Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Lecture with Computer Exercises:
Modelling and Simulating Social Systems with MATLAB

Project Report

Effects of a general speed limit on two-lane highway traffic

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Contents

1 Abstract

As highways are an important part of infrastructure all around the world, we analysed the effects of a general speed limit, a measure employed by many, but not all (e.g. Germany) countries around the world, on highway traffic. For this purpose we created a simulation in Python, which implements the Intelligent Driver Model and the Lane-change Model MOBIL, to simulate the effects of a general speed limit on a two-lane highway. For this, we worked under the assumption, that a speed limit serves as a kind of guideline, so there would not be a large deviation from it. If there is no general speed limit in place, we assume, that drivers want to go faster on average, but that there is also a larger deviation from this average.

In our model we compare this difference in speed and deviation and find that, as expected, the varying velocities create traffic jams. To make the model more realistic we also include some extensions: Disturbances modeled with random perturbations and Trucks modeled as a type of driver with parameters realistic for trucks. With these Extensions we also have more emergent traffic jams in our model with a general speed limit, but we still find there to be less than in the one without a speed limit.

2 Individual contributions

The main contributor to the code base was Diego de los Santos, while minor contributions were made by Victor Vitez, Daniel Nezamabadi and Róbert Veres. The Simulations and visualizing the results were done by Diego de los Santos, Daniel Nezamabadi, Róbert Veres, Victor Vitez. The report was compiled by Natalie Suter, Daniel Nezamabadi, Róbert Veres and Victor Vitez. Even though not everyone contributed to all parts of the project, we made an effort to ensure that the overall work was distributed evenly.

3 Introduction and Motivations

Highways are an important part of infrastructure all around the world and are used by a lot of people every day for different reasons: To commute to work, transport goods or to go on holidays. Thus it is only natural to want to optimize the use of highways. One idea that is often brought up in this context is the idea of a general speed limit for highways. The arguments for such a speed limit include, but are not limited to, an increase in road safety and environmental protection.

While many (European) countries have a general speed limit in place, Germany is one of few countries that doesn't have such a limit and where controversial debates surrounding a general speed limit happen regularly. One article from the German newspaper ”DIE ZEIT” from 1975 refers to the debate as an ”old dispute reignited” [1], while in 2019 the German Minister of Transport Andreas Scheuer was against the new speed limit debate [2]. Both sides seemingly use the same argument: A general speed limit decreases travel time by reducing traffic congestion, while without such a speed limit travel time is decreased because people can drive faster and thus reach their destination quicker. The goal of our research is to analyse the effect of a general speed limit on vehicle velocity and to determine whether a general speed limit is a useful tool in the quest of optimizing highways for everyone.

3.1 Fundamental Questions

As mentioned above, the main goal of our project is to analyse the effect of a general speed limit on highway traffic. More specifically, we want to determine whether a general speed limit increases or decreases average vehicle velocity in different situations. The situations we want to simulate vary in types of vehicles and the possibility of "forced" speed changes, for example due to sudden stop of a car.

3.2 Expected Results

While both arguments in regards to the effect of a general speed limit on highway throughput make sense, we expect that a general speed limit decreases traffic congestion and thus increases highway throughput in basically all situations by narrowing the speed distribution of cars.

4 Description of the Model

We base our simulations on the Intelligent Driver Model (IDM) as described in [3] and add some extensions to it, as described below. We also use a slightly adapted version of the Lane-change Model MOBIL. [4]

4.1 Intelligent Driver Model

The Intelligent Driver Model [3] is an accident-free, deterministic follow-the-leader model. The model parameters, which describe the driving style, can be seen in table 1. The model output is the acceleration. It is determined by the velocity v_α, the bumper-to-bumper gap s_α to the leading vehicle and the velocity difference Δv_α between the two vehicles:

$$\dot{v}_\alpha = \alpha^{(\alpha)} \left[1 - \left(\frac{v_\alpha}{v_0^{(\alpha)}} \right)^\delta - \left(\frac{s^*(v_\alpha, \Delta v_\alpha)}{s_\alpha} \right)^2 \right] \tag{1}$$

where

$$s^*(v, \Delta v) = s_0^{(\alpha)} + s_1^{(\alpha)} \sqrt{\frac{v}{v_0^{(\alpha)}}} + T^\alpha v + \frac{v \Delta v}{2\sqrt{a^{(\alpha)} b^{(\alpha)}}} \tag{2}$$

The acceleration (1) is an interpolation of the desired acceleration $a_f(v_\alpha) := a^{(\alpha)}[1 - (v_\alpha / v_0^{(\alpha)})^\delta]$ on a free road and deceleration $-b_{int}(s_\alpha, v_\alpha, \Delta v_\alpha) := -a^{(\alpha)}(s^*/s_\alpha)^2$ induced by the leading vehicle. This deceleration term is calculated, using the ratio between the desired minimum gap (2) and the actual gap s_α.

Description	**Model Parameter**	**Realistic Values**
Desired speed	v_0	We simulate different values and compare
Safe time headway	T	Between $0.8s$ and $2s$
Maximum acceleration	a	Between 0.8 and $2.5\frac{m}{s^2}$.
Desired deceleration	b	Around $2\frac{m}{s^2}$
Acceleration exponent	δ	4
Jam distance	s_0	Around $2m$
Jam Distance	s_1	0
Vehicle length	l	Around $4.5m$ for cars

Table 1: The IDM Parameters [5]

4.2 Lane-change Model MOBIL

We use the Lane-change model MOBIL [4]. Lane changes take place if both the Incentive Criterion and the Safety Criterion are satisfied, where the Incentive Criterion is satisfied, when the target lane is more attractive and the Safety Criterion is satisfied, when the change can be done safely.

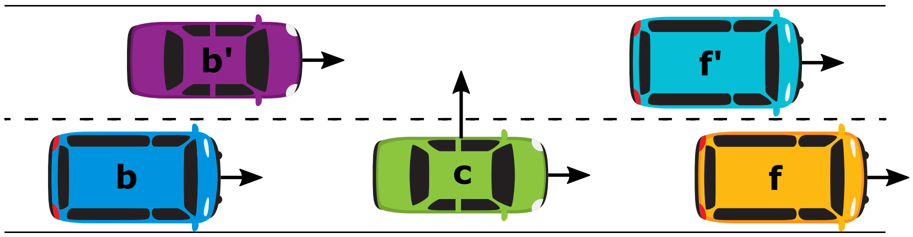

Figure 4.1: Lane-changing [6]

4.2.1 Safety Criterion

For the safety criterion we view the Intelligent Driver Model breaking deceleration $a_{b'c}$ of the following car on the target lane. If it does not exceed the limit b_{save}, the Safety Criterion is satisfied.

$$a_{b'c} \geq -b_{save} \tag{3}$$

where

$$a_{\alpha\beta} = a^{IDM}(v_\alpha, s_{\alpha\beta}, v_\alpha - v_\beta) \tag{4}$$

is the acceleration of vehicle α that would be calculated with the Intelligent Driver Model if vehicle β changed into the lane in front of it.

Description	Model Parameter	Typical Value
Politeness factor	p	Between 0 and 0.5
Maximum safe deceleration	b_{save}	Around $4\frac{m}{s^2}$
Threshold	δ	Around $2\frac{m}{s^2}$
Bias to the right lane	Δb	Around $2\frac{m}{s^2}$

Table 2: The MOBIL Parameters [7]

4.2.2 Incentive Criterion

The Incentive Criterion is satisfied if a potential lane change increases the sum of the accelerations, weighted with a politeness factor p, more than $\delta + \Delta b$ ($\delta - \Delta b$). Where δ is a threshold, which ensures that cars don't frantically change lanes with every change in acceleration and Δb is a bias to the right lane. For a right to left lane change we have:

$$R \rightarrow L \text{ IF } a_{cf'} + p(a_{b'c} + a_{bf}) > a_{cf} + p(a_{bc} + a_{b'f'}) + \delta + \Delta b \tag{5}$$

where the accelerations on the right side are the current values and the ones on the left are the accelerations after the lane change, calculated with the Intelligent Driver Model.

4.3 Extensions

4.3.1 Disturbances

We simulate disturbances by introducing random disturbances into our simulation. Each time step, cars are disturbed with the probability p_{fail}. When a car is disturbed it's velocity is set to zero for a predetermined time.

4.3.2 Trucks

To have our simulation reflect a realistic highway, we differentiate between two types of vehicles: Cars and trucks. The only difference between these two types lies in the arguments passed to the Intelligent Driver Model, as described in the following table:

Parameter	**Value Car**	**Value Truck**
Desired speed v_0	varied	varied
Safe time headway T	1.4 s	1.6 s
Maximum acceleration a	2 or 0.3 m/s^2	1 or 0.3 m/s^2
Desired deceleration b	$2.5m/s^2$	$1.5m/s^2$
Acceleration exponent δ	4	4
Jam distance s_0	$2m$	$2m$
Jam Distance s_1	$0m$	$0m$
Vehicle length l	$4.55m$	$16.5m$

Table 3: IDM parameters for trucks and cars

Almost all parameters have been chosen to be as realistic as possible, with the exception of the acceleration parameter a, for which we also do simulations with very low values to reinforce the formation of stop-and-go traffic [5].

5 Implementation

We use the before described models for our agent-based simulation. Each simulation step simulates a time interval Δt, after which the state of all the cars is captured. This new state is only determined by the previous and there are no intermediate states in between, so every car is first locally updated before the new state is committed globally.

The implementation of the Intelligent Driver Model and the Lane-change Model MOBIL [4] is done in the class `DriverModel`.

To run simulations, one can instantiate the `Simulation` class with all its necessary parameters. For this we use `main.py`. This file handles creating multiple simulations, creating the data and saving it to a JSON file for use in the visualizer (`Metrics`), which it also calls afterwards.

For every simulation, an instance of the class `Simulation` is created. This class gets a list of car types and other necessary parameters like the road length and the amount of lanes, and handles creating a `Road` object. This `Road` will insert `Car` objects into the road, by randomly selecting a lane and checking if there is a sufficient distance to the leading vehicle, so cars are only inserted if it can be done safely. Once cars are at the end of the road, they are deleted. During a simulation step, every `Car` object is updated locally, then the new state is made visible globally.

A `Car` object can find the surrounding cars and update its velocity and position using the `DriverModel` class. Every time the state is updated, all cars have a probability p_{fail} of failing, which is how we model random perturbations. For our visualization, the position, velocity and other information about each `Car` object is saved each time they are updated.

The `Metrics` class handles the creation of all the graphs and plots which will be presented in this paper.

For further information, consult the *documentation* in the project repository.

6 Simulation Results and Discussion

We run the simulation with multiple settings and compare how the traffic dynamics and average velocities differ. Firstly we look at different simulations with a speed limit and then at a range of simulations without a speed limit and we compare them.

6.1 Sanity Check

To confirm that the implementation works as expected, we run the simulation without deviation of speed or random perturbations ($v_0 = 90, p_{fail} = 0$) . To represent our simulation graphically, we plot the cars' position after every update. The distance is plotted on the horizontal axis, where the left of it is the beginning of the road and the right is the end. The vertical axis represents the time passed since the beginning of the simulation, it is directed downward. We expect a graph that consists of parallel lines with a negative slope. If we plot the graph we can confirm this assumption.

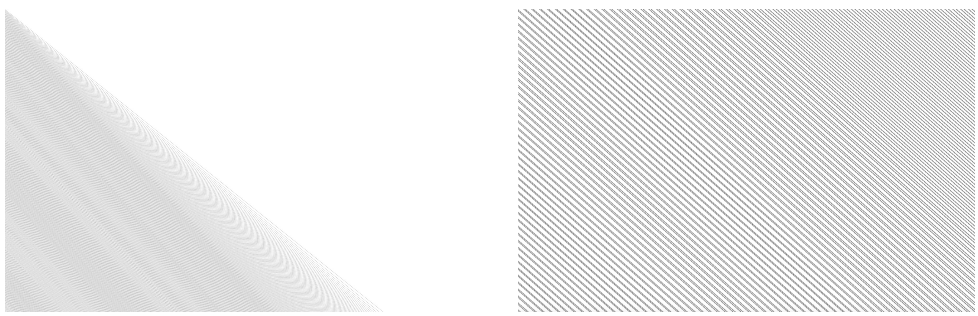

Figure 6.2: Result of the Sanity Check (Left: Complete Simulation - Right: Zoomed in)

6.2 Speed limit

After confirming that our implementation works as expected, we can start simulating traffic with different speed limits. Before that, however, we need to define the notion of a speed limit in our simulation.
The speed of a car is based on a normal distribution: Every value that deviates from the mean μ more than twice the standard deviation σ gets set to the mean. To describe this, we will introduce the following notation: $v_0 \in (120, 5)$, which means that the value v_0 is a value between 110 and 130, with the probability determined by the above defined distribution. It should be noted, that in the report the mean μ and standard deviation σ are given in km/h, unless stated otherwise, even though

the implementation requires a value in m/s. This is to minimize unnecessary calculations between units.
For the simulation of various speed limits, we let $\mu \in [80, 100, 120, 140]$ and $\sigma = 5$. This is based on the assumption that a majority of vehicles will drive exactly what the speed limit allows, while some vehicles will drive 10 km/h slower or faster than the speed limit. In addition to setting a speed limit, we make sure that around 5,6% of the vehicles are trucks with $v_0 \in (80, 2.5)$, modelling the distribution of larger trucks on a highway [8] and their associated speed limit of 80 km/h. It should be noted that we only consider a vehicle as a truck if it is heavier than 7.5 tons, since lighter transport vehicles can be seen as cars that are on the slower interval of the truncated normal distribution.
To model the possibility of a vehicle breaking down on the road, we set their velocity to 0 with the probability p_{fail} and keep it there for around 4,5 minutes (inside the simulation).
If not specified otherwise, the simulation parameters are the values from Table 3, with the acceleration parameter a being the larger of the two possibilities.

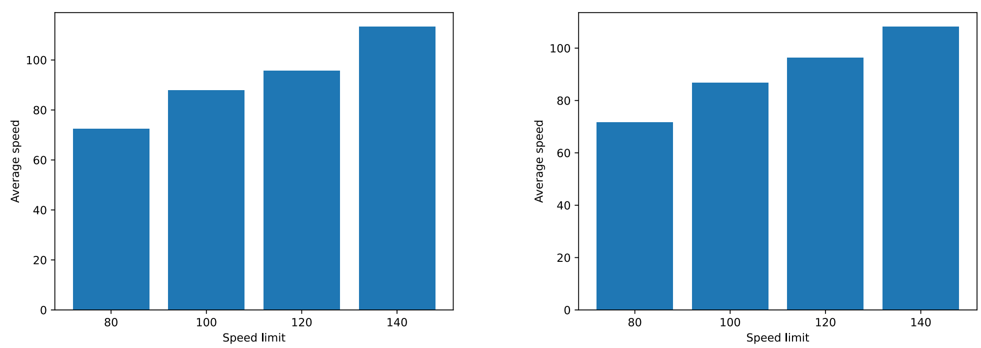

Figure 6.3: Average speed of cars: left: $p_{fail} = 0$, right $p_{fail} = 10^{-6}$

As we can see in Figure 6.3, the average speed of all cars increases with increasing the speed limit, when we have a low probability of a disturbance happening. The same is true for no disturbance. It does however not increase by the same amount as we increase the speed limit, meaning there is more congestion with higher speed limits.

Since we do introduce quite a bit of randomness into the simulation with the disturbances, looking just at the average speed is not a very good indication. For example we could have 3 disturbances in one simulation and none in another. We will only look at the average speed as a general indication, but the actual dynamics are seen in the dot graphs.

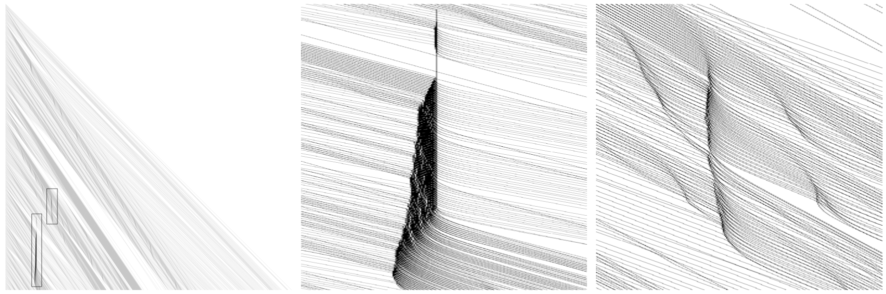

Figure 6.4: Simulation graph: $v_0 = (120, 5)$ and $p_{fail} = 10^{-6}$ (Left: Entire graph - Middle and Right: Zoomed in)

We can see that there are two different kinds of traffic jams. The first kind is caused by a car breaking down as shown in Figure 6.4 (middle). These usually cause a sudden sharp dark line, as the cars are suddenly stacking up at a given location. The second kind of traffic congestion is caused by slow cars blocking both lanes. On the graph, they make up an area slowly fading into a darker shade of gray as the arriving cars overreact to the slower moving vehicles, which results in either traffic flow coming to a full stop, which turns the gray area into a sharp black line, or the problem gets resolved and the darker area slowly fades back to a lighter shade.

6.2.1 Reducing the acceleration parameter a

In this part we want to investigate the effects of decreasing the acceleration parameter a to a value of 0.3. While this might not be a realistic value, it enhances the formation of stop-and-go traffic [5], allowing us to investigate the effects of a speed limit on stop-and-go traffic.

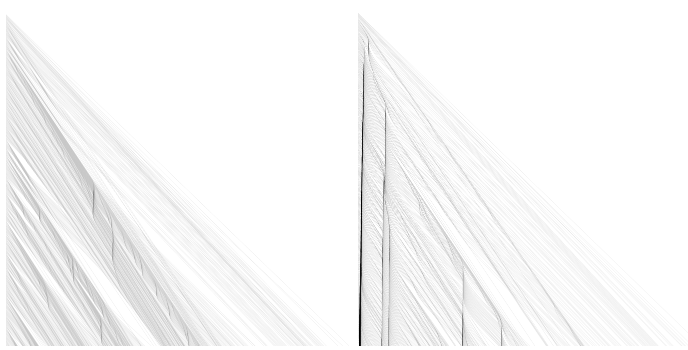

Figure 6.5: Graph: $v_0 = (120, 5)$ and $p_{fail} = 0$ (Left: $a = 2$ - Right: $a = 0.3 m/s^2$)

As we can confirm, if we increase increase the acceleration of the participants, there is less disturbance in traffic. This is caused by the stop-and-go traffic that can occur more easily in the slower environment, since cars need more time to reestablish their speed and therefore the vehicles behind them catch up and they need to slow down too.

6.2.2 Changing the breakdown probability

After having analyzed the effects of reducing the acceleration parameter a, we want to identify the effects of changing the breakdown probability p_{fail}. As we can see in figure 6.6, the cars bunch up more and more when we increase the fail probability. This happens due to multiple disturbances happening in the same region. This effect is also self enhancing, since when more cars are bunched up together, the probability of a disturbance happening in there is higher than for the few cars which are ahead.

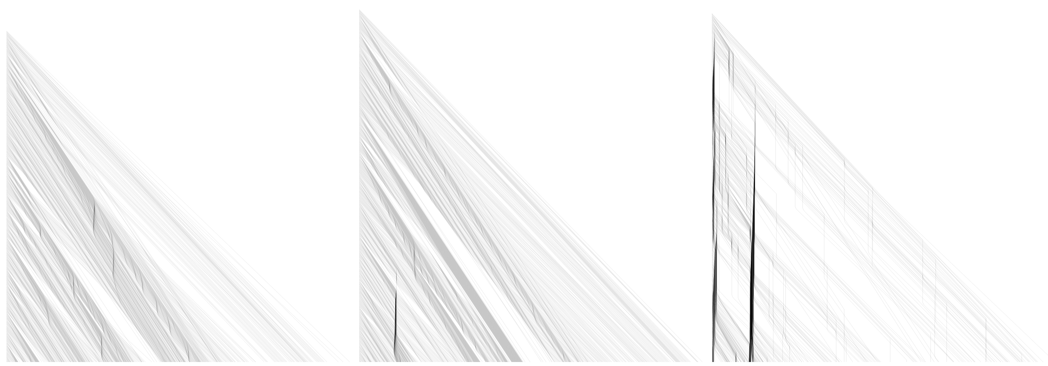

Figure 6.6: Simulation graph: $v_0 = (120, 5)$, left to right: $p_{fail} = 0$, 10^{-6} and 0.0001

6.3 No Speed limits

When it comes to ideas about increasing the average velocity, increasing the speed limit (or removing it entirely) is a naive, but very common idea. The expectation is, that even if some jams are caused by the speed difference, you still get through a part of the highway faster when you drive 160km/h instead of 130km/h. In order to test this, we created a simulation with $\mu = [100, 120, 140, 160, 180]$ and $\sigma = [10, 15, 20]$ to model a wide range of possible speed distributions on the highway.

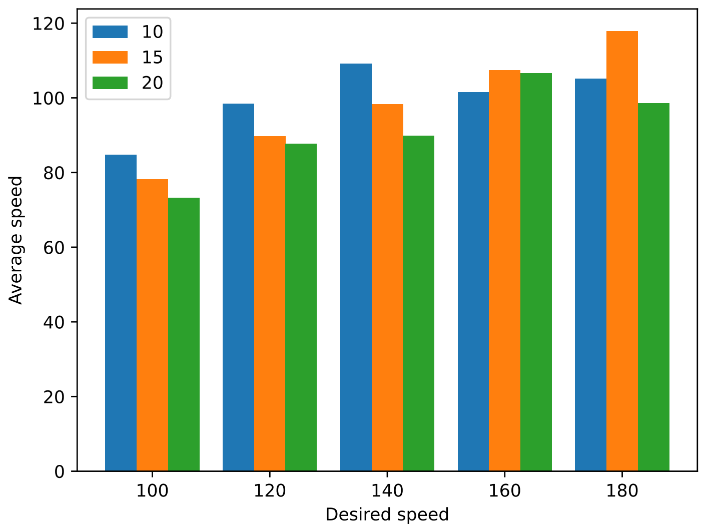

Figure 6.7: Simulation without speed limit without perturbations

We can see that the average speed does not increase nearly as much as the average desired speed is increased. Note that 140km/h with $\sigma = 20km$ (meaning a range of +/- 40km since we truncate at 2σ) is the most realistic average for desired speed.

For most of the simulations the average speed is lower with a higher deviation from the average desired speed, but in the simulation with the average desired speed $160km/h$ there is a spike, so we want to have a closer look at the particular dynamics that caused this result: In figure 6.8 we can see that for this particular simulation (middle) there are a lot of fast cars that get past the jam in the beginning, so these increase our average.

We can obviously still see a general trend of the simulations with a smaller deviation resulting in a faster average speed and we see that the speed increases less and less.

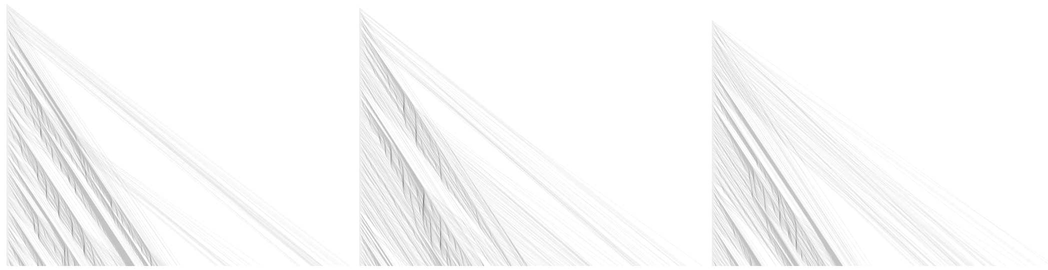

Figure 6.8: Simulation graph: $p_{fail} = 0$, left to right: $v_0 = (160, 10)$, $v_0 = (160, 15)$, $v_0 = (160, 20)$

The stronger congestion can be seen even more when we add perturbations: In figure 6.9 we observe the impact of adding perturbations to the simulation with an average desired speed $140 km/h$ and in figure 6.10 the effect on varying desired velocities is seen.

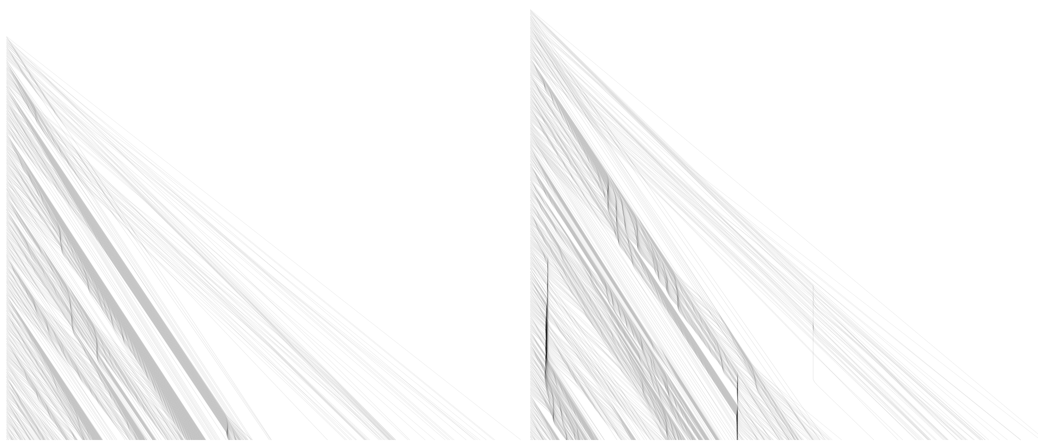

Figure 6.9: Simulation graph: $v_0 = (140, 15)$ left: $p_{fail} = 0$, right: $p_{fail} = 10^{-6}$

If we look at 6.10 we can see that the simulation with the highest desired velocity has a larger traffic jam and more perturbation.

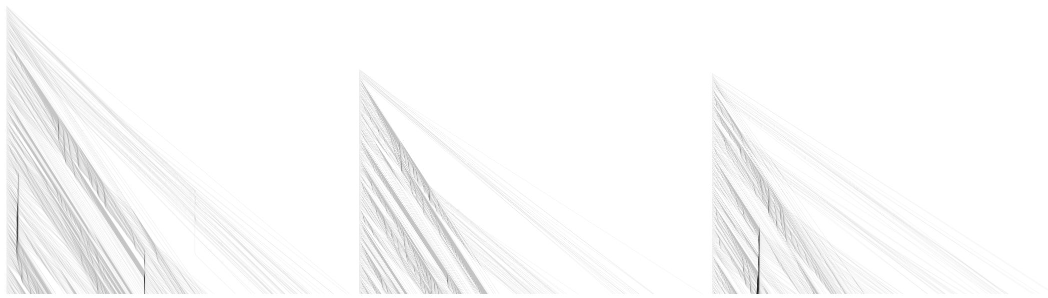

Figure 6.10: Simulation graph: $p_{fail} = 10^{-6}$, left to right: $v_0 = (140, 15)$, $v_0 = (160, 15)$, $v_0 = (180, 15)$

6.4 Comparison

We observed that our simulations without a speed limit tend to show more traffic congestion because of the large difference between velocities. The average speed is not the best metric to compare, since the first couple of cars have an open road in front of them and their speed will increase the average. But even so the average is still higher for the simulations with a speed limit.

6.5 On Limitations and Validity

Our results roughly fall in line with the current consensus, but they should be taken with a grain of salt. Not only does the model have its limitations, creating a very predictable driver scenario which rarely reflects messy reality, but we also use the same values for almost all parameters. Since there was barely any data on desired speed on both speed-limited and limitless highways, we had to draw our own conclusions. And using actual speed statistics to model desired speeds would have carried its own problems, favouring the speed-limited highways from the start, since the data from limitless highways would have been more affected by perturbations, warping our results from the start.

There's a case where a slow car changes lanes for its own profit while slowing down a car behind it. This is intended in the model and the slow car's altruism is defined by the politeness value. The problem is that the Lane-change Model MOBIL does not account for multiple cars in the target lane that will all have to slow down as a result of a lane change. This doesn't seem that bad until for example a truck switches lanes to overtake, slowing down the entire traffic behind it and causing a small traffic jam. Judging by the Swiss truck overtaking ban [9], this seems to have been recognized as a current problem in real traffic too, which poses the question whether one should even attribute this much consideration to a human driver and whether it would even make the model more realistic.

Another problem results from our implementation of disturbances. Every car at every time step has a probability to break down. This results in fast cars having a much lower probability of breaking down per meter than slow cars, since they spend much less time on the simulated road.

A last, small problem regards traffic jams: if there is a traffic jam right at the start of our road, less cars will be generated, resulting in it being populated by less cars, impacting our data. This is almost no concern if there are no random disturbances, though, since it's much less likely to happen in that case and would resolve more quickly.

7 Summary and Outlook

Because of the aforementioned reasons, comparing speed averages from our simulations with disturbance, while interesting, aren't very significant. When comparing the results of our simulations without disturbance for a speed limitation of 120km/h against the "limitless" simulation with an average desired speed of 140km/h and $\sigma = 20$, judging by the average speed, our throughput is actually higher in the former simulation, suggesting that, regardless of accidents, throughput on high traffic highways could profit from a speed limitation, meaning a narrower speed distribution.

An interesting addition could be a mechanism to actually prohibit overtaking from the left. If one wanted to model real highway conditions more accurately, entries and exits as well as a better disturbance model could be implemented.

This project could benefit from more computational power. This would allow us to simulate every environment multiple times, which seemed very time consuming with our current setup, as a single simulation could take up to 20-30 minutes. If we had multiple samples of the same simulation, it would also make it easy to derive a mathematical formula how the parameters we use affect the average velocity.

Concluding, this report has only scratched the surface of a very interesting topic to answer whether limitless or limited highways have better throughput, with the latter seeming to be the better option.

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