INDIVIDUAL TRAVELLERS' ADVICE:
SYSTEM SETUP, MEASURES, AND EXPECTED RESULTS

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ABSTRACT

Traffic congestion can be reduced by traffic control. Individual traffic control gives the largest range of possibilities to control traffic. However, having more possibilities to intervene also raises the question what is the best process to control. This paper first explores the possibilities to intervene in the traffic processes. Then, the paper lists the best possibilities to alleviate traffic congestion based on insights from traffic flow theory. It is discussed which measures are best to take in which conditions, taking into account that drivers can be advised on headway, speed or lane. The paper also shows the structure and the elements required to calculate the optimal advice. Finally, the paper shows what, qualitatively, are expected to be the best control strategies for a variety of traffic conditions.

1 INTRODUCTION

Recent technological developments enable giving car drivers individual advice. It is thought that a controlled adjustment of speeds and headways can avoid congestion, as well as a controlled lane changing process.

A project "Connected Cruise Control" (CCC) was set up in order to create a system in which vehicles communicate with the infrastructure. The aim of the system is to reduce traffic congestion by providing advice to the drivers regarding speed, headway and lane choice. The compliance of the drivers is important and should be incorporated in the optimisation of the advice. The compliance depends on the way drivers are instructed. An optimisation of this Human Machine Interface (HMI) is part of the project, but is not within the scope of this paper. This paper gives an overview of the steps to be taken in the process of developing a system for traffic control by providing advice to individual drivers. Also, the optimisation of the control is discussed. To this end, the paper presents an overview of the literature in traffic flow focusing on potential problems and the corresponding control measures. The goal of the paper is to show how such a project is best set up, which elements are important and which tools can be used.

The paper first gives an overview of the literature on traffic flow (section 2). Similar projects which aim improving the traffic flow situation by giving individual advice are mentioned as well as their results (section 3). Section 4 gives the resulting propositions to improve the traffic situation. The technical side of the modelling is discussed in section 5. An element which is necessary in the optimisation procedure to predict the effects is a lane-specific macroscopic traffic flow model. Such a model is introduced in section 6. Section 7 shows the options of traffic control which are considered best for different situations, given the possbilities of control of CCC. Finally, section 8 presents the conclusions and the outlook.

2 THEORY ON TRAFFIC FLOW

A first step in solving traffic congestion, is the understanding of the phenomena leading towards congestion. This section gives an overview of the literature with respect to queuing. First some definitions will be laid out. Section 2.2 discusses the different ways of describing observed traffic flows. Sections 2.3 and 2.4 review the mentioned causes for the transition to stop and go waves and the existence of the capacity drop respectively.

2.1 Definitions

This section first presents the terms we will be using in the remainder of the paper. We try to stick as much as possible to commonly accepted terms in traffic flow theory.

For an overview of literature traffic flow stability, we refer to Pueboobpaphan and van Arem (*1*) and a figure from their paper, figure 1. They point out that there are 3 forms of stability: local, platoon and traffic stability. If a vehicle pair is not locally stable, the following vehicle will make an oscillating (possibly increasing in amplitude) movement once his leader will decelerates. A platoon is unstable if a vehicle in the platoon, possibly the last, will make an oscillating (possibly increasing in amplitude) movement once the platoon leader decelerates. Traffic is unstable if a disruption of a vehicle in a platoon will be amplified by other vehicles in another platoon. Even with unstable platoons, the traffic flow can be stable because there is enough space between the platoons. We define furthermore two phases of driving on a microscopic scale: free driving, which means a driver can drive his desired speed, and constrained driving. In that case, the driver follows his predecessor and the car is said to be in car-following mode.

Laterly, we restrict to lane-chainging, where we distinguish mandatory lane changes, desired lane changes and courtesy lane changes. A lane change is mandatory if (1) the lane ends or (2) the driver needs to change lane to reach his destination (e.g., off-ramp, motorway junction). A lane change is desired if the driver wants to change lane in order to have a better utility – often a higher speed. If a driver changes lane
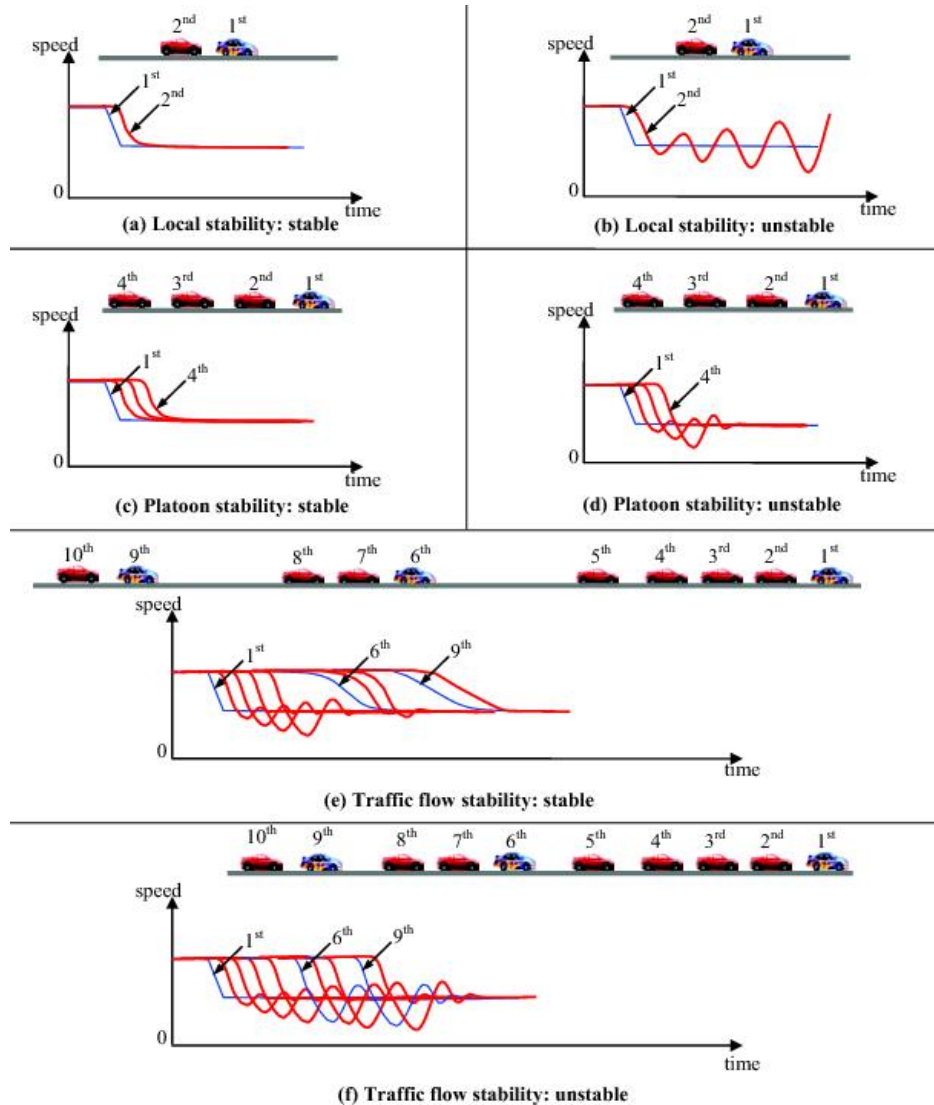
Figure 1: Illustration of stability definitions, figure after Pueboobpaphan and van Arem (*1*)

in order to help someone else (either in a desired lane change or in a mandatory lane change), this is called a courtesy merge.

2.2   Empirics and description of traffic flow

To quantify the traffic operations, flow, density and speed are used. The best accepted definitions are those by Edie (*2, 3*), which defines density, flow and speed for an area in space-time. However, it is not always possible to find calculate these variables in practice. Often, traffic is measured by loop detectors which have difficulties to measure slow moving traffic; standing traffic will not be measured at all since it is not passing the loop detectors

Nevertheless, most traffic flow theories use aggregated loop-detector data as main empirical underpinning. The most important ones are two-phase traffic flow theory (e.g., Helbing (*4*)) and the "three phase traffic flow theory" by Kerner (*5*).

Two-phase traffic flow theory assumes there are two basic traffic phases, a free flow traffic phase

and a congested traffic phase. These are separated by the capacity point (or a plateau, (*6*)), the point where the maximum flow is obtained. If the demand is higher than the capacity, drivers have to wait for their turn and traffic is congested.

Kerner (*5*) proposes that traffic can occur in three phases: free flowing, synchronised, and wide moving jams. Free flow traffic moves fast and there is a difference in speed between different lanes. In synchronised flow, the speed is lower and moreover the speed in the different lanes is the same: the flow in the lanes is "synchronised". Remarkable in the theory of three-phase traffic theory is that the flow in this phase might be higher than in free flow traffic. In synchronised traffic disturbances occur. They might grow to areas where the cars are stopped. These areas move upstream on the road. This is seen as the third traffic phase.

All descriptions have a part on free flow traffic. We also find that in all empirical studies, there is a part with light congestion and a part where heavy congestion travels upstream in repetitive waves. For now on, we will refer to these three traffic situations as: free flow traffic, congested traffic, and stop-and-go waves respectively. Although these phenomena can be seen, we will try not to intervene in the discussion whether congestion is a different traffic *phase* compared to stop-and-go waves, or that stop-and-go waves are simply an occurrence of congestion.

Once traffic has been in a congested phase and moves to a non-congested phase, the capacity is lower than before congestion set in. This is the so called capacity drop, as described, amongst others, by Hall and Agyemang-Duah (*7*), Dijker et al. (*8*), Cassidy and Bertini (*9*) and Chung et al. (*10*). Values of quoted capacity reduction differ from several percents to several tens of percents. Up to now, the reason of this capacity reduction is not known.

2.3   Causes of start of stop-and-go waves

This section discusses various possible explanations for the start of stop-and-go waves. A first explanation lies in car-following behaviour. Tampère et al. (*11*) show that these can originate from drivers' behaviour. The authors use a diver behaviour model to show the phenomena regularly found in traffic, including shock waves and a capacity drop. The model is not calibrated on individual drivers, but the parameters are chosen to get a representation of the macroscopic traffic models. Sugiyama et al. (*12*) show that stop-and-go waves occur even if there is no lane changing and no external influence. Their experiment consisted of several vehicles (22, 23 turned out to be critical) on the on a roundabout where drivers were instructed to keep a steady speed and a steady but safe headway. It shows that if the traffic density is too high, small disturbances grow. Since it is a roundabout, they continue growing and traffic will come to a complete standstill.

At the other hand, Daganzo et al. (*13*) show that there always is a reason for breakdown, and there is no reason to assume that any small disturbance can grow to a stop-and-go wave. They studied loop detector data in the US and in Germany. The used data shows that the breakdowns happen often near an on-ramp, off-ramp or merging section, indicating that lane-changing could well be the cause of the breakdown.

A more detailed data set is studied by Ahn and Cassidy (*14*). They study individual vehicle trajectories, collected in the NGSIM project. They study the start of shock waves and they find that all stop-and-go waves emerge from lane change maneuvers. The origin of the waves are merges into gaps which are too short (measured in distance). Disturbances are then formed and these disturbances will grow, as is shown in the paper.

A theoretical model explaining these shocks is presented by Yeo and Skabardonis (*15*). For this study, also NGSIM data is used. They focus on the growth of a disturbance, caused by for instance a lane chance. A car-following model with two boundaries, one for accelerating and one for decelerating, can predict the shock propagation well.

2.4 Capacity drop

This section mentions the explanations given for the capacity drop.

Chung et al. (*10*) shows the empirical relationship between density and the capacity drop. It shows that for higher densities there is a drop in capacity, and moreover that this density is the same for all three studies locations. The paper indicates that this finding can be used in combination with density control. However, the paper does not provide a microscopic explanation for the observed phenomenon.

Daganzo (*16*) argues the capacity is reduced by lane changing and traffic heterogeneity. In particular, the article focusses on the difference in desired speed between two categories of drivers. The second part of this article, Daganzo (*17*), applies this idea to an on-ramp with merging traffic. Once the faster vehicles that have already merged onto the right lane want to change lanes towards the faster lanes the capacity of the road drops due to mixing effects.

Laval and Daganzo (*18*) show the impact of lane changes and pose a model. The model predicts a lower flow due to lane changing. In fact, the created voids due to lane changing reduce the flow. The model is validated using preliminary data from Cassidy and Rudjanakanoknad (*19*). By Cassidy and Rudjanakanoknad (*19*) it is shown that metering the on-ramp actually increases the total outflow. The explanation given for this observed fact is that there are less lane changes to avoid congested parts of the road, which, in accordance with Laval and Daganzo (*18*) increases the total flow.

Menendez and Daganzo (*20*) show a theoretical idea why an HOV lane would reduce the capacity. A "smoothing effect" would take place, according to this theoretical idea. This is confirmed by Daganzo and Cassidy (*21*) with an empirical evidence. The observed phenomenon (in trajectory data) is that once an HOV lane is opened, there are less lane changes and the traffic is smoother. This increases the total flow on all lanes, even if the HOV lane is under-utilised.

3 OTHER STUDIES WITH INDIVIDUAL DRIVERS' ADVICE

Giving in-car advice to improve throughput is not new. Various projects have been undertaken in the past that are of use for the research described in this paper. These projects (cases) were studied in a short literature study. Most of the case studies deal with improvement of traffic flow by changing the drivers' speed, headway and/or lane with ITS systems. Besides this other cases (that do not necessarily change drivers speed, headway and/or lane) have been looked at, to learn what kinds of systems are effective in changing driver behavior. The literature study included pilots and experiments, computer simulation experiments and other literature studies.

At the end of this chapter some general conclusions are derived from the case studies. Case studies that deserve some special attention because of their usefulness for the design of the CCC system are the following. The Dutch Road Authority (*22*) and Van Driel (*23*) both studied and tested Automatic Cruise Control (ACC). These systems are particularly helpful when it comes to driver behavior with regard to following distance. In Van Driel (*23*) the impact of a congestion assistant on the driver was studied by means of a driving simulator experiment. The congestion assistant consists of a stop & go system (a mandatory low-speed ACC which operates in slow, congested traffic to follow the car immediately ahead), a warning and information system (about the length of a traffic jam) and an active pedal: while approaching the traffic jam, the driver feels a counterforce in the throttle when his speed is higher than the system's advice. All variants of the congestion assistant resulted in less congestion and higher queue discharge flows in comparison with the reference situation. The active pedal caused a reduction in the amount of congestion by intervening in approaching a jam, this way reducing the congestion inflow. However, a much bigger reduction in the amount of congestion was obtained by the stop & go function. This function intervened in driving in a jam and showed a more efficient car-following behavior. Thus, both functions have positive effects on the dissipation of jams, but the effects due to the stop & go function are much larger. This is partly caused by

the fact that the participants could not overrule the stop & go. The Dutch Road Authority (*22*) tested an ACC system that automatically maintains distance for speeds higher than 30 km/h. 40 drivers used a car equipped with ACC and LDW (lane departure warning) for five months. The main effect on throughput was an increase in headway time (the majority of the drivers chooses the minimum headway time of 1.0 s), and a use of ACC in free and heavy traffic. Overall the effect of ACC on traffic flow throughput was expected to be neutral. At an extremely high penetration rate, a decrease of throughput is expected.

In the SASPENCE project (*24*) a system that advises on speed and headway was researched. The goal of the system was to improve safety: the primary function of SASPENCE is to assist the driver in avoiding accidents related to excessive speed and/or too short headway. SASPENCE suggests the most appropriate speed and distance according to the actual driving context. Using a microscopic simulation model, the effect of the system was evaluated. It showed that the system increased the total travel time (this effect is largest in high traffic demand and for high penetration rates) and increased the average distance headway.

When it comes to congestion caused by shock waves, Hegyi et al. (*25*) have developed an algorithm that decreases shock waves with the use of variable speed limits. This algorithm was tested on the A12 motorway in The Netherlands, on part of the motorway where shock waves occur regularly (*26*). In normal situations, the speed limit is 120 km/h on that motorway, but when a shock wave is detected the speed limit is lowered to speed limit 60 km/h (with intermediate speed limits 100 km/h and 80 km/h). Most of the "interventions" of the shock wave algorithm concern short traffic jams with a length of at most some kilometers and a duration of several minutes. It is evaluated that the shock wave algorithm does improve throughput when it is active: there are less vehicle loss hours (empirically approximately 40 vehicle hours per intervention, according to Hegyi and Hoogendoorn (*27*)).

In The Netherlands on the A270 motorway between Helmond and Eindhoven various experiments were performed in February 2010 (*28*), as part of the SPITS-project (*29*). The aim of these experiments was to demonstrate the potential of cooperative systems intended to improve traffic flow on motorways. One of these experiments concerns a cooperative system that gives advice on acceleration and braking. The system was tested for one day on a test track with two lanes. The drivers of the cars in the right-hand lane were assisted by an advisory system that consisted of a number of parts: a MobilEye camera that determines the relative position and relative speed of the car immediately ahead, wireless communication to receive the position, speed and acceleration of the five cars ahead, a GPS system to determine the vehicles own position, speed and acceleration, and a computer to combine the information from the various systems and to provide an ideal acceleration for the vehicle. This acceleration is communicated to the driver by means of the GPS device.

At the start of the experiment, vehicles were placed at two adjacent lanes, 47 vehicles per lane. The drivers were instructed to follow the vehicle at the head of their lane as closely as possible (driving at a speed of 100 km/h). After a certain time, the first cars of both lines braked hard to reduce its speed (to approximately 30 km/h). Several seconds after this braking action, the first cars of the lines accelerated back to 100 km/h. The shock caused by this action was clearly evident among the braking cars following. The effect of the shock lasted some time because the vehicles took longer to accelerate than they do to brake.

From the analysis of the experiment it was concluded that the technology that was demonstrated can significantly improve traffic flow. The lane of vehicles with the system drove faster and more fluently than the control group. After a brake action on both lanes the effect of the shock wave was much smaller in the equipped lane and the drivers in that lane accelerated much swifter. In the experiments an improvement of 12% was realized in the traffic flow on average, rising to a maximum of 25%.

From the cases that are described in this chapter, and from other cases, the following general conclusions are derived, that can be of help for the development of CCC:

- In general, a mandatory system has a (significant) larger impact on driver behavior than a voluntary

system. This comes forward in Van Driel (*23*), where various systems that support drivers in congestion have been investigated: a mandatory stop & go system (a system that takes over the longitudinal driving task while driving in a traffic jam) leads to smaller accelerations and decelerations (smoother driving) and smaller headways. The Dutch Road Authority (*22*) tested four Advanced Driver Assistance Systems (ADAS's): headway monitoring and warning, adaptive cruise control, lane departure warning and lane keeping system. In this study, it was concluded from that advisory systems have no real effect on driver behavior. The systems that automatically do or correct something do have effect on driver behavior.

- When a voluntary system is used, incentives are a good way to get drivers to comply. This is seen in the "Belonitor" project (*30*), where drivers get awarded for showing desired driving behavior. However, when the awarding stops, the effect is gone. In Wilmink et al. (*31*), it is shown that enforcement (punishing instead of awarding) helps when there are variable speed limits.

- When driving with an ACC system, drivers tend to drive with a larger headway then they usually do (without system), see for example Pol et al. (*32*). This has consequences for a system that gives advice on following distance or keeps to a preset distance. Usually this set headway is larger than average headways during high density. This can cause a decrease in capacity.

- There is a tendency for advisory systems to be overridden on roads and by people when it is perhaps needed most. For example a system that warns when the speed limit is exceeded is used less by drivers who tend to override the speed limit most (*33*).

- In general, acceptance is higher when drivers experience the benefits from the system.

There is a lot of experience with systems that give speed and headway advice. Lane advice however, is quite an undeveloped area. Since CCC is an advisory system, close attention should be paid to the incentives for drivers to comply with the system. Experience learns that voluntary systems have a smaller impact than mandatory systems. Also attention should be paid to the fact that drivers tend to drive with a small headway and may drive with a larger headway when having an ACC-like system in their car. The CCC system should take this into account, to make sure capacity does not decrease.

4 IMPROVING THE TRAFFIC SITUATION

This section gives several solutions based on the literature overview in section 2. The solutions are split into three different categories, and numbered. The numbers are found in figure 2, which shows where they influence the traffic process.

4.1 Aiming for synchronised flow

In three-phase traffic flow theory (*5*), the maximum flow is possible in a phase of synchronised flow. This means that in order to increase the flow in the bottleneck, one has to aim for a phase of synchronised flow. For instance ramp metering control can be used to do so, see Kerner (*34*), but also dynamic speed limits can help giving the same speeds to drivers.

Solution 1: One of the possibilities is that the higher flows in case of synchonised flow are caused by a better, more equal lane usage. In fact, the right lane is currently under-utilised at flows near capacity (*35*). This means that having a more equal lane distribution can increase the capacity. Therefore, lane advice (usually being "use the right lane") is an interesting control option to consider. Both the phenomenon and the solution can possibly be related to a different phase of traffic, a one-pipe phase as described by Daganzo
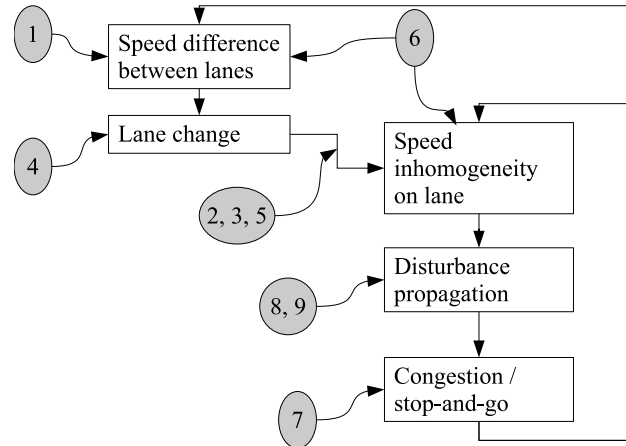
Figure 2: A graphical representation of the traffic processes and where the solutions (in gray ellipses) interfere with the processes

(*16*). Graphically, figure 2 shows with a "1" that this solution changes the speed differences between the lanes, and therefore immediately at the basis changes the processes.

4.2 Hypotheses to reduce congestion and stop-and-go waves

Solution 2: Most articles indicate lane changes as main cause of shock waves and a lower capacity. Some articles give easy-to-implement solutions, like Ahn and Cassidy (*14*). If one can prevent lane changes in too short gaps, this would avoid large disturbances which cause a traffic breakdown and stop-and-go waves. This solution is numbered "2" in figure 2. Intelligent and communicating vehicles could "look" at the available gaps and based on the gap length advise the drivers (not) to merge in a particular gap. For this, it is needed that the intelligent vehicle has accurate and actual (typically, the update frequency should be once a second) information of the position of other vehicles.

Solution 3: Alternatively, drivers could be advised to first adapt their speed before moving to the new lane (solution number "3"). Disturbances can also be avoided if the future follower will anticipate on the merging and gradually make space, rather than suddenly respond to the insertion of a new leader vehicle. This can be done by speed advice, provided that there is an fast communication in the order of seconds.

Solution 4: For the capacity drop, the paper of Daganzo and Cassidy (*21*) provides another idea to improve capacity, namely reduce lane changes as much as possible. However, a lane-change prohibition is not a which will work over a longer time span and a longer distance. It could be implemented in a dynamic environment with temporal lane change prohibitions. Difficulties arise once there are mandatory lane changes, because drivers have to change lanes in order to reach their destination or because the lane at which they are currently driving ends. Current ideas are to combine lane change advice with speed adaptation in both lanes. However, there is no idea yet how of an algorithm to implement.

Solution 5: Another improvement can be derived from Laval and Daganzo (*18*). As long as voids can be avoided, the flow will be maximised. This can be realised by avoiding low speed vehicles merging onto fast lanes. It would be better to first increase speed, such that the new follower (in the fast lane) will not need to reduce speed.

Solution 6: Another possibility is to try to avoid large differences in speeds between two lanes. This, at one hand, will reduce the number of lane changes. At the other hand, the drivers which do change lanes, will be able to merge into a gap without disturbing the traffic flow too much.

Solution 7: Although a stop-and-go wave is very difficult to predict with high accuracy, it is possible to identify traffic conditions which might lead to a stop-and-go wave. One of the characteristics is traffic density. An option would be to reduce speed in case traffic density is too high. Although this does not decrease the density, this will probably decrease the traffic fluctuations causing stop-and-go waves.

Solution 8: Hegyi et al. (*26*) have developed an algorithm for solving stop-and-go waves. The idea is once a stop-and-go wave is detected, the speed is reduced for a road stretch of several kilometres upstream of the stop-and-go wave. Since this is done on a stretch of road, the density does not change. A reduced speed will then lead to a reduced flow. Thus, the inflow in the stop-and-go wave is reduced and it will solve. A similar system is used to avoid the onset of congestion at the upstream end of the area with speed limit. This system – reducing the speed to reduce the inflow – can also be applied on a microscopic level. However, this system cannot be used to prevent stop-and-go waves, only to solve the stop-and-go waves.

4.3   Reducing spillback effects by dynamic lane assignment

Solution 9: It is possible that a queue grows backward onto the motorway from the underlying road network or another motorway. If this is the case, also drivers which do not need to pass the bottleneck are captured in congestion. This can be avoided by a dynamic lane assignment. In case traffic to one direction is congested, traffic to this direction need to be separated from traffic to another direction upstream of the tail of the queue. Then, on one motorway, there could be two different traffic streams: one with traffic heading to the congested direction (congested stream) and a free flowing stream of traffic heading towards another direction. This way, spillback delays (or blocking back delays), which are an important source of delays, according to Knoop et al. (*36*), are avoided.

5   SYSTEM ARCHITECTURE: FROM DATA TO ADVICE

The previous sections showed how traffic should be controlled. To come to an advice, first the traffic state has to be estimated from traffic, and then an advice has to be made. This section explains what data form the basis for the advice, how they are treated and what the final form of the advice is. This is done based on the schematic view of the functionality of the system, depicted in figure 3.

5.1   Data collection

Data are collected on motorways (and on- and off-ramps) only, and this is also the only area covered in the simulation and predictions. Although control actions can be performed on the underlying road network, this will not be considered (nor simulated) in this project.

5.2   Data processing

The majority of the available data will be data from the double loop system on motorways. In the Netherlands, loops are installed about every 500 meters and provide lane-specific one-minute aggregated data on flow and time-average speed. The delay between moment of data collection and their availability in the traffic management centre is 2-3 minutes. Besides, typically 10% of the collected data is erroneous and should therefore be discarded.
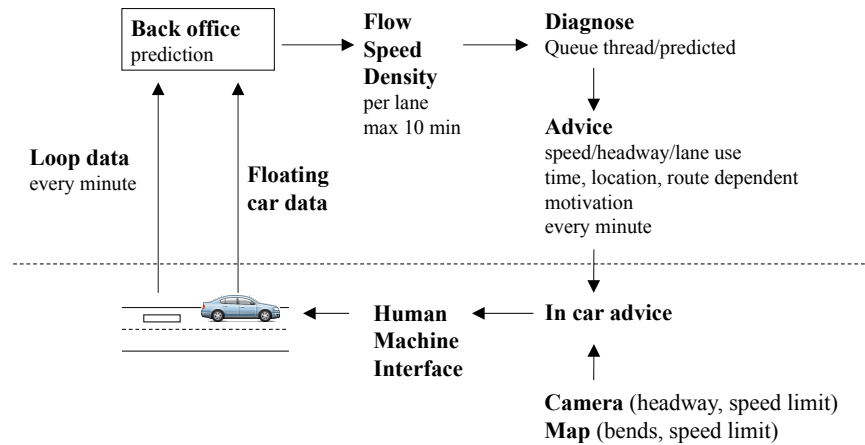
Figure 3: A schematic view of the information flows in the system

For research purposes, the there are perhaps other data sources available. Maybe the log files of the loops, containing individual passing times of vehicles, can be accessed for several loops. Furthermore, remote-sensing data (helicopter, or fixed video above the road) can be incorporated. Also floating car data can be used.

5.3 Data prediction

For the vehicle, it is needed that his trajectory is predicted typically 1 km ahead. The time horizon of the prediction need to be adjusted to this distance. Assuming a minimal speed of 10 km/h, the required time horizon is at maximum 6 minutes. Even if the speeds are lower, it is not needed to have longer prediction since it is updated every 10-30 seconds. Note the 6 minutes prediction starts at the moment of giving the advice. The data on which this advice is based, are already 2-3 minutes old by then. Therefore, the system needs to predict approximately 10 minutes in advance. Section 6 introduces a model which has these capabilities.

5.4 Diagnose

The processed data has to show where (possible) problems occur or will occur. This means showing where are the areas of congestion, as well as showing where are the areas where stop-and-go waves might emerge. It is difficult to predict exactly the time and location of the start of a stop-and-go wave.

5.5 Advice

Due to communication bandwidth and computation time for a new advice, a new advice can be sent at maximum once every 10-30 seconds. Even with more advanced technology, a higher update frequency would not be desirable. A higher update frequency would give an overload of input to drivers, and they are unable to follow the advice.

There are two possibilities for the type of advice. The first one is an recommendation on the best lateral and longitudinal position, being an advices headway and an advised lane. This is better than advising

a change in headway of lane, because (1) the update frequency is not high enough to have a constant adaptation of the position (and hence, drivers will be advised, for instance, to accelerate for 30 seconds, which is too long) and (2) the constant input from a device is tiresome for drivers.

The second way of sending an advice to the on board unit (OBU) is giving the traffic regime in which the car is heading. This could be for instance "free flow", "risk of stop-and-go waves", or "heavy merging". The result should be an advice to the driver to improve the predicted traffic conditions. However, the in-car unit will decide upon that itself, based on the regime. In one regime, it can be needed that a part of the drivers will take a larger headway or a part of the drivers will change to another lane. Another part of the drivers should continue driving in their normal way. The particular advice and which part should be given this advice is coupled to a regime. The in-car unit will decide, based on drivers' characteristics, what advice will be shown to the individual driver.

The final advice to the driver will be composed out of three elements:

1. The advice by the traffic management centre
   This would mainly be an speed or lane advice, as mentioned above.

2. The possibilities based on the direct surroundings of the vehicle
   The OBU will not advise traffic behaviour which is unsafe, e.g. moving towards a lane in case the lane is occupied by another car. This can be determined by the positions of the other cars found by the OBU.

3. The capabilities of the vehicle itself
   The OBU will not advise unreachable conditions. For instance, if the the advice is to accelerate very fast, but the vehicle is not powerful enough or in the wrong gear, no such an advice will be given.

Element (1) and (2) can provide advices themselves, whereas part (3) only restricts the given advice.

5.6   Optimisation loop

The prediction of the traffic situation will be made using one particular setting of the advice, and thus assuming one type of drivers' behaviour. Another advice will lead to another prediction. The loop indicates that several settings for the driver advice will be tested and the best will be chosen. Note that for each advice setting a prediction is needed. Therefore, the traffic prediction needs to be fast.

6   MACROSCOPIC TRAFFIC FLOW MODELLING PER LANE

An important step of our functionality is to predict traffic conditions. A lane level traffic state prediction is required, because advice may be directed to drivers on a certain lane and because the advice may also be about which lane to use. In this section we explore whether a first order macroscopic traffic flow model at lane level is able to give satisfying results to base advice on.

6.1   Forecasting model

We base our forecasting model on the Cell Transmission Model (*37*), or CTM. A first adjustment is to have cells for each section and each lane. A logical next step would be to incorporate lane changes, as for instance done by Laval and Daganzo (*18*). However this approach does not include mandatory lane changes which probably have a more significant effect on traffic flow. Moreover we found that given a homogenous stretch of road, the inflow and outflow limits at the network edge are more significant. Generally there are three ways to deal with inflow and outflow given a live application with a limited forecasting period: (1)
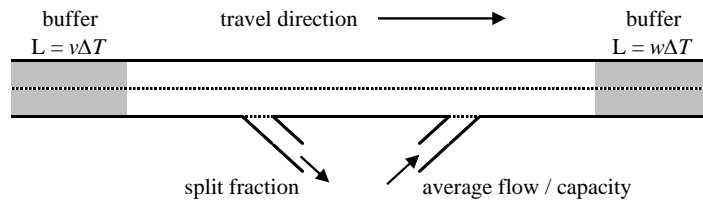
Figure 4: In- and outflow solutions

A constant flow equal to the average flow over the last few minutes, (2) split/merge fractions derived from the last few minutes, and (3) buffer zone. A buffer zone is an additional part of the network that contains upstream traffic that may reach the area of interest within a forecasted period ΔT or downstream traffic that can cause shockwaves that may reach the area of interest in the same period. The length of the buffer is thus related to the free flow speed v or the shockwave speed w. The buffer option has the highest level of accuracy but requires an extension of the network. Usually this may be feasible for motorways but not for on-ramps and off-ramps as the underlying road network is more dens. For off-ramps we use split fractions to determine the outflow demand. Spillback at the network edge cannot be predicted since it is not measured. However, if spillback occurs a limit on outflow could be used. This limit can be based on the average flow of the last few minutes. For on-ramps a merge fraction is the split fraction equivalent. Mainline flow and on-ramp flow can however not be directly related. The remaining solution is to assume a constant inflow, equal to flow over the last few minutes. For congested conditions this may not produce accurate results as the actual demand is higher than measured flow. Therefore in congestion it would be better to assume an inflow equal to capacity, continuing existing shockwave patterns instead of absorbing them. Figure 4 summarizes the recommended inflow and outflow solutions.

6.2   Exploratory experiment

We have tested the accuracy of a lane level CTM for a 6.6km long homogenous stretch of road with 3 lanes. For the inflow we use option 1 and for the outflow we use option 3. Instead of actually adding a buffer zone, we ignore a downstream region that grows with the shockwave speed. We ignore lane changes although some effect could be expected as the road section is between a lane-drop and an off-ramp. Detector data was collected on the A4 between Leidschendam and Leiden on Tuesday 13 April 2010 between 17:00h and 18:00h. This section has detectors each 600m or less and a few shockwaves are present in the data. The Adaptive Smoothing Method by Treiber and Helbing (*38*), or ASM, was used to derive data in a CTM grid that was based on a time step of 6s, see figure 5a. From several moments within the hour the CTM was used to predict the remaining time.

6.3   Results

Figure 5b shows one of the traffic state forecasts. The inflow of the right lane has been low from t = 15 to t = 20, causing the assumed inflow to be too low to continue the shockwave that starts around t = 10. For the other two lanes the shockwave nicely progresses. For the middle and right lanes it is predicted that at t = 20 a shockwave starts that is not quickly absorbed. In the actual data this shockwave is not present. Apparently either 2nd order effects or lane changes cause the high densities to be absorbed. The CTM is not able to represent complex traffic situations such as pinned localized clusters as described by Schönhof and Helbing (*39*). Generally it was found that high densities result in shockwaves. Depending on the accuracy of the assumed inflow the shockwaves could disappear but seldom did so within 8-9 minutes. Some shockwaves are predicted that actually do not occur.

A more extensive calibration and inclusion of lane changes could well improve on this situation. Mandatory lane changes could be included in this framework using measured density distributions. A principle based on densities similar to the IT principle from Laval and Daganzo (*18*) could be used to balance
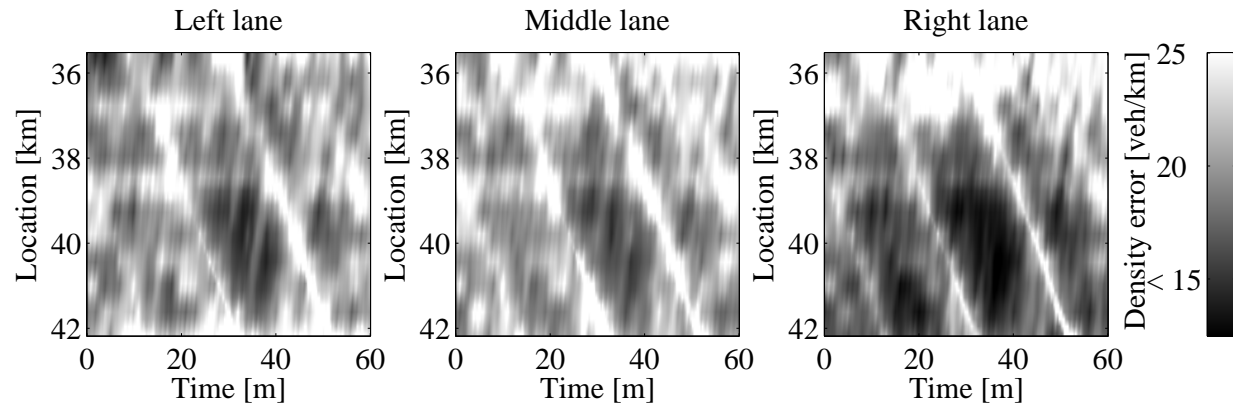
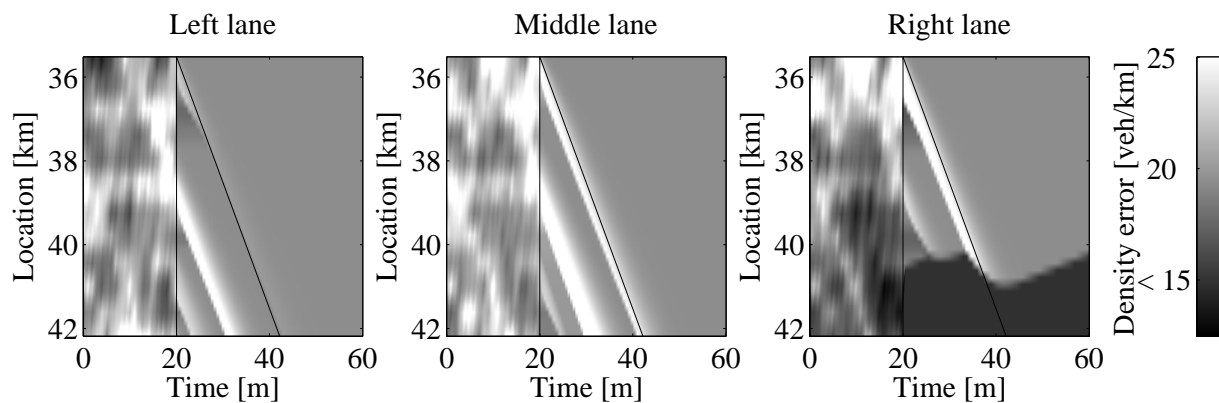(a) Densities from smoothed detector data

(b) Traffic state prediction from t = 20 minutes

Figure 5: Measured densities and the prediction using the lane-based macroscopic CTM model . Note that the direction of travel is upwards in the figure.

sending and receiving flows. A transformation to density will be required as actual lane changing flows are not determined when using measured density distributions.

7   EFFECTS OF INDIVIDUAL ADVICE ON TRAFFIC FLOW – INITIAL SOLUTIONS

This section will explore what individual advisory systems can achieve and what type of advice should be given. We also look at systems that include V2V communication which may be part a communication platform.

7.1   Simulated effects of a cooperative cruise control

To evaluate the benefits of a cooperative cruise control system, a microscopic traffic simulation program was run Schakel et al. (*40*). The outcomes of the simulation are compared with the field test on the A270 with induced shock waves (*28*) mentioned in section 3. The most important findings are:

1. For both the automated and advice versions of the Cooperative Adaptive Cruise Control shockwaves are damped more quickly but move faster.

Table 1: Expected effects of CCC for given situations

Situation	Advice	Expected effects
(Near) saturated conditions	Lane	Some articles, for instance Ahn and Cassidy (*14*), indicate that lane changes cause instabilities. We expect this to be true given the right circumstances of high density. Therefore lane advice will be given to prevent high densities if there is room to spare on other lanes. Drivers may not do this naturally for several reasons: (1) unable to as they notice the high density too late, (2) unwilling to because of a lane-drop or route. Ideally the lane advice is given depending on the destination (mainline or off-ramp).
	Speed	High densities may increase the chance of shockwaves and form a problem for mandatory lane changes. Speed advice is expected to result in more homogenous and possibly somewhat lower speed, reducing the impact of lane changes on traffic flow. Lower speed may reduce the capacity. Therefore a lower speed should only be advised at sections with many (mandatory) lane changes.
	Headway	Headway advice could be used to manage the merge process by creating gaps in the traffic stream or leading lane-changing vehicles towards the largest gaps.
Bottleneck	Headway	In case a bottleneck is active (produces upstream congestion) the capacity drop occurs. By giving headway advice it is expected that drivers will pay more attention and will create smaller headways while accelerating out of congestion.
Stop & go waves	Lane	In case of uneven lane distributions the remaining capacity of other lanes may be used to solve the stop & go wave.
	Speed	If stop & go waves occur and lane distribution is some what even, stop & go waves can only be absorbed by an inflow reduction. This is similar to the SPECIALIST algorithm Hegyi et al. (*25*).
	Headway	Headway advice can be another means to solve stop & go waves by temporarily reducing the wave's inflow. Also the stop & go wave outflow may be increased using headway advice similar to bottleneck situations.

2. The increased speed of shockwaves may have adverse consequences on anticipatory driving for human drivers in mixed traffic. This may negatively influence safety and/or capacity.

3. Time headways showed less variation as soon as drivers were advised about their headway

Also if there is no direct V2V communication, conclusions 1 and 2 may still be useful, as long as there is a central server which can communicate between the vehicles. In that case, as information may even travel faster. An on-board camera can register reducing headways and advice deceleration before the driver would decelerate. Also information via the back office may cause longitudinal driver behavior that regular driver anticipation does not take into account. The third conclusion indicates that drivers show more homogenous behavior in case they are advised. It should be mentioned however that compliance is an important aspect of human behavior. Compliance during an experiment can be expected to be higher than in reality.

7.2 Expected results of individual advice

The drivers' advice system will be designed to minimize collective travel time by preventing congestion and solving shockwaves. Table 1 summarizes the expected effects of advice in several situations in a qualitative sense. At this point it is difficult to quantify the effects as advisory systems are dependent on user response. Driver compliance can vary a lot between systems, methods and HMI designs. Also behavioral adaptation, misuse, driver capability etc. may affect the results.

8 CONCLUSIONS

This paper presented a system in which drivers get individual advice on headway, speed and lane choice. The information which is used to generate this advice is collected by road side devices as well as by on-board devices. The on-board divice is partly the same as the device which is used to show the advice to the driver. Additionally, there is a camera in the vehicle to monitor the direct surroundings of the vehicle.

The paper presented a framework how the best traffic control strategy can be found. The required steps to come to an optimal advice are given in the paper. In fact, a lane-specific macroscopic traffic flow model was presented which showed promising results to predict the traffic flow over a short time-horizon of approximately 10 minutes. This is sufficient, since this is larger than the time-interval at which the system gives new advices.

Also, several possible solutions to reduce traffic congestion are listed, based on the current theories of traffic flow. For these ideas it is also shown what type of advice (headway, speed and/or lane choice) is required for the drivers.

The current paper describes the framework in which the system can be tested, as well as possible solutions. The ongoing work includes optimising the traffic simulation program and calibrate it for a particular road stretch. Furthermore, the practical development continues, which means building in-car devices according to the requirements laid out in this paper. The paper showed that there are large potential benefits of the system. This justifies further investment of the system, by policy makers, car manufacturers, and car supply manufacturers.

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