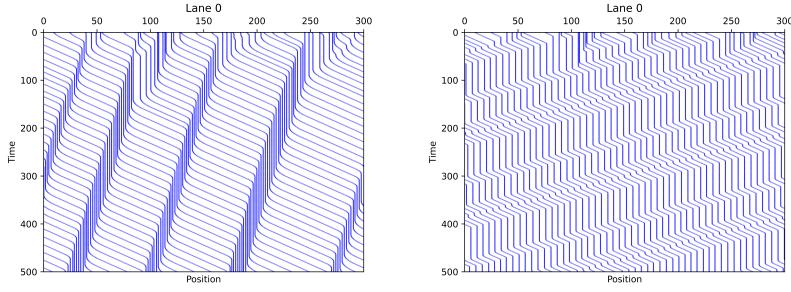


Figure 1: Simulation results with parameters identical to those in [1].

lanes, experiments with similar parameters can be run to ensure that the traffic behavior does not change drastically compared to one-lane traffic.

3.3 2D model extension

The next step in understanding traffic jams is attempting to simulate them for multi-lane roads. For this purpose, the model was extended to work with two lanes. Several changes were made in order to achieve this. These changes also required several parameters to be added to the constants the simulation is run on. Some alterations were also made which introduce new functionality unrelated to the two-lane extension. It would be fairly easy to extend the simulation to more than two lanes, but this is not implemented to keep the complexity down and to make the results readable.

The main component of extending the simulation was writing lane-switching strategies. The rest of the simulation could be reused almost exactly. After consideration, two possible lane-change strategies were conceived.

3.3.1 Space-based lane change

This strategy relies purely on checking whether there is enough space in the other lane. The cars are given the ability to look ahead and behind in the other lane. They are allowed to change lanes if the distance to the cars ahead and behind them in the other lane is more than the safety distance.

Under this strategy, the cars switch lanes when they're about to slow down in their own lane. There is a input parameter `lane_change_max_speed` which controls this behavior. The parameter represents the speed threshold which the cars will try not to go below, i.e. if the parameter is 0.1, the car will consider switching lanes if it is about to slow down to less than 0.1 speed.

3.3.2 Speed-based lane change

This strategy stems from real-life observations. In the students' experience, cars switch lanes in traffic jams if they think that the other lane is moving faster than their own lane. To implement this, cars use the ability to look for the car ahead and behind in the other lane. They evaluate the speed of the other lane as the average speed of those two cars. They then compare this to the expected speed of their own lane by taking into account whether they are able to speed up or slow down at the moment. They only switch if the speed of the other lane seems higher and if there is enough space (to avoid collisions).

These strategies are actually quite similar to each other. The initial plan was to make speed-based lane change disregard the distance to cars in the other lane, but it was quickly found that this causes crashes extremely often and therefore the distance check had to be added. This in turn made the strategies similar, as will be seen in [Section 4](#). Due to this fact, most experiments are not run with both strategies as the results are very similar.

After implementing these lane switching strategies, some other options were added to the original model. These include:

- Random slowdown - Each car has a probability of randomly slowing down drastically in each time step. If enabled, this introduces jam-generating slowdowns to the simulation. The slowdown is twice the deceleration constant, since otherwise the cars were able to ignore the slowdowns without any major effect on flow. A possible improvement on this is to introduce memory and make a car randomly slow down for multiple time steps in a row which would be closer to reality and more impactful.
- Initial car distribution patterns - The initial distribution can be set to be random, uniform, jammed or jammed-random. The first two options are exactly what their names suggest. The jammed option starts all the cars uniformly spaced half a safety distance apart. The jammed random option starts all the cars randomly positioned within a safety distance from each other. These various starting states can be used to examine different potential situations under various conditions. Lane distribution is always random. A future improvement could be to allow the lane distribution to be defined.

The improved simulation is able to model two-lane traffic. It is up to investigation if it is realistic and whether the two lane switching strategies produce accurate results. There are also some new parameters which can be investigated in order to make the simulation more realistic or be able to mimic more phenomena.

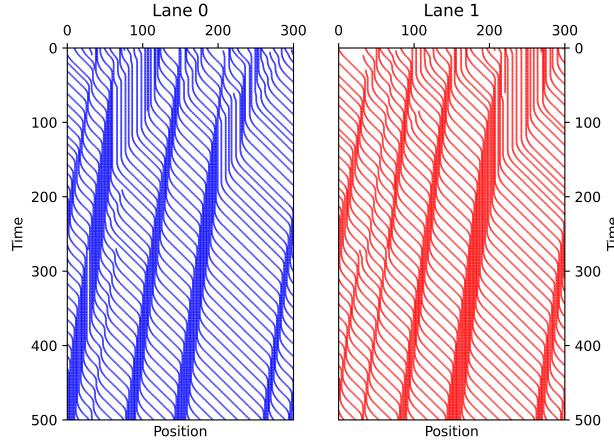


Figure 2: Space-based lane switching with parameters identical to Listing 1.

4 Results

4.1 Comparison with the 1D model

To compare the obtained simulation results with the base simulation from [1], the simulation was applied to the same constants as shown in the paper. The results should match the phenomena observed in order to verify that the lane-switching stays true to the nature of the simulation and can be regarded as accurate. In order to visualize multiple lanes, the visualisation was divided into a separate graph per lane and the lanes are given different colors. The results are shown in Figure 2 and Figure 3. It can be observed that these do in fact match the 1D version in the general traffic jam pattern. Some smaller new patterns can be observed which are induced by the lane-switching which will be addressed later in this section.

The simulation was also verified against the other set of parameters [1] provides, namely using Listing 1 and changing the acceleration to 0.2. The results as shown in Figure 4 and Figure 5 also match the 1D results to an extent. Noticeably, one lane comes to a standstill while the other exhibits behavior similar to that of a 1D simulation. This can be explained by the initial random distribution over the two lanes. It can be seen that multiple cars switch to lane 2 at the beginning. Lane 2 clearly starts with a lower density than lane 1. Some cars manage to make the switch in time while the rest get stuck in the congested lane which never moves due to the density being too high. This is realistic given that the simulation wraps around, since it is conceivable that in real life one lane can be moving but the other is stationary for some time. To alleviate this, the same experiment was run with slightly lower density (density = 0.13). The results can be seen in Figure 6. In this one, the left lane exhibits similar behavior to

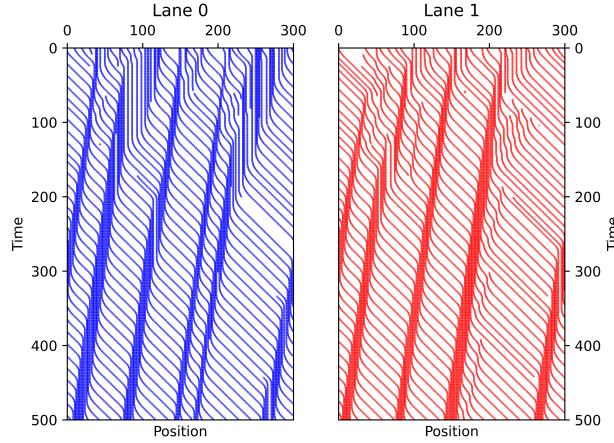


Figure 3: Speed-based lane switching with parameters identical to [Listing 1](#)

the original simulation while the right moves with almost no interruptions. This indicates that the density of the two lanes is slightly uneven but the distances are distributed in a way that doesn't allow cars to change lanes and balance out.

4.2 Observations

Here the two simulations are pitched against each other in order to analyze whether the extension maintains the characteristics of the 1D simulation and mimics the phenomena accurately.

- If the density is set low enough, no traffic jams form. It is intuitively evident since if the road is empty enough, all cars can go at maximum velocity without interruption. This can be seen in [Figure 7](#), and it happens in both the 1-dimensional and 2-dimensional simulations.
- If the acceleration is very low, it affects the cars' ability to stop quickly enough. Since this model uses the acceleration to define the speed at which cars decelerate (the deceleration constant is always set to twice the acceleration unless specified otherwise), if the acceleration is too low, the cars can not decelerate fast enough and end up crashing. This behaviour is observed in [Figure 8](#) where the acceleration is set to 0.01 and the safety distance is not big enough for cars to be able to stop if they enter it at max velocity. Due to the way the model is implemented, a crash can be identified on the plot as a car trying to decelerate, the going in front of the car because it could not stop and lastly accelerating again because the obstacle is now behind it. Again, this messy behavior is observed in both 1D and 2D simulations. This is a limitation of this model and has

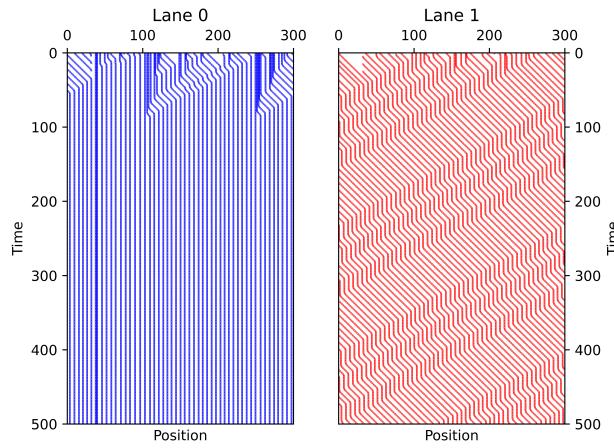


Figure 4: Space-based lane switching with parameters identical to Listing 1 except acceleration = 0.2

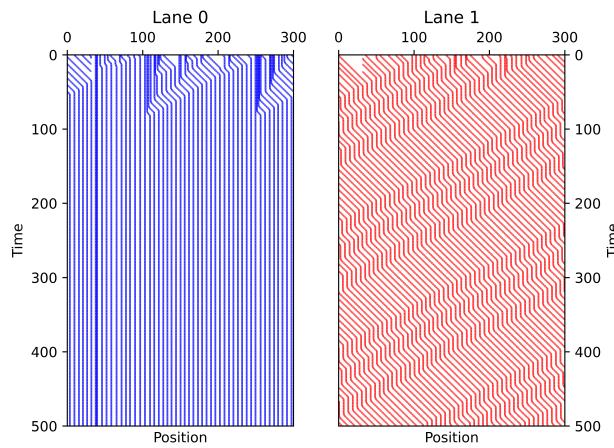


Figure 5: Speed-based lane switching with parameters identical to Listing 1 except acceleration = 0.2

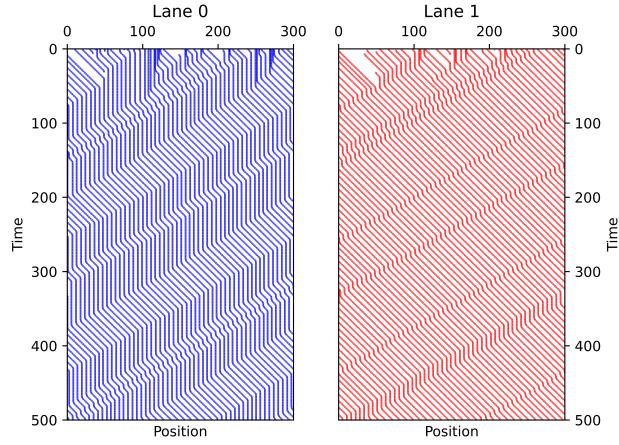


Figure 6: Space-based lane switching with parameters identical to Listing 1 except acceleration = 0.2, density = 0.13

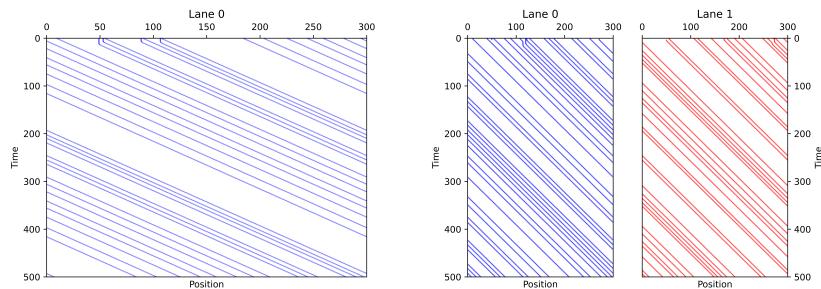


Figure 7: Simulation with low car density where all cars can go at maximum velocity. Left: 1D; Right: 2D.

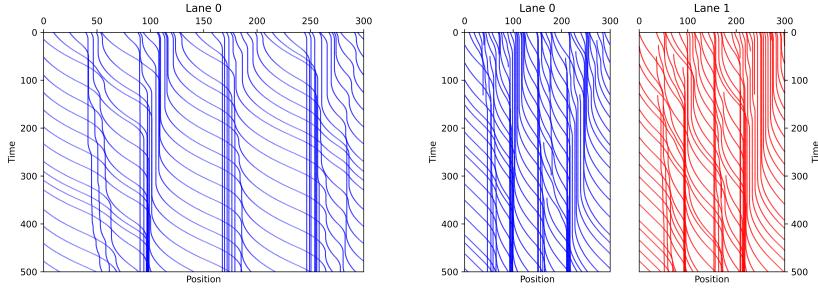


Figure 8: Simulation where the acceleration is too low, causing crashes. Left: 1D; Right: 2D.

to be avoided by setting the input parameters with some care. Alternatively, this could be avoided by allowing cars to look further ahead and calculate how much time they need to stop, but that would complicate the calculations a lot and was therefore not implemented.

- If the maximum velocity is set quite low, the cars have the opportunity to evenly distribute themselves along the road. The result of this depends on the safety distance that is set too. If the safety distance is set to the usual value, 7, then all cars arrive at a stand-still, as can be observed in [Figure 9](#)(top left). However, if the safety distance is lowered, the cars arrive in a perfect arrangement where they can all cruise at maximum velocity, which is visible in [Figure 9](#)(bottom left). However, in 2D, interesting behaviour can be observed. If the safety distance is too low in 1D, in 2D, the cars will be stopped on one lane and keep moving on another lane. This is because at the beginning of the simulation, the cars are randomly distributed across the 2 lanes. In the case seen in [Figure 9](#)(top right), there were more cars in Lane0 and less cars in Lane1. The difference was enough that the cars in Lane1 were still able to move.
- If the acceleration is equal to the maximum velocity, we expect to observe start-stop traffic only as the cars are able to stop and accelerate to full speed instantly. This is indeed the case as shown in [Figure 10](#).

An interesting phenomenon can be observed by letting the starting position be jammed immediately. To achieve this, all cars are spawned less than 1 safety distance from each other. This results in a clear wave-like propagation of the traffic jam as cars leave from the front and new cars join the back of the jam. The effect is shown in [Figure 11](#). This is realistic to how traffic jams propagate in actual traffic. The effect could be improved by adding stochastic slowdown to the cars or otherwise adding realism, however this is an incredibly simple model capable of modelling a realistic traffic jams scenario on a one-lane road.

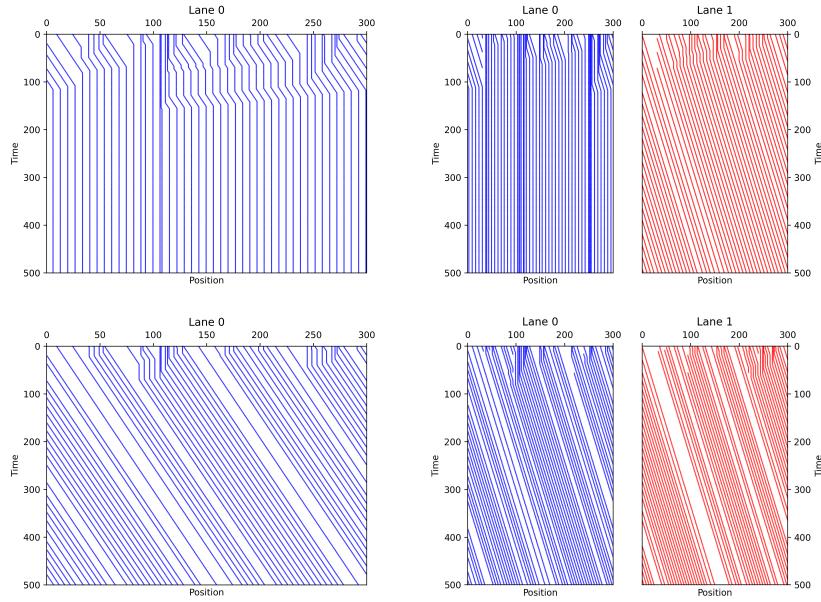


Figure 9: Comparison of changing the max velocity and safety distance in 1D and 2D.

Top left: low safety distance, 1D;
 Top right: low safety distance, 2D;
 Bottom left: high safety distance, 1D;
 Bottom right: high safety distance, 2D.

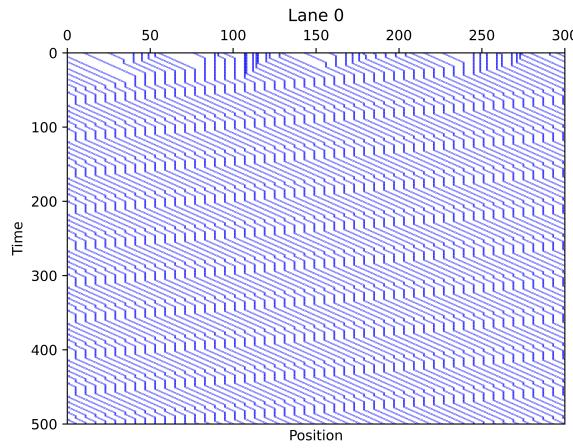


Figure 10: Acceleration equal to maximum velocity

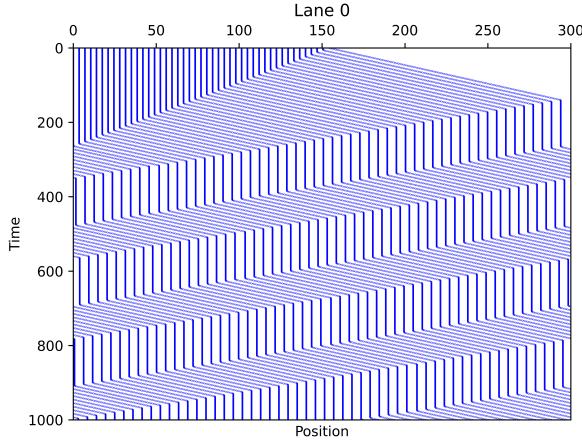


Figure 11: Starting in a jammed state

4.3 Parameter analysis

In order to draw some conclusions from the simulation, some metrics need to be defined in order to measure the impact of changing parameters on the traffic behavior. These are:

- Full speed fraction - This metric measures the fraction of cars which were moving at full speed during the simulation. It is measured as the average of the fraction of cars travelling at full speed at each timestep.
- Stopped fraction - This metric measures the opposite of the full speed fraction and is calculated in the exact same way, taking stopped cars into account only.
- Distance travelled - This is the fraction of the maximum possible distance the cars could have travelled during the simulation. This metric is directly correlated to traffic flow.

To simulate the impact of one variable changing, these three metrics were calculated for a range of variable values and plotted. The parameters of these simulations are mostly kept same as [Listing 1](#) except for some exceptions where the circumstances required changes in order to see underlying patterns better. The parameter values for these can be found in [Section 7](#).

1. Density

The plot can be seen in [Figure 12](#). As expected, the density has clear influence on the metrics and an ideal window can be identified. This is around 0.15, which corresponds to the density used for most experiments. This also makes sense with relation to the safety distance and road length

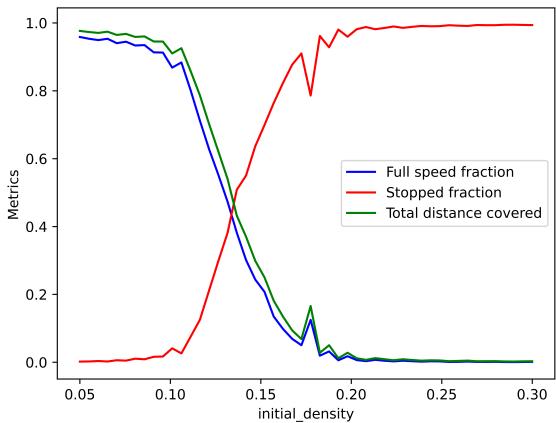


Figure 12: The impact of varying density

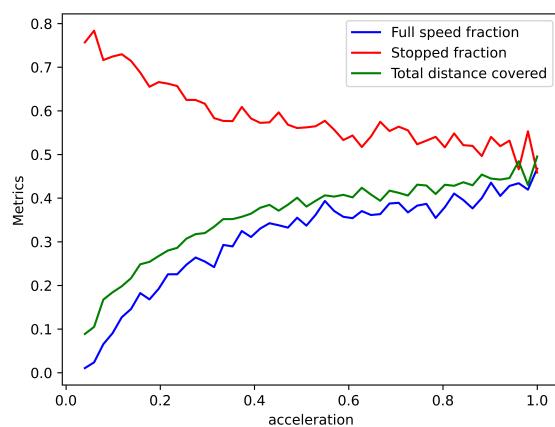


Figure 13: The impact of varying acceleration

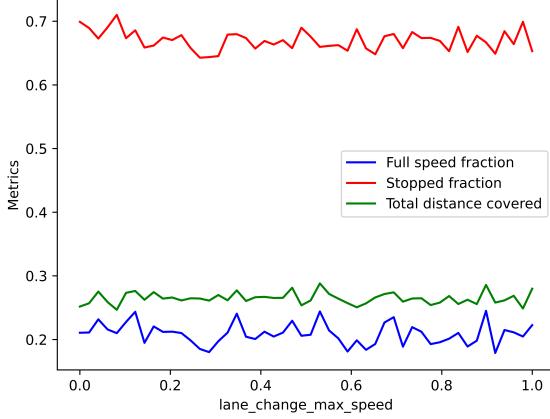


Figure 14: The impact of varying maximum lane change speed

values since if there simply isn't enough space on the road it will become congested inevitably.

2. Acceleration

It can be seen from [Figure 13](#) that an increase in acceleration tends to favor traffic flow. This is to be expected as higher acceleration allows better driver reactions and smoother flow.

3. Space based lane change max speed

The plot in [Figure 14](#) shows that this parameter actually has no impact on the flow. Except for small variations, it seems that the space-based lane change strategy does not actually get influenced by the speed at which lane changes occur. This can be explained by the fact that if a car is slowing down, it will eventually slow down to a speed at which it will consider changing lanes. Hence, the parameter only makes a small change in the timing of lane changes and does not influence traffic flow.

4. Random slowdown probability

As seen in [Figure 15](#), the impact is as could be expected. Higher probabilities cause traffic flow decrease and even lead to the full speed fraction nearing 0 as the cars struggle to accelerate to full speed before they are randomly slowed down again, especially if the same is happening around them. The total distance shows that the lanes are both still moving.

5. Safety distance

This parameter has a similar but inverse effect to density, as the two are related. The effect is shown in [Figure 16](#). This makes sense as lower safety distances allow higher density of cars without complete congestion.

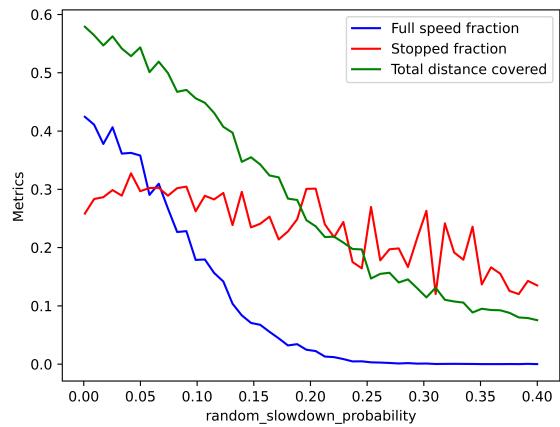


Figure 15: The impact of varying random slowdown probability

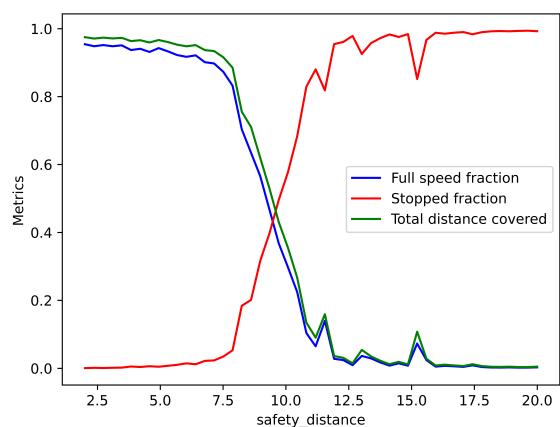


Figure 16: The impact of varying safety distance

Overall, it can be seen that there are interesting conclusion to parameter analysis. Conclusions can be made about the space based lane change strategy as well as the impact of acceleration on traffic flow. If the simulation was extended and ran for more cars, more lanes and other increased parameters, it could provide valuable insight into traffic dynamics.

5 Discussion

The model used in this project is quite powerful, especially considering the complexity involved. Even though no parallelization was used, the simulations were able to mimic the results obtained by [1]. Additionally, the model provided enough flexibility to test the behaviour of traffic under different conditions and setups. This testing led to interesting observations. There are several simplifications in the model to allow ease of implementation and efficient running which are discussed in [Subsection 3.1](#). These could be made more realistic in future simulations with more time and computational power.

5.1 Future research and improvements

- Parallelizing the movement of the cars;
- Investigating systems of 3 or more lanes
- Creating new cars instead of wrapping the road around
- Adding new strategies for line changing;
- Adding new strategies for the movement of the cars (braking, accelerating, etc.)

6 Conclusion

In the beginning phase of this project, a basic model was implemented with the goal of reproducing the results obtained by Nagatani in [1]. Once this model was ready, some experiments were carried out to try to understand the importance of the parameters, and some observations were noted. Later, the model was expanded. The biggest change was the addition of support for 2 lanes (2-dimensional model). Some smaller changes include the addition of the deceleration parameter, as well as overall improvements to the code quality. The 2D model was used to further check the behaviour of the previous observations and to see how they expanded to more dimensions. Parameter studies were also carried out to analyze the influence of some important parameters on traffic flow.

References

- [1] T. Nagatani, “Effect of car acceleration on traffic flow in 1d stochastic ca model,” *Physica A: Statistical Mechanics and its Applications*, vol. 223, no. 1, pp. 137–148, 1996.

7 Appendix

This section contains all the parameter setups used to create the figures shown this report.

Figure 1

Left: "initial density": 0.15, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 0.05, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0

Right: "initial density": 0.15, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 0.2, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0

Figure 2

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Figure 3

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Figure 4

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Figure 5

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Figure 6

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Figure 7

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Figure 8

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Figure 9

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slowdown probability": 0.0

Figure 10

"initial density": 0.15, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 1.0, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0, "deceleration": 2.0, "dimensions": 1, "lane change max speed": 0.0, "lane change method": "space-based", "random slowdown probability": 0.0

Figure 11

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Figure 12

"initial density": 0.3, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 0.2, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0, "dimensions": 2, "lane change max speed": 0.1, "lane change method": "space-based", "random slowdown probability": 0.01, "deceleration": 0.4

Figure 13

"initial density": 0.15, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 1.0, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0, "dimensions": 2, "lane change max speed": 0.1, "lane change method": "space-based", "random slowdown probability": 0.01, "deceleration": 0.4

Figure 14

"initial density": 0.15, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 0.2, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0, "dimensions": 2, "lane change max speed": 1.0, "lane change method": "space-based", "random slowdown probability": 0.01, "deceleration": 0.4

Figure 15

"initial density": 0.1, "initial velocity": 0.3, "max velocity": 1.0, "acceleration": 0.05, "safety distance": 7, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0, "dimensions": 2, "lane change max speed": 0.1, "lane change method": "space-based", "random slowdown probability": 0.4, "deceleration": 0.1

Figure 16

"initial density": 0.1, "initial velocity": 0.3, "max velocity": 1.0, "acceleration":

0.2, "safety distance": 20.0, "max distance": 300, "pattern": "random", "max time": 500.0, "time step": 1.0, "dimensions": 2, "lane change max speed": 0.1, "lane change method": "space-based", "random slowdown probability": 0.01, "deceleration": 0.4