Avoiding phantom jams in traffic

- Simulations with agent-based models

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

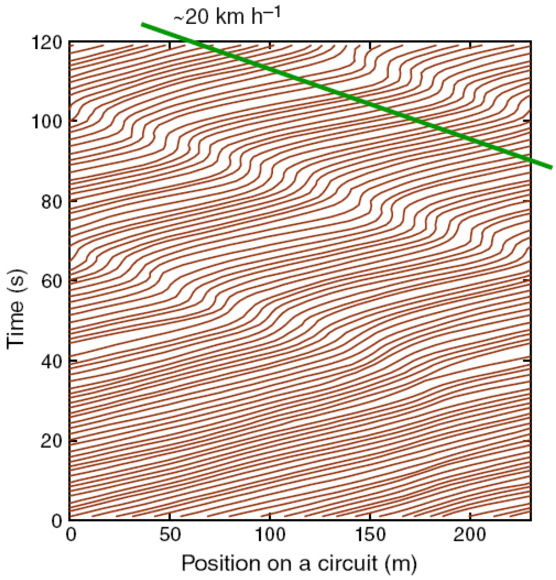

Figure 2: Data measured during the experiment seen in fig 1. A disturbance can bee seen after 40 s and is quickly amplified into a phantom jam, traveling backwards around the circle at approximately 20 km/h. Diagram by Y. Sugiyama el al. [2].

Traffic flow and thereby the efficiency of roads, is severely reduced by traffic jams such as phantom jams. 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.

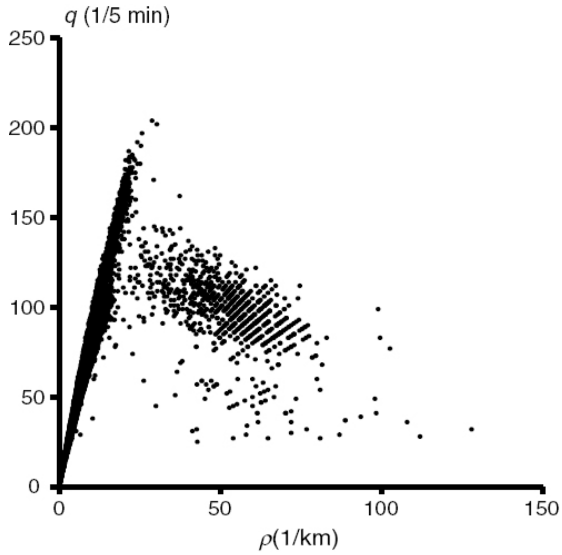

Figure 3: Traffic flow as a function of traffic density. The data is clearly divided into two sets, one representing free flowing traffic and the other (above the threshold of 25 vehicles per km) representing congested traffic (with traffic jams). Results from article by Y. Sugiyama el al. [2]. Data 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, model each vehicle while macroscopic models model 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 simulator created there was a one-lane circular road with a length of 800 m. Different amount 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 circle, but then every car was moved forward randomly between 0 and 1 metre to create some initial perturbation that speed up the upcoming of phantom jams. The design of the simulator can be seen in Appendix. (FIXME: picture of the simulator).

4.1 Implementation of mathematical models

The three systems described in Sections (FIXME: ref till dessa tre modeller) were implemented as described below. Since the simulator used a circular road position of the car was transformed into an angle from 0 to 2π but since the acceleration and velocity were not affected by this, the car was only aware of a straight road where the car going out in one end started over from the other end.

4.1.1 Normal driver

The IDM is developed to describe a normal behavior of cars in traffic and hence we have implemented the model in our simulations with only one difference. A delay of the acceleration has been added which represents a 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 which affects the acceleration.

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 believe that the system has a reaction time of about 200 ms. Table **??** shows the parameter setings.

4.1.3 Enhanced adaptive cruise control

How to implement a system that can adapt to changes further ahead than the car infront is not obvious. In our model we have assumed that the system can get the exact information about the position and velocity of the cars further ahead. The dynamics that should be considered from the car in front is the difference of velocity between the two cars. This is implemented in the effective desired distance equation (2) from the IDM. The enhanced model was then realized by changing the equation of the desired distance and also include the difference of velocity of the car further ahead. To add this feature to the implemented model we changed equation (2) to have one extra term.

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

where $\Delta v_2 = v_\alpha - v_{\alpha+2}$. Since the enhanced model is controlled similar to the ACC system we also 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] since data can be compared. Figure 4 shows the absolute position on the circular road of all the 60 cars with normal drivers for 150 s. In this plot it can be seen that several of the cars come to a complete stop after 30 s. These stops can then be characterized as waves [3] that are moving backwards in the lane with a constant speed of 13 km/h.

In figures (FIXME:) there are data from the simulator when the cars are equipped with ACC and EACC respectively and the jam dynamics can be seen. In these cases the cars are never forced to stop completely. When the cars are equipped with ACC the jams does not occur until after 300 s. If they instead are equipped with the enhanced model the jams do not occur until after 1200 s. In both these cases the waves are travelling backwards in a speed of 15 km/h.

Differences between the systems can easily be seen in Figure 5. In the model with a normal driver instability occurs almost immediately and on many occasions the car is forced to a complete stop. When the ACC-system is implemented

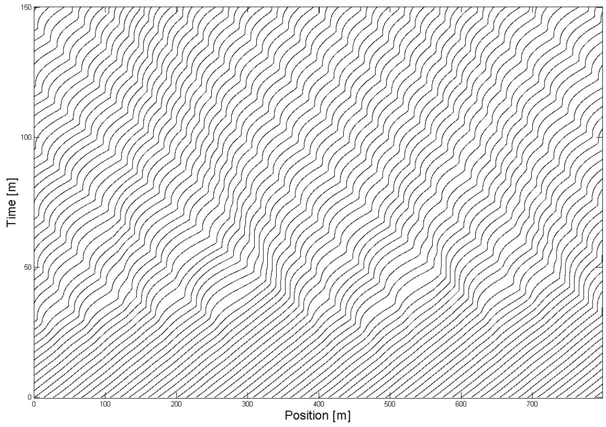

Figure 4: Absolute position of 60 cars for 150 s. Data from simulator. After 30 s phantom jams are emerging.

there are still large oscillations but they occur later and the average velocity is higher than the normal driver. The enhanced model is able to to keep the traffic stable for about 800 s and then oscillations occur.

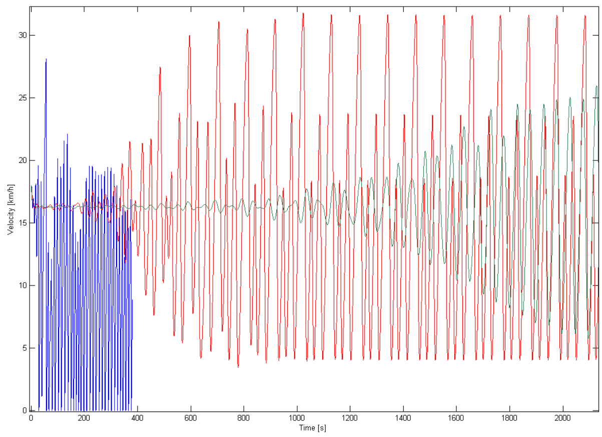

Figure 5: Velocity of one specific car on the road during 2000 seconds and using the three different models.

5.1 Comparison of Performance

We measure 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 **??**.

Initially, the performance of all three systems grow linearly as traffic is light enough to allow all cars to keep maximum allowed speed. As traffic grows denser, the cars have to slow down to keep constant time headway. All three system follow the same performance curve until a density of 50.0 vehicles/km is reached. At this point, phantom jams appear in the *normal driver* system and traffic flow drops 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. Fig 6 also shows that the performance of these two systems is not reduced by the phantom jams as severely as for the *normal driver*.

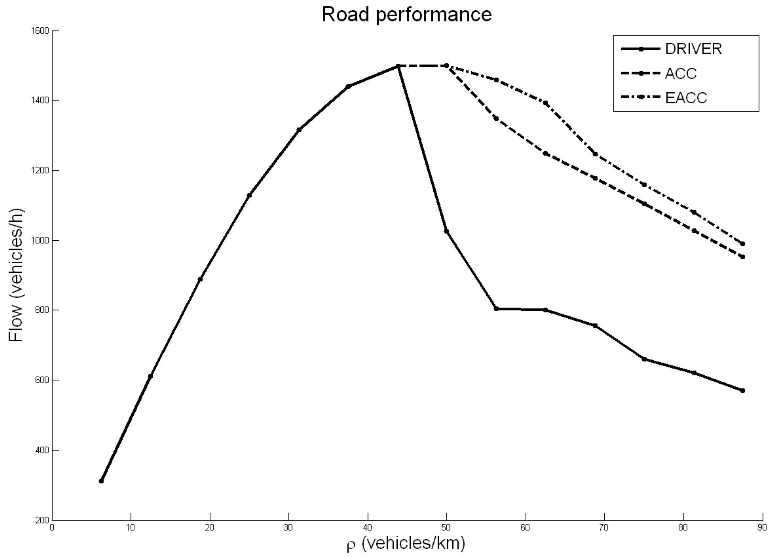

Figure 6: Traffic flow as a function of traffic density. Data from simulator. $RoadLength = 800\,\mathrm{m}$, $SpeedLimit = 50\,\mathrm{km/h}$, $TimeHeadway = 1.5\,\mathrm{s}$. Traffic flow was measured when traffic conditions had stabilized.

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.

7 Acknowledgements*

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

inputappendix

References

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