Avoiding phantom jams in traffic

- Simulations with agent-based models

Simon Lindkvist   Sebastian Johansson

December 18, 2009

Abstract

Traffic jams occur all the time for no appearent reason. These jams are called *phantom jams* and occur when the traffic-system reaches instability at a certain traffic density. In this state very small changes in the flow are amplified and form a sustained travelling traffic-jam wave. We have created a simulator from a microscopic traffic model that mimics the behavior of a normal driver and the dynamics of a car to reproduce these phantom jams. We have analyzed two technical systems that could reduce the effects of phantom jams, the Adaptive Cruise Control system and an enhanced version of it, suggested by us. In our simulations, both systems have been found to reduce phantom jams and increase traffic flow.

1 Introduction

Huge amounts of resources are used every year to build and maintain roads around the globe. The Swedish Road Administration alone, has a annual budget of 21 billion SEK [5]. Reducing traffic jams, and thereby reducing the need for building new roads is highly motivated.

Figure 1: Experiment by Y. Sugiyama el al. [2]. 22 cars on a circular road of length 230 m. A traveling phantom jam has appeared and can now bee seen in the upper-right part of the photo.

In free flowing traffic, traffic jams can appear for no apparent reason. Even without the presence of bottle-necks such as traffic-lights, crossroads or slip roads. In light traffic, drivers adjust to any instabilities, but as soon as traffic reaches a certain level of density, jams occur. This phenomena is known as jamitons or *phantom jams* and has recently been confirmed experimentally by Y. Sugiyama et al. (see fig 1 and 2) [2]. Once a phantom jam has been established, the jam travels backwards in traffic as a wave. Recently it was shown by M. R. Flynn et al. [3] that these waves are mathematically similar to travelling shock-waves caused by explosions.

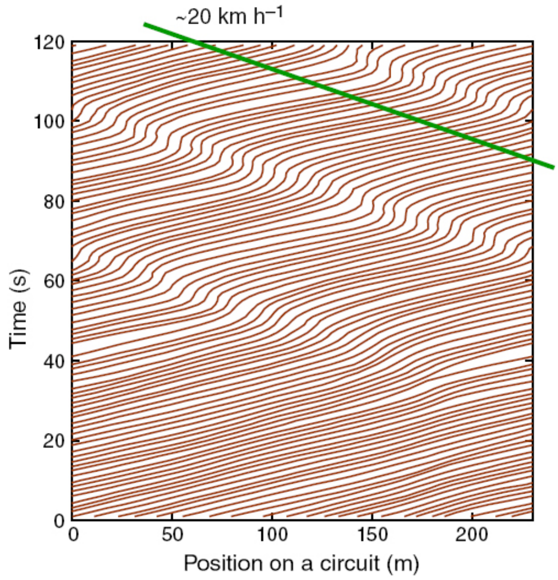

Figure 2: Data measured during the experiment seen in fig 1. A disturbance can be seen after 40 s and is quickly amplified into a phantom jam, travelling backwards around the circle at approximately 20 km/h. Diagram by Y. Sugiyama el al. [2].

Traffic flow and thereby the efficiency of roads, is severely reduced by traffic jams such as phantom jams (see fig 3) [2]. If we implement a system that shifts the critical level of traffic density at which phantom jams occur upwards, we improve road efficiency. In this report we evaluate two such systems: Adaptive Cruise Control and an improved version that we have named Enhanced Adaptive Cruise Control. Results are taken from our simulator based on agent-based modelling.

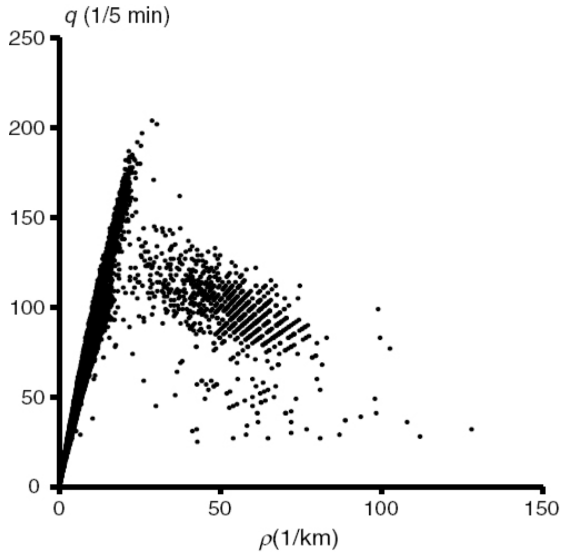

Figure 3: Traffic flow as a function of traffic density. The data is clearly divided into two sets, one representing free flowing traffic and the other (above the threshold of 25 vehicles per km) representing congested traffic (with traffic jams). Results from article by Y. Sugiyama el al. [2]. Data was measured by Japan Highway Public Cooperation on Japanese highways. Similar observations have been made in many places and seems to be almost a universal property of highway traffic.

2 Driver model

There are two main types of simulation models for traffic systems: microscopic and macroscopic. A microscopic model describe each vehicle while macroscopic models describe traffic flow. Since microscopic models describe the position and velocity of each car in the simulation, they can easier be compared with empirical data than macroscopic models. The Intelligent Driver Model (IDM) is a car-following model and belongs to the deterministic kind of microscopic models [6].

The IDM controls the position of the car on a single-lane road. The position depends on the velocity and acceleration of the car. Acceleration is described by the velocity v_α and distance to the car in front s_α. These two parts are related to the desired velocity v_0 and effective desired distance s^*. The equation for acceleration then becomes:

$$\dot{v_\alpha} = a\left(1 - (\frac{v_\alpha}{v_0})^\delta - (\frac{s^*}{s_0})^2\right) \tag{1}$$

Desired distance between the cars is calculated from minimum distance s_0, time headway T and difference in velocity $\Delta v = v_\alpha - v_{\alpha+1}$.

$$s^* = s_0 + max\left(v_\alpha T + \frac{v_\alpha \Delta v}{2\sqrt{ab}}\right) \tag{2}$$

3 Methods to reduce jams

A technology to increase safety for drivers in traffic is Adaptive Cruise Control (ACC) which is the next generation of cruise control. This kind of system is able to measure the distance to and speed of the car infront and then adapt the own speed so a certain time gap is maintained between the cars. ACC is already commercially available on the market and there is much research going on to determine the effects on traffic flow when more and more vehicles are equipped with this system [1]. The biggest advantage of the system is the increased comfort of the driver but also safety is increased. A human driver is mostly not very good at estimating the distance to or the velocity of the car in front. This can cause unneccessary brakes or accelerations. Also because of some drivers behaviour, time headway between cars is shorter than a normal driver require to adapt to changes in traffic flow. Since ACC is able to measure the distance and velocity with good precision and adapts the speed to always keep a safe time headway to the car in front, not much braking and accelerating is needed. (FIXME: ref till not)

One ability that human drivers have but ACC lack is the possibility to look ahead in traffic. One example is the breaking light that can be seen through several cars. A problem with this is the difficulty to estimate the speed of the cars ahead. The only information available is that the cars further ahead are breaking. We have thought of a system that have the advantages of the ACC and the possibility to look further ahead in traffic. This enhanced model could be realized by communication between the cars that are travelling in the same direction. There has been some research on communication between cars; (FIXME: Kesting et al.) have tested the connectivity of such a system. The enhanced system can then adapt speed to the cars further up in line and possibly reduce fluctuations in traffic flow even more.

4 Simulator setup

In the created simulator we had a one-lane circular road with a length of 800 m. Different amounts of cars could be placed on the track corresponding to a certain traffic density. During one simulation this meant that the density was constant since no cars could be added or removed during one run. Initially all cars were positioned equally spaced on the circular road, but then every car was moved forward randomly between 0 and 1 metre to create some initial perturbation. This speeded up the emergence of phantom jams. The graphical user interface of the simulator can be seen in Appendix A.

4.1 Implementation of mathematical models

The Intelligent Driver Model has been used as basis for the controll system for all agents (cars). We have done simulations with three different versions:

4.1.1 Normal driver

The IDM was developed to describe a normal behavior of cars in traffic and hence for our normal driver, we have implemented the model with only one modification. A delay of the acceleration has been added which represents a human reaction time. For human drivers it takes about 1 s to react to changes in traffic [6]. Our model is then implemented as equation (1) but with a time delay T_r.

4.1.2 Adaptive Cruise Control

The purpose of the ACC is to keep a constant time gap to the car in front and since IDM already has this ability only the reaction time of the model has been changed between the normal driver and ACC-driver. The ACC system is electronically controlled and we assumed that the system has a reaction time of about 200 ms. Table 1 shows the parameter settings.

4.1.3 Enhanced Adaptive Cruise Control

It is not obvious how to implement a system that can adapt to changes further ahead than the car in front. In our model we have assumed that the system can get the information about the position and velocity of a car one step further ahead. The data was used to the calculate the difference in velocity of the two cars. This was then implemented through the effective desired distance equation (2) from the IDM:

$$s^* = s_0 + max\left(v_\alpha T + (1-\epsilon)\frac{v_\alpha \Delta v}{2\sqrt{ab}} + \epsilon \frac{v_\alpha \Delta v_2}{2\sqrt{ab}}\right) \tag{3}$$

where $\Delta v_2 = v_\alpha - v_{\alpha+2}$. Otherwise the system is similar to the ACC system and we have used the same parameters in both systems. See table 1 for parameter settings.

Paramter	*Description*	*Value*
a	Max acceleration	$0.73\,\mathrm{m/s^2}$
b	Max brake	$1.5\,\mathrm{m/s^2}$
T	Time headway	1.5 s
l	Car length	5 m
T_r	Reaction time	1 s, 0.2 s (normal driver, ACC EACC)
ϵ	Communication influence	20% (only for EACC)

Table 1: Parameters for the three models.

5 Results

Our simulator was designed to be similar to the experiments made by Sugiyama et al.[2] for simple data comparison. Figure 4 shows the absolute position on the circular road of 60 cars with normal drivers for 150 s. In this plot it can be seen that several of the cars came to a complete stop after 30 s. These stops can then be characterized as waves [3] moving backwards in the lane with a constant speed of 13 km/h.

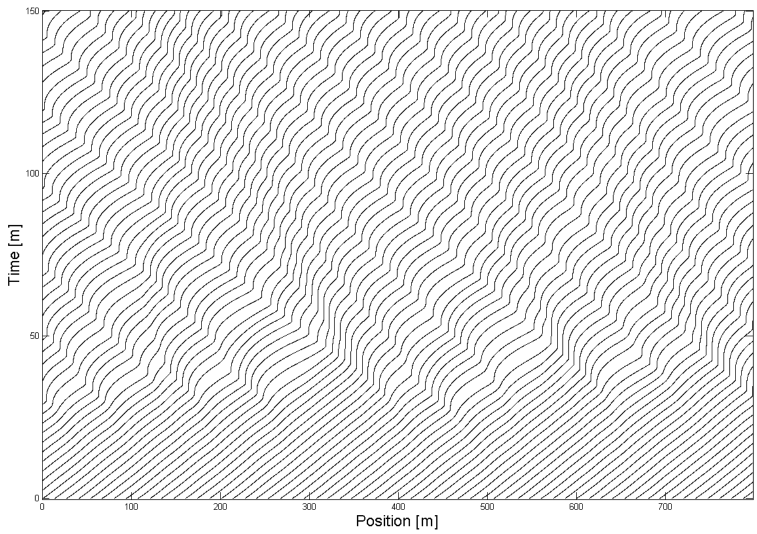

Figure 4: Absolute position of 60 cars for 150 s. Data from simulator. After 30 s phantom jams were emerging.

Simular plots for cars equipped with ACC and EACC can be seen in Appendix B. In these cases the cars were never forced to stop completely. When the cars were equipped with ACC the jams did not occur until after 300 s. If they instead were equipped with the enhanced model the jams did not occur until after 1200 s. In both these cases the waves were travelling backwards at a speed of 15 km/h.

The differences between the systems is clearly illustrated by data in figure 5. In the model with a normal driver instability occured almost immediately and on many occasions the car was forced to a complete stop. When the ACC-system was implemented there were still large oscillations but they occured later and the average velocity was higher than for the normal driver. The enhanced model was able to to keep the traffic stable for about 800 s and then oscillations occured, but with lower amplitude.

5.1 Comparison of Performance

We measured performance of the different systems as average traffic flow [vehicles/h] as a function of average traffic density [vehicles/km]. The speed limit was fixed to 50 km/h in all experiments. Data is presented in fig 6.

Initially, the performance of all three systems grow linearly as traffic was light enough to allow all cars to keep maximum allowed speed. As traffic grew denser, the cars had to slow down to keep constant time headway. All three systems follow the same performance curve until a density of 50.0 vehicles/km is reached. At this point, phantom jams appeared in the normal driver system and traffic flow droped dramatically. For the Adaptive Cruise Control system and the Enhanced Adaptive Cruise Control system, phantom jams were first observed at 56.3 vehicles/km and 68.8 vehicles/km respectively. Figure 6 also shows that the performance of these two systems was not reduced by the phantom jams as severely as for the normal driver system.

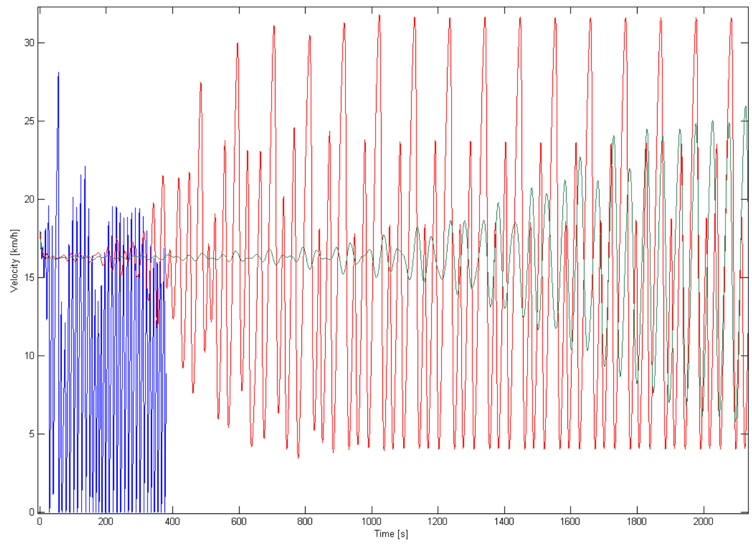

Figure 5: Velocity of one specific car on the road during 2000 seconds using the three different models. Blue cureve - normal driver. Red curve ACC. Green curve - EACC.

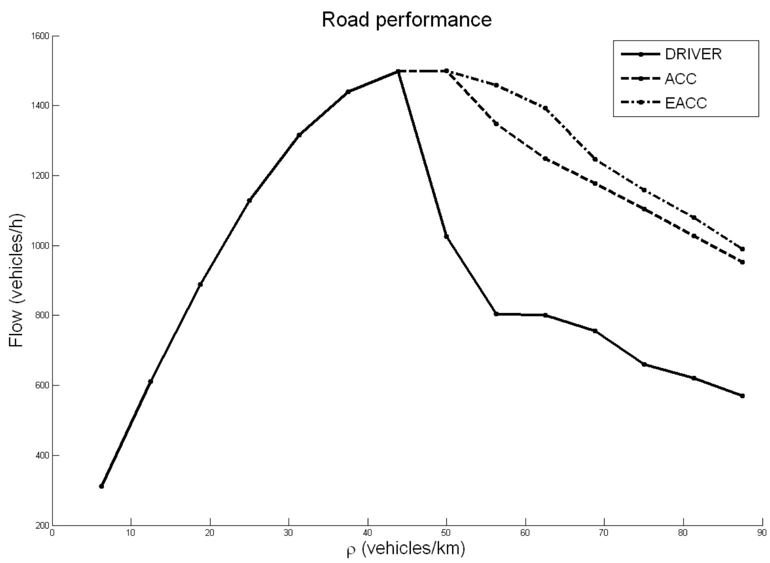

Figure 6: Traffic flow as a function of traffic density. Data from simulator. $SpeedLimit = 50\,\text{km/h}$. Traffic flow was measured when traffic conditions had stabilized.

6 Conclusion

Real-world traffic systems are complex, composed of light and heavy vehicles, complex road systems, individual drivers etc. We have chosen to work with a minimalistic model, still capable of reproducing phantom jams as observed in real-world traffic.

We have investigated two systems that show promising results in our simulations compared to a *normal driver*. The normal driver used in our simulations is, however, not a normal driver. It is capable of perfectly assessing the distance to and the velocity of, the vehicle if front of it. All cars also share the same driver model. In fact, the only thing separating the normal driver system from the ACC system is the reaction time. We have done some simulations with mixtures of vehicles with different dynamics and with non-deterministic driver models. Our impression is that this worsens the problem with phantom jams, and reduces traffic flow further. We also believe that ACC and EACC has the ability to stabilize these systems, which more closely resembles reality, and expect the performance gap to normal drivers to be even larger in reality. But, more investigations and simulations on the topic is need.

So, what's the catch? Using systems such as ACC and EACC in real world situations to improve road capacity might not be a straight-forward task. G. Marsden et al. address some of the problems with ACC in *Towards an understanding of adaptive cruise control* [4]; A lane with ACC vehicles can experience increased instability, compared with manual driving, in some traffic situations. For instance, when a manually controlled vehicle cut in between two ACC vehicles, a sharp deceleration caused by the suddenly decreased time-gap might start a travelling traffic jam. Also, speed and traffic capacity has been shown to vary with ACC target time-gaps and penetration rates.

To sum up; Traffic jams constitute a severe problem in the world today. Building new roads or modifying old road systems to reduce jams and improve road performance costs huge amounts of money. Our simulations clearly indicates that automatic or semi-automatic vehicle control systems have the potential to shift the critical level of traffic density at which phantom jams occur upwards. Also, the performance penalty for any occurring jams is reduced. This means that, if such is systems are successfully implemented, existing roads could handle heavier or much heavier traffic.

Acknowledgements

This work was performed as part of the course *Simulation of Complex Systems* at Chalmers University of Technology. Thanks to our advisor Kolbjørn Tunstrøm.

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A GUI

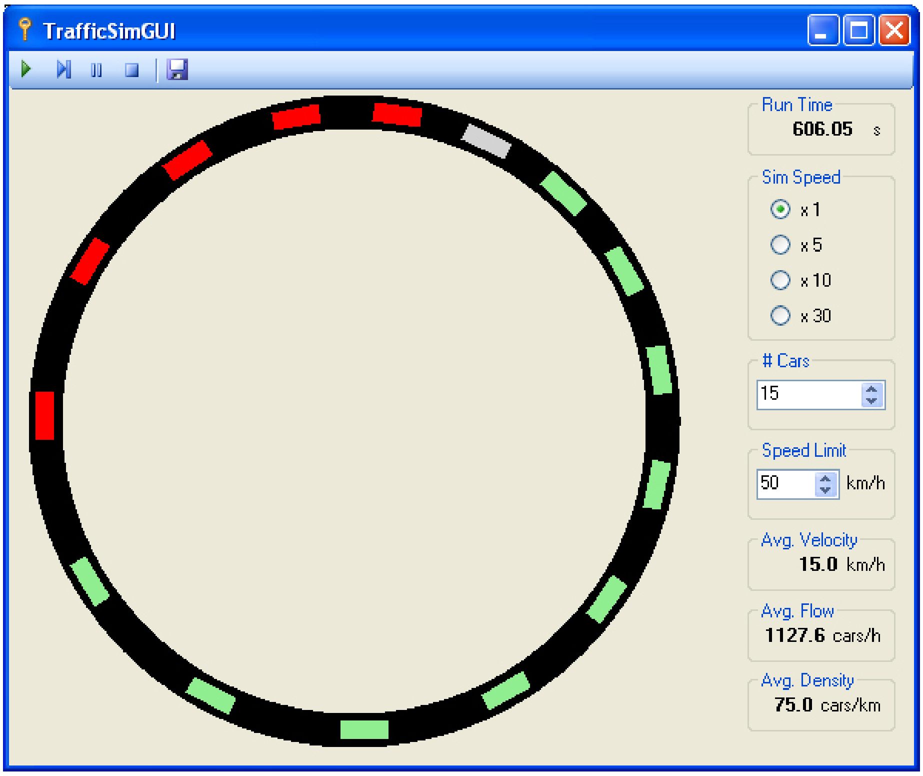

Figure 7: Graphical interface of the simulator which is programmed in C#. In this figure the road is 200m long with 15 cars. Red cars are braking, green cars are accelerating and the grey car is keeping a constant speed.

B Results

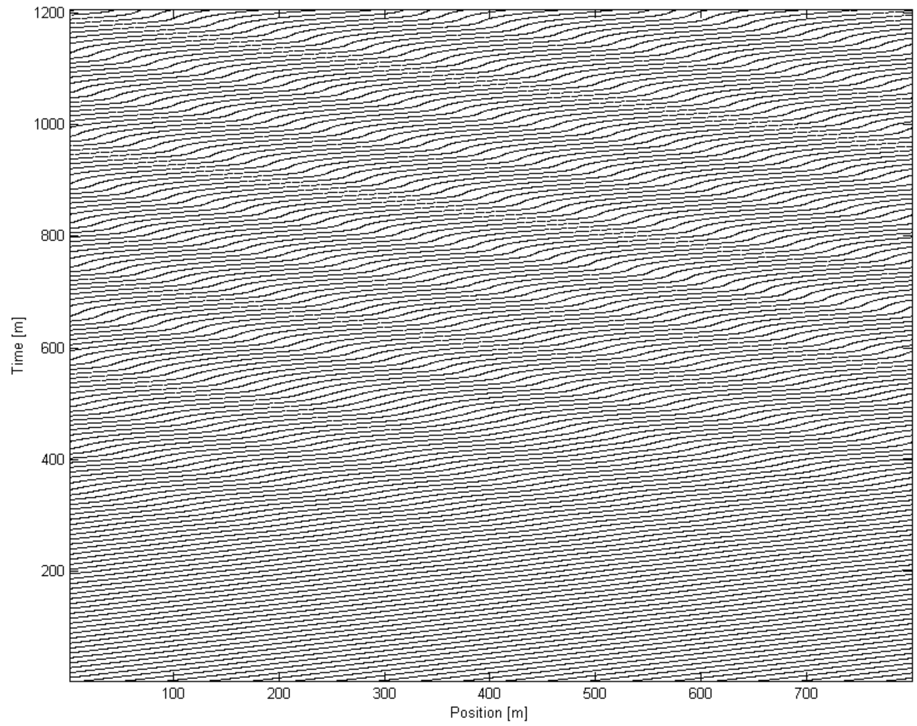

Figure 8: Absolute position of 60 cars equipped with adaptive cruise control during 1200 s. Data from simulator. After 400 s phantom jams are emerging.

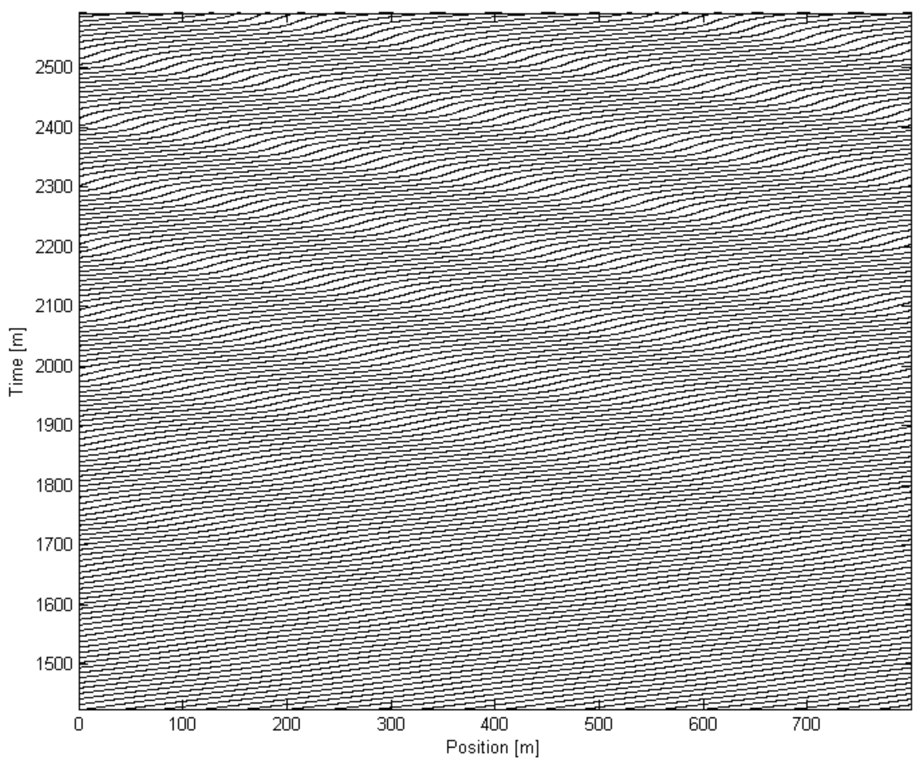

Figure 9: Absolute position of 60 cars equipped with enhanced adaptive cruise control in the timegep 1200 − 2600 s. Data from simulator. After 1300 s phantom jams are emerging.