European Transport Conference 2014 – from Sept-29 to Oct-1, 2014

Phantom jam avoidance through in-car speed advice

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Abstract

The existence of phantom jams can be explained following the definition of Kerner & Konhäuser (1993) who state that a phantom jam occurs without the existence of a physical bottleneck and is caused by the imperfect driving style of road users under metastable traffic conditions. In order to prevent a phantom jams to occur, one can either focus on the cause of the perturbation, or on the metastability of the traffic flow. Previous studies have shown that the use of dynamic speed limits, displayed by road-side equipment, is a successful instrument to stabilize traffic flow and to dissolve formed phantom jams (e.g. Specialist algorithm tested in Dynamax project in The Netherlands). However, the increasing attention and possibilities for in-car application can provide more accurate and personalized or differentiated advice possibly increasing the impact. In our research we have tested several strategies implementing in-car dynamic speed limits in order to prevent phantom jams from occurring. Penetration rate and the compliance rate of car drivers were varied to investigate the effects. For this, a microsimulation study was set up based on the VISSIM software, for a stretch of highway without any on- and off-ramps. Different strategies for speed advice have been evaluated, where the actual speed and the thresholds were varied. For this purpose we processed the speed and flow data that were detected by dual loop detectors, by using fuzzy logic rules in order to determine the spatio-temporal traffic conditions. Based on these traffic conditions a speed advice is given. The spatio-temporal traffic conditions are derived from Kerner's three phase theory and the forecasting of traffic objects method (FOTO) by Kerner et al. (2004). Subsequently, this data is processed using clustering techniques to determine when and where on the network advice should be provided in order to prevent a phantom jam from occurring. It turned out that prevention based advice systems, making use of the presence of high intensity waves, are successful in preventing phantom jams from occurring. A significant reduction of both the number of phantom jams as the total jam weight has been measured. Consequently this also contributes to the traffic safety as traffic is stabilized and speed differences between vehicles are reduced.

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Selection and peer-review under responsibility of Association for European Transport

Keywords: Phantom jams; ITS; Traffic management

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1. Introduction

During the first decade of the twenty-first century, congestion has been rapidly increasing. This has not just led to growing frustration under road users but has also serious implications on traffic safety. Of all congestion, over 20% is recognized as shockwave jams or so-called phantom jams. A phantom jam can be best defined as the spontaneous formation of traffic congestion which is not caused by obvious reasons such as an accident or a bottleneck, but by tiny fluctuations, caused by finite reaction times of drivers, which lead to speed perturbations. A phantom jam consists of two sharp fronts bounding a plateau of slow moving traffic with a downstream front which is not fixed at a bottleneck and which propagates upstream. A reduction of the number of phantom jams originating on highways can help to improve travel times and moreover can it help to improve traffic safety by means of a reduction of head-tail collisions.

To prevent phantom jams from occurring, either the cause of the perturbations or the metastability of the traffic flow can be focussed on. Earlier research has shown that dynamic speed limits, communicated by road-side systems, can be a successful instrument in stabilizing traffic flow (Smulders,1990), increase traffic safety (Smulders,1990) or suppressing phantom jams (Hegyi, Hoogendoorn et al. 2008). However, road-side systems are of decreasing importance to drivers as in-car advice systems are able to provide personalized advice which is much more accurate (Rutten et al. 2013). This trend is reflected by the fact that in-car advice plays a major role in more and more traffic management projects in the Netherlands and also other countries in Europe (e.g. Praktijk Proef Amsterdam (PPA), the CHARM project and the pilot-project "Spookfiles").

This paper continues on the use of dynamic speed advice in the battle against phantom jams. This proved concept has been combined with the rising importance of in-car advice. Therefore, dynamic speed advice has been brought to an in-car driver support system. This enables more flexibility in the design (the nature) of the advice system and makes it independent of the availability of road-side systems. However, it brings a large dependency on the penetration rate of the system. This paper describes the results for two prevention based in-car speed advice systems. Both these systems have in common that it is aimed for to prevent phantom jams from originating.

2. Theoretical background

The existence of phantom jams can be explained using the traffic flow theory of Kerner (2003). Based on the difference between the theoretical relation and non-heterogeneous traffic, Kerner developed its related three phase theory and the stability of flow (Kerner 2003). The three phases which Kerner distinguishes are visualized in the flow density diagram in figure 1: Free flow (F), Synchronized flow (S) and moving jam (J).
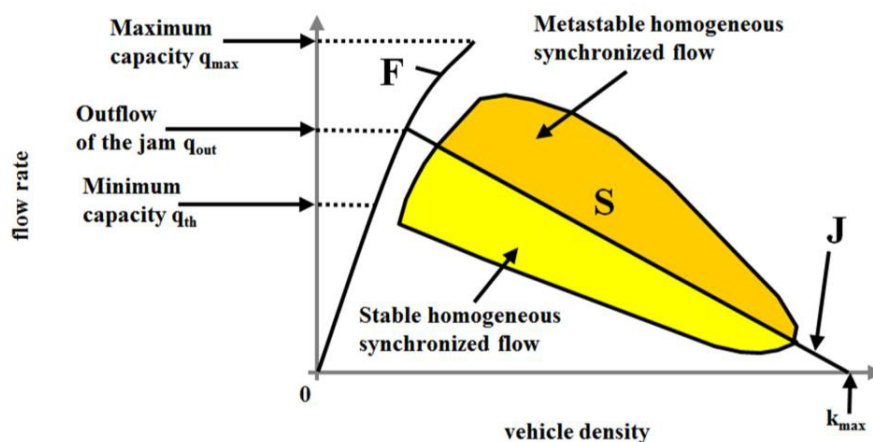

Fig 1. Three phase theory of Kerner and stability (Kerner, 2003).

The existence of phantom jams is highly related to the stability of the traffic flow and the magnitude of a perturbation in traffic flow. Under stable traffic conditions perturbations will not result in decay from free flow to

synchronized flow. However, under metastable conditions perturbations can develop into phantom jams. The less stable traffic flow is, the easier small perturbations can develop into congestion. Whether traffic is metastable depends on the combination of density and speed. Both stable as metastable traffic conditions can be recognized in figure 1. Traffic state is metastable (or unstable) if it is related to a point above line J in the flow density diagram. Under metastable traffic conditions perturbations which exceed certain critical amplitude can grow and lead to a phantom jams (i.e. wide moving jam).

Various studies have been performed on affecting the stability of traffic flow using variable speed limits. Smulders (1990) aimed to influence the stability of the traffic system through the homogenization effect. Others (Hegyi et al. 2008; Carlson et al. 2009; Popov et al. 2009), focussed on reducing the flow by means of speed limits in order to prevent traffic breakdown or to resolve arisen shockwaves. An algorithm called Specialist was tested by Hegyi et al. (2008) in a field operational test. This pilot has been successful in resolving arisen shockwaves. However, it needs to be remarked that this research did not focus on phantom jams solely but also on the phenomenon of congestion tails.

3. Case study

A case study has been performed in order to evaluate the effectiveness of various speed advice systems. Therefore, the VISSIM micro-simulation software has been used in which a 10 kilometers highway has been simulated. This network is based and calibrated on a realistic part of the Dutch highway network (A58) which is known for the appearance of phantom jams. To be able to evaluate traffic handling, the network has been equipped with detection loops. These detectors are located each 500 meter on the network. This is in line with detector configuration on the Dutch highway network. With the use of actual traffic measurements, car following and lane change behaviour are calibrated in such way that it meets most important traffic characteristics (i.e. free flow capacity, speed at capacity and queue discharge). Therefore, calibration parameters in VISSIM have been varied within the ranges determined by Qi & Park (2005).

3.1. Phantom jam originating

In figure 2, time-space diagrams for speed as well as intensity are shown. In the left figure the average speed (per minute per road section) on the network is visualized through time. It can be seen that the speed drops at detection loop location 15 around minute 40 of the simulation, which is a clear indication for a platoon of slow moving traffic (phantom jam) on the network. As no physical bottlenecks are present on the network the cause of this congestion can be nothing else then the imperfect driving style of road users. Through time it can be seen that the phantom jam moves upstream through the network. Although less clear, the same phantom jam can also be recognized in the right figure in which the intensity is visualized through time and space. When the phantom jam passes a detection loop, the measured intensity is clearly reduced compared to up- and downstream intensities.

Not only can the presence of the phantom jam be deduced from the analysis of the speed- and intensity diagrams, also the movement speed of the phantom jam can be deduced. For these model conditions, the movement speed of the phantom jams appeared to be constant over various simulations with a speed of around 22 km/h in opposite direction of the traffic. This movement speed is slightly above the movement speed of roughly 20 km/h observed by other researchers based on real traffic observations (Kerner, Rehborn et al. 2004; Sugiyama, Fukui et al. 2008).

Besides the phantom jam, no exceptional speed patterns can be observed within the speed-diagram in figure 2. However, the intensity-diagram shows a clear pattern of alternating high and low intensity shockwaves. These high and low intensity waves have been visualized in figure 3. In the left figure the low intensity waves are encircled. These are in fact platoons of traffic in which the density is relatively low. As a result, relatively low intensities are measured by detection loops while such low intensity wave passes the loop location. In contrary, high intensity waves are platoons of traffic with a relatively high density. This can for example be caused by traffic assembled behind overtaking trucks. Such platoons of high density traffic passing detection loops will result in measurements of high intensities. In the right figure these high intensity waves are encircled. Following Kerner's three phase theory, the traffic state in such high intensity waves is relatively unstable. This means that traffic state can decay easily to congestion in case of perturbation of certain amplitude. In the right figure can be seen that both phantom jams find their origin in such high intensity wave. It has been found that over 80% of all phantom jams were originating from

such high intensity waves. Therefore, an algorithm has been developed which clusters traffic measurements into intensity waves using a similar process to the free flow filter by Treiber and Helbing (2002) and classifies these intensity waves into three "danger levels". The danger level is related to the metastability of the traffic flow and is determined using a fuzzy inference system. It turned out that a higher danger level (higher metastability) increases the probability of an intensity wave to result in a phantom jam.
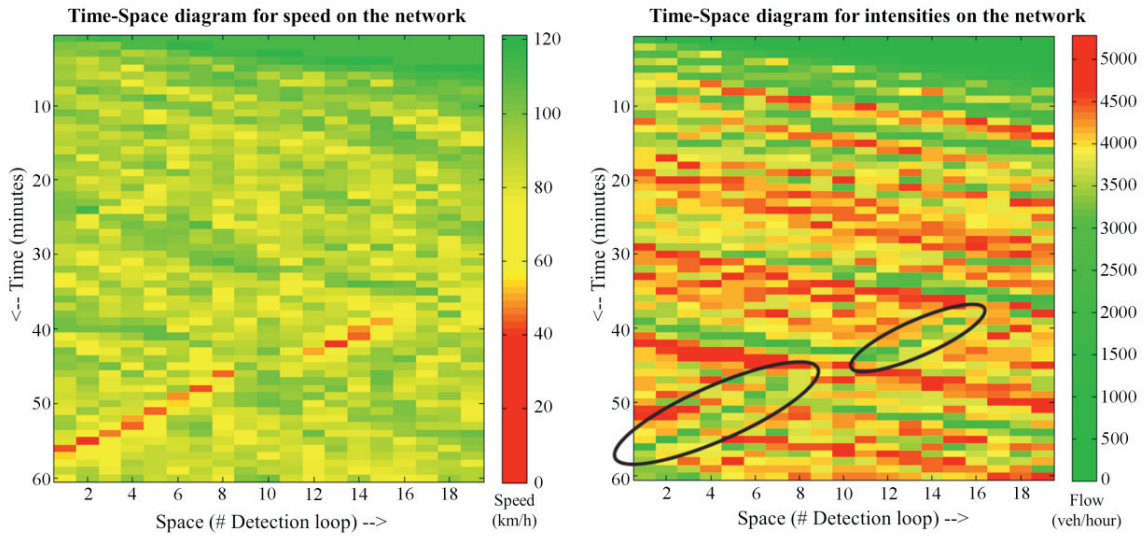

Fig 2. Time-Space diagram for speed (left) and intensity (right) on the network during simulation. Phantom jams are encircled.
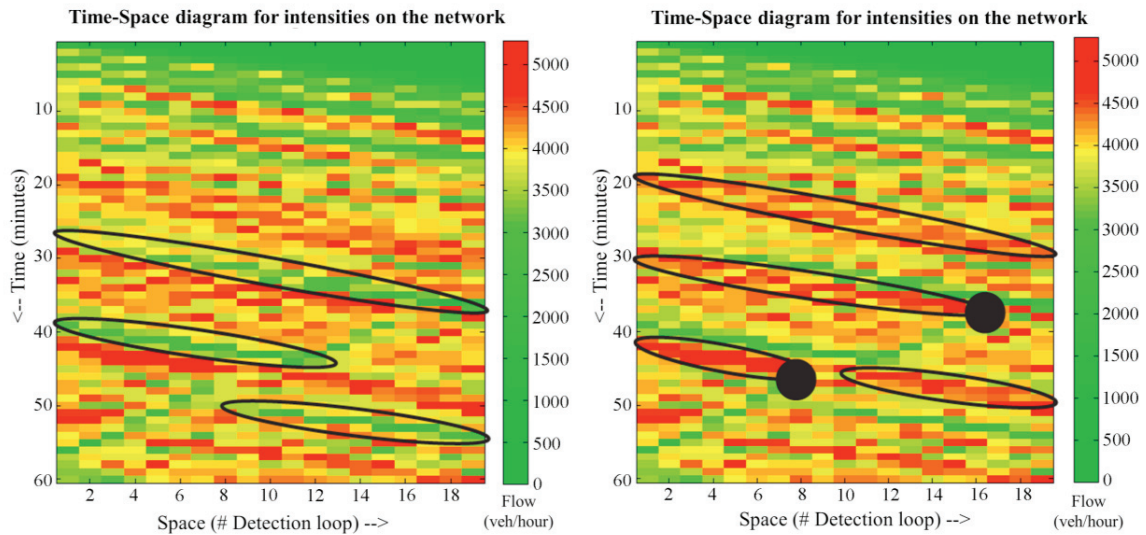

Fig 3. Space-time diagram for intensities on the network with low (left) and high (right) intensity shockwaves encircled.

This pattern of alternating high and low intensity waves is not only observed in model data, but can also be observed in field data. In figure 4, the intensity measurements for a small section of the A58 are presented for an early Friday morning peak. Just as in the model data, clear high and low intensity waves are seen.
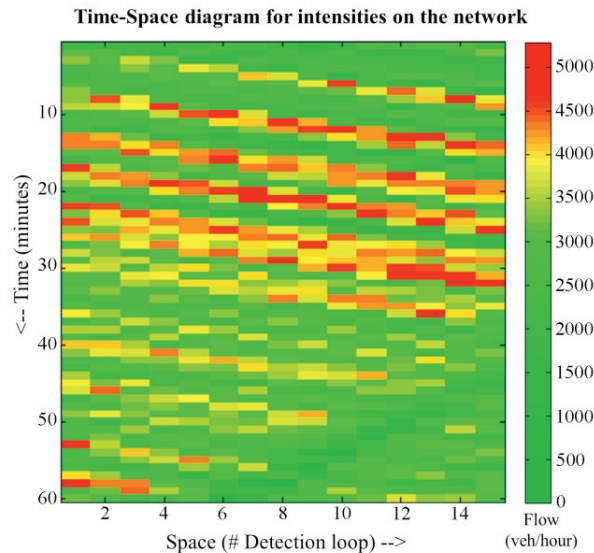
Time-Space diagram for intensities on the network

Fig 4. Space-time diagram for intensities on the A58 (Friday, April 13th 2013, 6.40-7.40 am).

3.2. Prevention based systems

Kerner's three phase theory suggests that free flow traffic with an intensity above the queue discharge capacity is metastable (Kerner 2003). Metastable traffic is sensitive for disturbances and traffic can easily fall into congestion. This is supported by the evaluation of traffic measurements as described in section 3.1. By preventing traffic from achieving such high intensities, it is theoretically possible to prevent the traffic from spontaneous decay into congestion. Note that if traffic flow never exceeds the queue discharge capacity, traffic is always stable and is able to overcome any disturbance. Not only the intensity is locally reduced using this methodology, also the traffic becomes more homogeneous. Smulders (1990) describes that homogenization by speed limits can result in a decrease of up to 50% of serious speed drops. This could contribute significantly to a more stable traffic flow with a reduced probability for head-tail collisions.

In line with this theory, advice can be given to vehicles in two ways: Non-controlled and controlled ("smart"). Non-controlled advice is given no matter what the traffic situation on the road is. All equipped vehicles receive the same pre-determined speed advice and are assumed to follow this advice. This way, the ambition is to achieve a more stable and homogeneous traffic situation over the whole network. On the other hand, a controlled "smart" strategy can be applied. This approach is more advanced and takes actual traffic measurements into account. As phantom jams originate under metastable traffic conditions accompanied with high flows only, one only needs to focus on network sections in which such traffic states occurs or is likely to occur. This way, it is strived for to stabilize and homogenize only there where it is really necessary according to traffic flow theory.

To do so, high intensity waves in traffic flow can be used to specify the selectiveness of the advice system. To this end the algorithm earlier described classifying intensity waves into three "danger levels" according to its metastability is used. If an intensity wave with a certain minimum danger level (minimal level of metastability) is detected on the network, the advice system is locally activated. If activated, speed advice is given only to equipped vehicles located within the detected high intensity wave. Note that only these sections need to be stabilized. This speed advice is typically lower than the actual vehicle speed. Consequently this results in a reduced speed within the high intensity wave. Together with the density, which does not change when speed drops on a longer stretch (no vehicles can appear or disappear), this results in a reduced intensity on the affected sections. This leads to a locally adjusted free flow branch of the fundamental diagram. The advised road sections are still in a free flow traffic state but at a lower speed. This way, the traffic flow is stabilized and it is able to recover from perturbation from itself. Figure 5 illustrates the effect of the speed advice in the fundamental diagram. Note that the red dotted free flow branch only holds for the advised traffic.
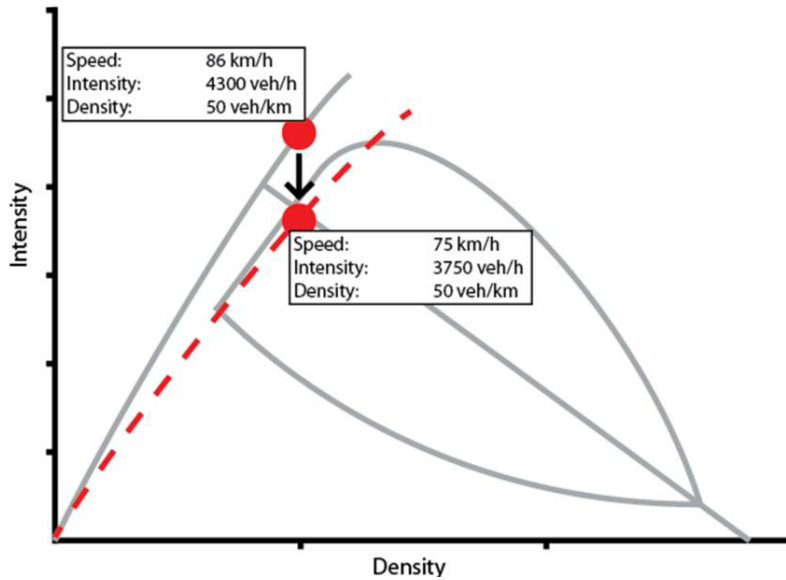
Fig 5. The effect of the intensity wave based advice system. The red dotted free flow branch represents the adjusted traffic states of the advised platoon of vehicles.

Three variants of this controlled advice system have been simulated during this study. Each variant uses the danger level provided by the algorithm which identifies the intensity waves. However, each variant uses a different threshold for the danger level from which advice should be given. This way, each system differs in its selectiveness to provide advice. In principal a higher danger level indicates a higher average intensity (a more metastable traffic flow) within the intensity wave.

4. Results

The non-controlled and the controlled advice systems are simulated and evaluated. Besides the selectiveness of the controlled advice systems, two other variables of the advice systems are varied in this research: the compliance rate and the actual speed advice. The compliance rate is in fact result of the combination of the share vehicles which have been equipped and the share of drivers with an equipped vehicle who follow the speed advice given. In this research this combination is varied (the actual share of all vehicles who comply with the given advice), resulting in penetration/compliance rates of 0%; 1%; 2%; 5%; 10%; 20%; 50% and 100%. This means that in case of a penetration rate of 10%, one out of ten vehicles will apply to the provided speed advice. The actual speed advice is the speed which is advised to the equipped vehicles. This has been varied over 80, 85, 90, 95 and 100 km/h.

The evaluation has been performed using a framework consisting of three indicators divided into two components (Table 1): The jam component and the network component. The jam component consists of jam indicators which help to analyse the performance of the network with respect to phantom jams and contains surrogate measures for traffic safety. On the other hand, the network component consist a network indicator which evaluates the macroscopic performance of the network.

Table 1. The evaluation framework.

Jam indicators	Network indicators
Number of phantom jams	Average network speed
Jam weight	

The number of phantom jams is a clear indicator to evaluate the effectiveness of the advice systems in terms of

the number of phantom jams which it is able to reduce. The jam weight on the other hand does not only evaluate the number of phantom jams which has arisen during the simulations but does also take the length and duration of the jam into account by multiplying the length and the duration of the jam. In case an advice system is not able to completely prevent a phantom jam from occurring but only postponing it, no effects are measured on the number of phantom jams but the jam weight on the other hand will reduce.

The non-controlled advice system has been simulated by reducing the desired speed of any equipped vehicle in the network no matter what the actual traffic situation is. This means that 100% of the equipped vehicles is provided with speed advice. The results of these simulations are presented in figure 6. The indicator values (vertical axis) are visualised against the penetration rate (horizontal axis) for each of the applied speed advices. The penetration rate is not plotted on a linear but on an adjusted logarithmic scale for better visualisation of lower penetration rates. The reference scenario in which no advice is provided has been added to the plot as a reference by means of a horizontal black line. The results of each of the advice systems are tested on significance difference with the reference scenario using a paired T-test. The plotted dots visualize results which indeed are significantly different from the reference scenario.
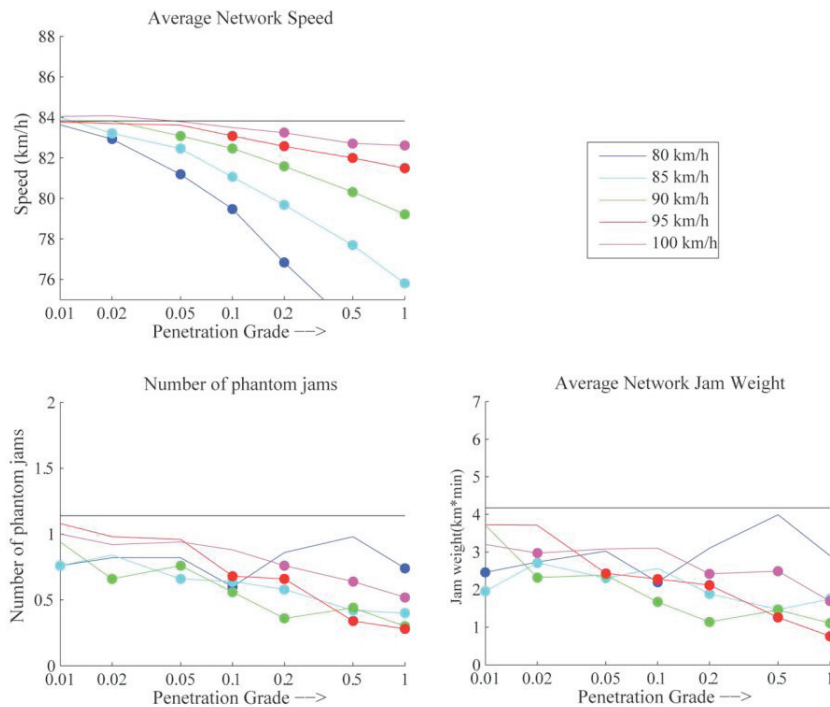

Fig 6. Results of the non-controlled advice system.

As can be seen in figure 6, independent of the given speed advice or penetration rate, the average network speed decreases if speed advice is given. The lower the speed advice and the higher penetration rate, the more the average network speed is reduced by the advice system. Looking at the average number of phantom jams per simulation, a clear trend can be recognized that the number of phantom jams decreases as a result of providing speed advice. Note that for any speed advice and any penetration rate the indicator values are below the reference value. For the average network jam weight a similar trend can be recognized. A decrease of up to 50-75% is seen with a penetration rate of 100%. An average jam weight of 1 to 2 km*min for the advice systems with a provided speed advice of 85-100 km/h with 100% penetration rate is measured versus an indicator value of over 4 km*min for the reference scenario. It needs

to be remarked that, due to the logarithmic scale of the penetration rate axis, the decrease is not as linear as it appears to be. In fact, the largest part of the decrease is achieved with only relatively low penetration rates.

The results for the controlled, intensity wave based, advice systems are shown in figure 7. The three variants vary in the "danger level" of the intensity wave which triggers the advice system. Variant 1 is already triggered with a relatively low danger level (metastability) while variant three is only activated if a high danger level is reached.
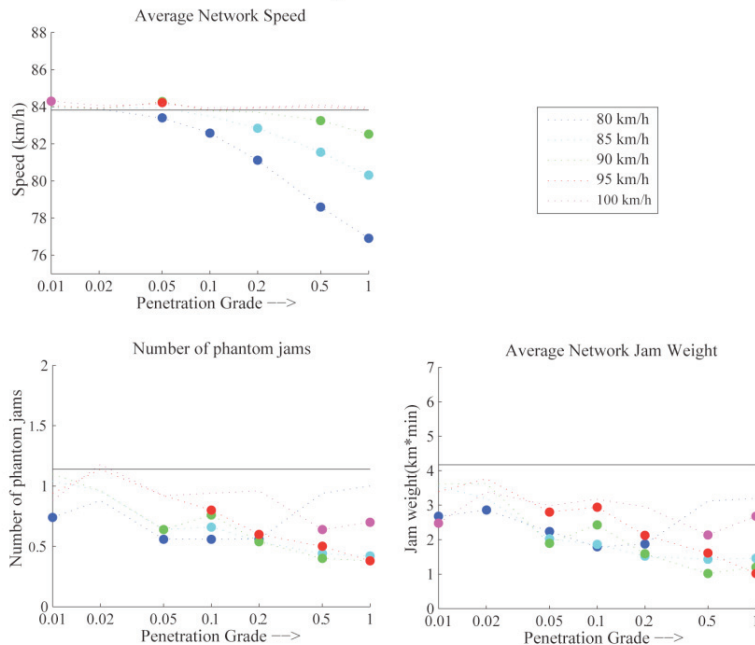

Fig 7a. Results for the controlled advice system variant 1.

The results of the controlled algorithms (variant 1 and 2) are very similar to the results of the non-controlled advice system for the jam indicators. Both indicators (number of phantom jams and average jam weight) are positively affected with increasing penetration rates. Indicator values for both advice systems are clearly lower than the reference value. The reduction of the average network speed is limited compared to the non-controlled advice. Note that for the non-controlled advice system already speed reductions have been measured with only very low penetration rates of around 0.02, while the controlled advice system of variant 1 and 2 only result in clear average speed reductions only from 0.1 and higher. This indicates that it pays to use a speed advice depending on the identification of high intensity waves. Hence, similar effects on the number of jams and the jam weight are achieved using controlled advice systems but the negative effects on the average network speed are reduced. The effects of variant 3 of the controlled advice system are clearly limited compared to variant 1 and 2. This can be explained by limited number of high intensity waves with danger level 3 during the simulation. Hence, the advice system was much less activated than the other variants.

Further analysis shows that higher penetration rates allow a higher speed advice to perform similar with advice systems with low penetration rates. When only a few cars are provided with information, a low speed advice is required to achieve a significant speed reduction on average. With higher penetration rates a "higher" speed advice can result in the same effect on the local network speed. Higher penetration rates do furthermore result in more reduction of the number of phantom jams as traffic flow is homogenized more effectively. However, the marginal effect is higher at low penetration rates. The largest part of the effect is found if 10% of the drivers comply with the given speed advice. However, this cannot be clearly deduced from the figure 6 and 7 as a result of logarithmic horizontal axis.
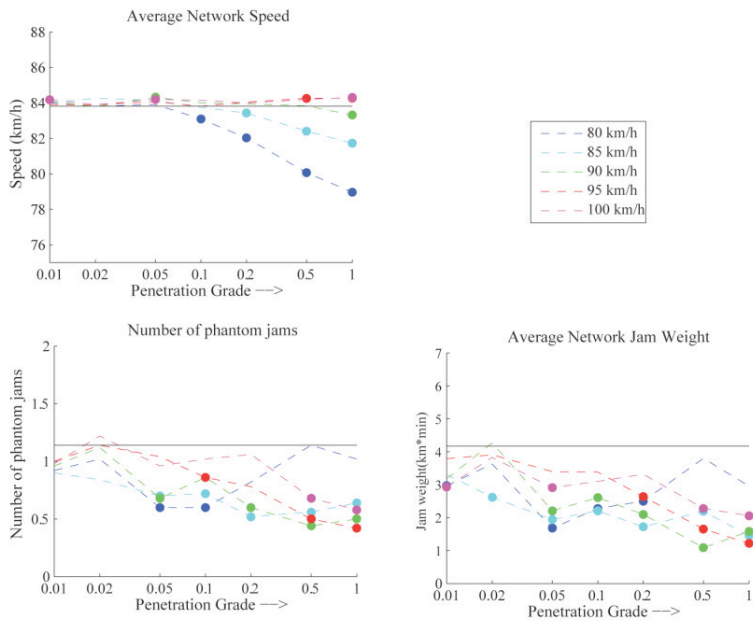
Intensity wave variant 2

Average Network Speed

Number of phantom jams

Average Network Jam Weight

Fig 7b. Results for the controlled advice system variant 2.

Intensity wave variant 3

Average Network Speed

Number of phantom jams
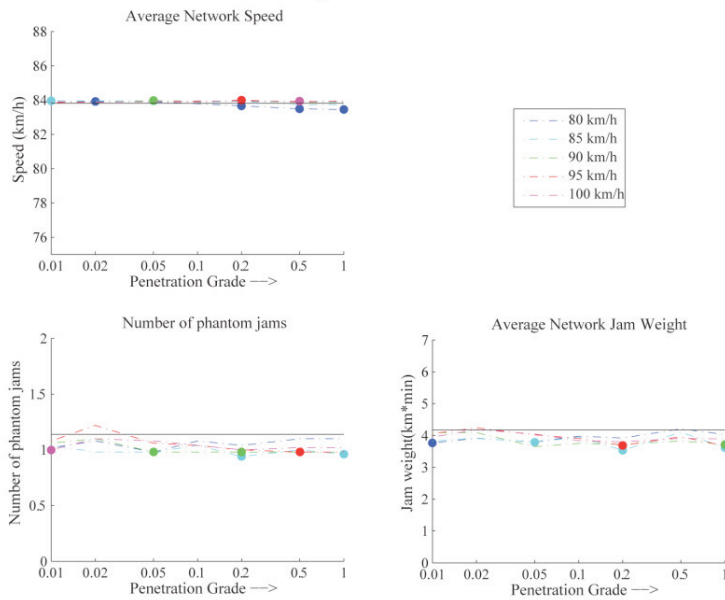
Average Network Jam Weight

Fig 7c. Results for the controlled advice system variant 3.

5. Discussion and conclusions

Using a micro-simulation environment phantom jams have been simulated and analysed. It is found that the origination of phantom jams is related to the appearance of high intensity wave. This is in line with Kerner's three phase theory which explains the metastability of free flow traffic with high flows. Perturbations in such metastable traffic conditions easily result in decay from free flow to congestion.

This study proved prevention based advice systems, making use of the presence of high intensity waves, to be successful in preventing phantom jams from occurring. The number of phantom jams and the average jam weight are significantly reduced. Speed differences between vehicles are reduced and traffic is stabilized which provides a contribution to traffic safety.

It is recommended to perform further research on the effect on the average network speed on a full-scale network, because it is expected that a reduction of the number of phantom jams can have a significant positive effect on the network speed due to reduced spillback effects. Spill back effects at on- and off ramps in combination with the capacity drop phenomena could possibly prevented. Also more research is needed, improving the selectiveness in activating the advice system and the optimal combination of current traffic state and speed advice given (what part of traffic and height of advice). Finally next to prevention algorithms, speed advice could also be used to dissolve phantom jams. In addition, also other in-car advice related to lane choice or following distance could be of interest to dissolve or prevent phantom jams. Further research on these types of in-car advice is needed to investigate the effectiveness of these approaches.

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