Reducing Traffic Jams via VANETs

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Date Submitted: 17 June 2012
Date Published: 19 June 2012

The final published version of this article is available at:
Knorr, *IEEE Transactions on Vehicular Technology*, 2012, pp. 1.
DOI: 10.1109/TVT.2012.2209690

Subject Classification Vehicular Technology > Intelligent Transportation Systems

Keywords Vehicular ad hoc network (VANET); Intelligent transportation systems (ITS); Vehicular and wireless technologies; Traffic control; Computer simulation; Traffic aid systems; Traffic control systems;

Submitting Author's Comments The paper has been submitted to the IEEE Transactions on Vehicular Technology.

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Manuscript received September 29, 2011; revised February 20, 2012 and May 18, 2012. Funding for this work has been provided by the state of North Rhine-Westphalia and the European Union within the NRW-EU Ziel 2 program 2007-2013 (EFRE).

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Reducing Traffic Jams via VANETs

Abstract

A transition from free flow to congested traffic on highways often originates spontaneously and despite the fact that the road could satisfy a higher traffic demand. The reason for a such a traffic breakdown is perturbations caused by human drivers in dense traffic. We present a strategy to reduce traffic congestion with the help of vehicle-to-vehicle communication. Periodically emitted beacons are used to analyze traffic flow and to warn other drivers of a possible traffic breakdown. Drivers who receive such a warning are told to keep a larger gap to their predecessor. By doing so, they are less likely the source of perturbations which can cause a traffic breakdown. We analyze the proposed strategy via computer simulations and investigate which fraction of communicating vehicles is necessary until a beneficial influence on traffic flow is observable. We show that penetration rates of ten percent and less can have significant influence on traffic flow and travel times. Besides applying a realistic mobility model we further increase the degree of realism by the use of empirical traffic data from loop detectors on a German Autobahn.

Index Terms

Vehicular ad hoc network (VANET), Intelligent transportation systems (ITS), Vehicular and wireless technologies, Traffic control, Computer simulation

I. Introduction

Traffic congestion is an annoyance most motorists are familiar with; it costs time, fuel and, thus, money. In 2010, for instance, the average US auto commuter spent an additional 34 hours in his car and wasted 14 gallons of fuel simply as a result of congestion [1]. A comparison with 1982 (14 hours, 6 gallons) shows the growing traffic volume poses an ever increasing problem to our transportation systems.

Simply extending the road network is not suited to fight congestion due to spatial, financial and environmental constraints. Recent progress in the area of information and communication technology, however, promises to make today's transportation systems not only more efficient, but also safer, more reliable and more convenient. Vehicular Ad Hoc Networks (VANETs) are considered a central part of these Intelligent Transportation Systems (ITS). VANETs enable all actors in traffic (e.g., vehicles, traffic lights or road side units) to exchange information and to coordinate their behavior. As no underlying infrastructure is required and message exchange is carried out with low latency times, we consider VANETs as an excellent tool to reduce congestion in the context of ITS.

We will address the question of how vehicular communication can be applied to make transportation more efficient. Our approach is based on two points: (i) vehicles autonomously estimate the current traffic situation and broadcast this information. (ii) Based on this estimate and if required by the traffic state vehicles adapt their driving behavior. We admit the first point, VANET based traffic state estimation, has already been investigated earlier (see Sec. III). The focus of the previous studies, however, was on the detection of congestion or of large vehicle densities w.r.t dynamic route choice or radio channel analysis. Our approach aims to identify 'critical' road segments and to prevent a traffic jam before it actually occurs. Therefore, we will show that for the estimation of traffic flow dynamics a purely density based analysis does not suffice. Consequently, it is necessary to understand the nature of traffic breakdown, which describes a spontaneous drop of the average velocity on a stretch of road; often a breakdown occurs spontaneously without an obvious cause like a construction site or an accident. It is actually caused by misbehavior of human drivers in dense traffic. Therefore, we suggest using periodically emitted beacons to analyze the current traffic state. Communicating vehicles change their driving behavior in dense traffic and inform following vehicles about the discovery of dense traffic. After a vehicle has changed its driving behavior it is expected to be less likely the trigger of traffic breakdown. This makes our method different from many previous approaches which guide vehicles to less congested routes to escape congestion.

Periodic beacons that we use for message exchange are essential for most safety applications [2] and have therefore been extensively studied (cf. [3] and references therein). Hence, this work will focus on the aspects related to traffic dynamics although we have to admit more innovative beacon schemes are the object of current research. The challenges for designers of inter-vehicle communication protocols for safety applications are discussed by, e.g., Moreno [4].

Due to the infeasibility of large scale real world experiments computer simulations have become a valuable instrument in this field of research. To assess the impact of the proposed strategy we use computer simulations with both very realistic propagation and traffic models. In addition to that we use empirical traffic data from a German Autobahn where a traffic breakdown was observed. The necessary penetration rate for the proposed strategy to become effective will also be in the focus of this paper.

The rest of the paper is structured as follows: The next section gives a short review of traffic flow theory. Related work concerning VANET based traffic state estimation and traffic flow optimization is discussed in Section III. In Sections IV and V we explain how the proposed strategy works on the level of message exchange and driving behavior, respectively. Section VI presents the simulation results. Finally, the conclusions drawn from our work are given in Section VII.

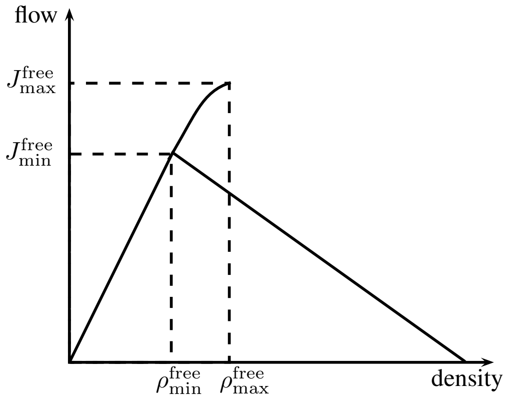


Fig. 1. Schematic sketch of a flow-density diagram showing a metastable region between $\rho_{\rm min}^{\rm free}$ and $\rho_{\rm max}^{\rm free}$ (see [5, p. 71]).

II. Some traffic flow theory

Traffic flow to which each vehicle driver constitutes shows a rich variety of phenomena – from dynamical phase transitions over self-organization to the formation of shock-waves. Hence, there is a large interest in understanding the relation between traffic flow J (typically measured in vehicles per hour and lane) and vehicle density ρ (vehicles per kilometer) both from a theoretical as well as from a practical point of view. This relation can be expressed in form of the *fundamental diagram* as in fig. 1: For low and high densities its shape is easy to understand. At low densities $\rho < \rho_{\rm min}^{\rm free}$ vehicles can travel at their desired speed and additional vehicles linearly increase the total flow. At high densities $\rho > \rho_{\rm max}^{\rm free}$, on the other hand, vehicles hinder each other and force others to slow down. For these two regions the functional relation between flow and density can be expressed by the linear equation $J = v\rho$ where v stands for the average velocity of vehicles on the considered road segment. Between these two regions, however, there exists a metastable range $\rho_{\rm min}^{\rm free} < \rho < \rho_{\rm max}^{\rm free}$ where a driver's desire to travel at maximum velocity and the tendency to hinder each other compete and where flow can take two[1] values depending on the system's history. Actually, flow can spontaneously switch from free (upper branch) to congested (lower branch) traffic in this density range without any obvious reason. Therefore, this phenomenon is also referred to as "phantom jam". This spontaneous breakdown[2] results in a stop-and-go wave that propagates against the travel direction (i.e., upstream). One found that the stop-and-go wave has some universal features:

[1]More recent studies suggest flow can take any value between the two branches and that congested states cover a two-dimensional region in the flow density plane [5].

[2]Please note that the term 'breakdown' in traffic theory describes a collective phenomenon where the average velocity on a stretch of road drops significantly. It must not be mistaken for a broken car.

its propagation velocity, for example, is approximately -15 km/h – no matter whether measured at a German Autobahn or a US highway [6].

The question of what causes this breakdown was not clear for a long time. One of the earliest and probably most simplistic models [7] that could reproduce the empirical findings incorporated a stochastic component to reflect drivers' incapability to maintain a constant velocity. The authors of [7] concluded, after a critical vehicle density is reached, small perturbations (e.g., a single driver hitting the brakes too hard) suffice to cause a traffic breakdown forcing all vehicles to slow down.

Empirical evidence for this assumption was given by an intriguingly simple experiment [8]: Drivers were asked to maintain a constant velocity and constant space gap while driving on a circular road. After several minutes one observed the formation of jammed vehicle clusters traveling against the driving direction exactly as predicted by simulations.

From the above observation one can draw three conclusions:

- Assessing traffic dynamics solely by vehicle density may fail in a certain density range.
- Traffic congestion can be eased by reducing perturbations of traffic flow and by keeping density below $\rho_{\mathrm{min}}^{\mathrm{free}}$.
- Any microscopic traffic model used for VANET simulations should be able to reproduce macroscopic phenomena like traffic breakdown and metastability of the fundamental diagram.

For a detailed review of traffic flow theory we refer to, e.g., [5] or [9].

III. Related work

VANETs allow a tight connection of physical driving and the communication system which requires us to consider the influence of both areas on each other. This is termed a cyber-physical system [10]. The need for an application-oriented approach that regards the specific goals of traffic for VANET protocol design has been stated recently for wide-area transportation networks w.r.t. simulators [11] as well as for understanding the influence of communication to driving safety on the microscopic level [12]. In this spirit, we discuss the application of reducing traffic jams to design a protocol for the behavior of vehicles. We exploit information sent by regular periodic beaconing so that no additional communication protocol is required. Therefore, we forgo discussing security related aspects of our approach and refer to the corresponding literature (e.g., [13]).

Traffic state estimation, which we apply to determine when to change driving behavior, has already been investigated in the context of adaptive beaconing. Due to the nature of VANETs where the topology is rapidly changing a static beacon scheme (i.e., constant beacon interval and transmission range) is likely to show an increase of package collisions at large vehicle densities. Therefore, it was suggested to adapt either transmission range [14] or beacon interval [15] depending on local vehicle density. To estimate the local density the authors proposed analyzing the vehicle's mobility pattern [14] or the number of package collisions and neighbors [15], respectively. They showed these adaptive schemes allow for a more efficient and reliable use of the network resources.

Applications aiming at easing congestion, however, require more information than knowledge about the local vehicle density: Several studies (e.g., [16]–[18]) suggested using VANETs to identify congested roads and to offer alternative, less congested routes. Besides the risk of causing congestion on the alternative routes, these strategies become effective only after a traffic breakdown already has occurred.

More innovative approaches search to influence the driving behavior that causes the breakdown. Kerner et al. [19] suggested the exchanged messages should comprise the length of a recommended space gap vehicles are to maintain. Vehicles that adapt their space gap according to the recommendation are less likely to provoke a traffic breakdown. Similarly, Fekete et al. [20] proposed vehicles adapt their own velocity to the average velocity of neighboring vehicles, which they determine via inter-vehicle communication, thus reducing inhomogeneities in traffic flow. The previous two works studied the influence of their strategies for relatively high penetration rates of communicating vehicles of 100 and 60 percent, respectively. Such rates will be reached only long after a successful market introduction of VANET devices. Moreover, it is not clear when, if at all, vehicles are to alter driving behavior.

Recently, two of the authors (FK and MS) found [21] beneficial impact of VANETs on traffic flow for penetration rates considerably below 50 percent. They gave both recommendations for when and how to change driving behavior. Their simulation, however, were based on some idealized traffic and communication conditions and did not take into account the human limitations, namely reaction time, in adapting driving behavior.

In the current work we will present a VANET-based strategy to reduce traffic jams which explicitly accounts for human reaction time and becomes effective at low penetration rates. Simulations not only use realistic radio propagation and mobility models but also empirical traffic data from a German Autobahn which makes the current paper stand out from all aforementioned studies.

IV. Beacons for congestion warning

Our approach to use vehicle-to-vehicle communication to ease congestion is solely based on beacon messages. Beacon messages are periodically broadcast status messages containing a vehicle's position, velocity, acceleration, a unique vehicle identifier and a time stamp. This information suffices to estimate the local state of traffic [14], [15]. In our approach we suggest expanding a beacon's content by two additional variables: a position c_s and a time stamp c_t marking a 'critical' road segment. In this context we will call a road segment critical when a breakdown is likely to occur. By employing the data that is already sent in regular beacons and merely extending it with two piggybacked data fields, we do not create overhead due to additional packets in the network. A beacon's payload size is estimated to be less than one hundred bytes, depending on the lengths of headers and other data not directly related to our approach; however, to pay attention to expected future demands, e.g., security, we fix the beacon size to 500 bytes in our following considerations to demonstrate that our approach is able to work with those beacon sizes.

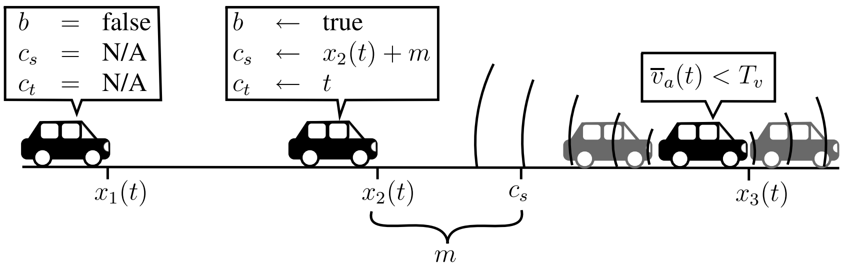
From the beacons a vehicle receives during an interval $[t, t + \Delta t]$ it may calculate the average velocity $\overline{v}_a(t)$ of all transmitting vehicles ahead. When the average velocity drops below a given threshold T_v for two successive intervals ($\overline{v}_a(t - \Delta t) < T_v$ AND $\overline{v}_a(t) < T_v$) it marks the segment as critical by setting $\mathrm{c}_t \leftarrow t$ and $\mathrm{c}_s \leftarrow x(t) + m$ where $x(t)$ denotes the vehicle's current position at time t and m an average communication range. Vehicles receiving a notification about such critical condition append the information to their own beacons (see fig. 2(a)).

Vehicles use this information to decide whether to change their driving behavior. For this decision a vehicle has to judge the relevance of the information. Information about a critical road segment is considered as relevant if the vehicle is close to the said segment, if it is approaching it and if the information is sufficiently up-to-date (see fig. 2(b)). By introducing a boolean variable b, which indicates whether to change driving behavior, as well as temporal and spatial thresholds T_t and T_s, respectively, the aforementioned conditions can be written as:

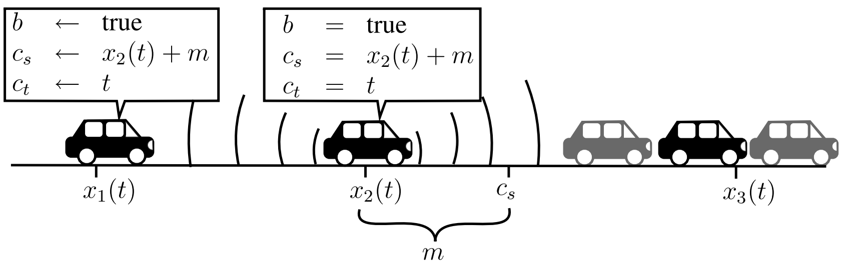
$b \leftarrow$ false
if $(t - \mathrm{c}_t < T_t$ AND $0 < \mathrm{c}_s - x(t) < T_s)$:
    $b \leftarrow$ true

Consequently, T_t and T_s define an area of relevance for traffic information. This area of relevance may help to reduce the load on the radio channel; the congestion warning is of value only for a limited number of nodes in the network and, thus, need not be broadcast outside this area. For simulations we set $T_t = 30$ seconds and $T_s = 3$ km. As will be discussed later we found our results to be relatively insensitive towards the concrete choice of T_s and T_t.

The threshold below which a traffic condition is classified as 'critical' is set to $T_v = 81$ km/h. This value is 10.8 km/h ($= 3$m/s) below the maximum velocity of trucks in our simulation (see table II) and indicates



(a) A critical road condition is detected at time t.



(b) Upstream vehicles are warned at time t_2 ($t_2 > t$) provided that the warning is still up-to-date ($t_2 < T_t + t$).

Fig. 2. Illustration of how the proposed strategy works: When a vehicle (at $x_2(t)$) detects that the average velocity of downstream vehicles $\overline{v}_a(t)$ is smaller than a threshold T_v it seeks to change its driving behavior ($b \leftarrow$ true). This information is appended to its beacons. Thereupon, a following vehicle (formerly at $x_1(t)$) that receives a beacon from the vehicle formerly at $x_2(t)$ changes its driving behavior, too – provided that this information is still considered as up-to-date (i.e., not older than T_t).

that vehicle interactions and perturbations are strong enough to make even slow vehicles (i.e., trucks) slow down. Empirical observations that show maximum traffic flow is reached at approximately 80 km/h (see, e.g., [22]) support this choice of parameter. Finally, we set $\Delta t = 1$ second and $m = 150$ meters. The variable m estimates the distance to the critical road segment. Compared to using the average position of transmitting downstream vehicles, choosing a constant value for m, proved as especially advantageous at low penetration rates when only a single communicating vehicle is sensed downstream.

V. Vehicle motion and adapted driving behavior

Vehicle motion is based on the comfortable driving model (CDM) [23]. The CDM is an advancement of the Nagel-Schreckenberg cellular automaton [7] with extensions for multi-lane traffic and anticipatory driving. In this section we describe the adaptions we made for a change of driving behavior in case of approaching a critical road segment. A detailed review of the model with the proposed modifications can be found in the appendix.

The CDM contains a probabilistic component p which causes minor fluctuations in a vehicle's velocity reflecting drivers' incapability to maintain a constant velocity. The original CDM distinguishes three cases when determining p for a vehicle labeled n:

$$p \leftarrow \begin{cases} p_b, & \text{if } l_{n+1} = \text{true AND } t_h < t_s, & (1) \\ p_0, & \text{if } v_n = 0 \text{ AND NOT} \\ & (l_{n+1} = \text{true AND } t_h < t_s), & (2) \\ p_d, & \text{otherwise.} & (3) \end{cases}$$

In the first case ($p = p_b$) the vehicle n, following the preceding car $n+1$ with time headway t_h, reacts to the predecessor's activated brake light ($l_{n+1} =$ true) if it is within an interaction horizon t_s ($t_h < t_s$). This case was introduced to appropriately mimic drivers' tendency to overreact in dense traffic. This phenomenon, sometimes called 'over-deceleration effect', results from a driver's finite response time to the preceding car's brake lights. If the time headway is too small (i.e., $t_h < t_s$) the following driver performs an unnecessarily strong braking maneuver to avoid collision. The second case ($p = p_0$), known as slow-to-start rule, effects a reduced acceleration rate for vehicles starting from rest provided there are no obstructions ahead ($l_{n+1} =$ false or $t_h \geq t_s$). The last case models the random fluctuations observed even in free traffic flow. From these explanations the reader may already conclude the relation $p_d < p_0 < p_b$.

In the modified model we require vehicles which changed their driving behavior, i.e., which set $b \leftarrow$ true, to keep a larger gap to the preceding vehicle. Such an increased gap is created simply by not accelerating until the gap is large enough. An additional gap whose length we denote by gap_n is considered as sufficiently large if it is larger than the distance traveled during the driver's reaction time t_r of one second ($t_r = 1$ s). It is intuitive that a larger gap decreases the probability for the occurrence of an 'over-deceleration effect'. (For a detailed discussion of the impact of driving behavior on traffic flow we refer to a recent article by Kerner [24].)

Consequently, we modified the calculation of the randomization parameter p by introducing a fourth parameter p_c $(p_0 < p_c < p_b)$ to model the situation described above:

$$p \leftarrow \begin{cases} p_b, & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ & \text{AND } \text{gap}_n \leq v_n t_r, \quad (1) \\ p_c, & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ & \text{AND } \text{gap}_n > v_n t_r, \quad (2) \\ p_0, & \text{if } v_n = 0 \text{ AND NOT} \\ & (l_{n+1} = \text{true AND } t_h < t_s), \quad (3) \\ p_d, & \text{otherwise.} \quad (4) \end{cases}$$

For the simulations we adopted the values for $p_b = 0.94$, $p_0 = 0.5$ and $p_d = 0.1$ from [23] and set $p_c = 0.8 \cdot p_b$.

VI. Simulation

In order to validate the proposed strategy we used the bidirectionally coupled network and vehicular traffic simulator JiST/SWANS [25], [26] with extension by [27], [28].

A. Simulation setup

We have chosen a dynamic highway scenario with empirical boundary conditions. Vehicles move on a 12 km long, two-lane highway segment with an on- and off-ramp. This segment corresponds to a section of German Autobahn A044 between the cities of Unna and Werl. Fig. 3 illustrates the geometry of the considered highway section. To model open boundary conditions, including the inflow and outflow via the two ramps, we used the detector data of November 4, 2010, which show a spontaneous breakdown in morning peak hour traffic (see fig. 4). The time series of detector $D06$ as depicted in fig. 4(a) is exemplary for all detectors upstream the on-ramp; after the breakdown occurred at approximately 7:15 a.m. upstream vehicles approaching the on-ramp have to slow down causing a congested traffic pattern that travels upstream. Flow in each direction is approximately 36 000 vehicles per day with additional 7000 vehicles joining the road via the on-off-ramp system. Vehicles leaving the system as required by the boundary conditions are selected randomly without any preference for (non-)communicating vehicles. Therefore, the off-ramp has no influence on the proposed strategy but it is necessary to partially compensate for vehicles entering via the on-ramp. Similarly, entering vehicles are communicating according to the given penetration rate. The on-ramp increases the probability for a breakdown as vehicles entering the systems are likely to provoke perturbations which are the cause of breakdown. For simplicity, we used identical vehicle

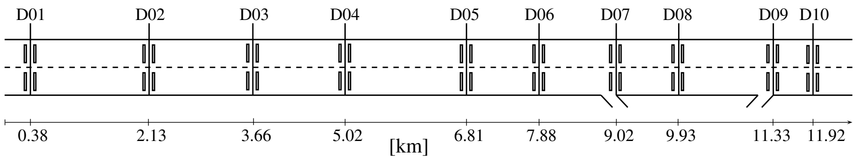
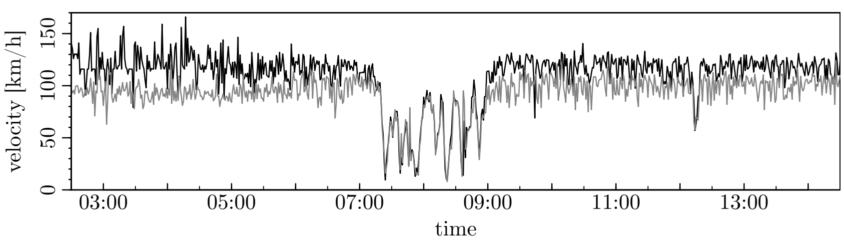
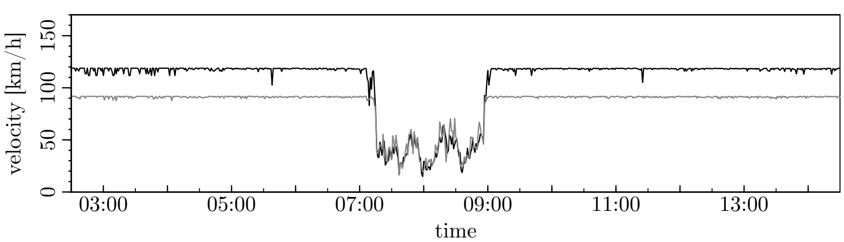


Fig. 3. Schematic sketch of the highway segment used for simulations. The locations of loop detectors are labeled as $D01, \ldots, D10$.

rates to model traffic flow on the opposite driving direction where we omitted the on- and off-ramp. Lane width is set to 3.75 meters with additional 2.5 meters between opposite driving directions. Simulations used two distinct vehicle types, namely "cars" and "trucks", which differ in vehicle length and maximum velocity as given in table II.



(a)



(b)

Fig. 4. A comparison between real detector data (a) from detector labeled $D06$ in fig. 3 and a detector in our simulation (b) which was placed at the same position. The detectors in the simulation measure the velocity of passing vehicles and return the average value aggregated over one minute intervals in analogy to the real detectors. Both time series show a breakdown in the detected velocities during the morning peak hour from approx. 07:15 a.m. to 9:00 a.m. The real detectors distinguish two types of vehicles, namely cars and trucks, which explains the two curves in above figures: the time series of cars is plotted with a solid black line whereas the corresponding time series of trucks is plotted with a solid grey line. We used two different vehicle types in our simulations to reflect this fact. As all vehicles of one type share an identical set of parameters (see table II) the fluctuations in free traffic flow are less pronounced in the simulations (b) than in real traffic (a).

Every radio equipped vehicle shares an identical set of physical parameters which are summarized in

TABLE I

PROPERTIES OF RADIO DEVICES AND RADIO CHANNEL.

PHY	
fading	Nakagami-m
interference	cumulative noise & capture effect
transmission power	17 dBm
reception threshold	-81 dBm
sensitivity threshold	-91 dBm
noise	-99 dBm
antenna gain	0 dBm
SINR	10
data rate	3 Mbits/s
MAC	
beacon size	500 B
beacon interval	250 ms
jitter	4%

table I. All values are in agreement with the draft standard [29]. As data rate we chose the minimum of the mandatory rates 3, 6 and 12 Mbits/s. For modeling radio propagation and signal fading we used the Nakagami-m model [30] which is well suited for highway environments as empirical studies [31] and [32] found. For communication distances of 80 meters and above we set $m = 0.75$. For smaller distances, however, we set $m = 1.5$ as for short distances a clear line of sight is likely to exist. (At this point it seems appropriate to refer to some very recent studies [33], [34] that promise a better path loss modeling by explicitly taking into account vehicles as obstacles for signal propagation.)

The MAC layer was implemented according to standard [29]. Status messages have a constant size of 500 byte and are broadcast with a frequency of 4 Hz. Note that both message size and frequency fulfill the communication requirements for safety applications presented in [2].

B. Simulation results

To assess the impact of vehicle communication on traffic flow we analyzed travel times for the considered highway segment and the given boundary conditions. Travel time is probably the most intuitive quality measure. Fig. 5 shows the average travel times for different penetration rates of communicating vehicles.

TABLE II

VEHICLE TYPES USED IN SIMULATIONS

vehicle properties	
max. velocity of cars	33.0 m/s
max. velocity of trucks	25.5 m/s
vehicle length of cars	7.5 m
vehicle length of trucks	15.0 m

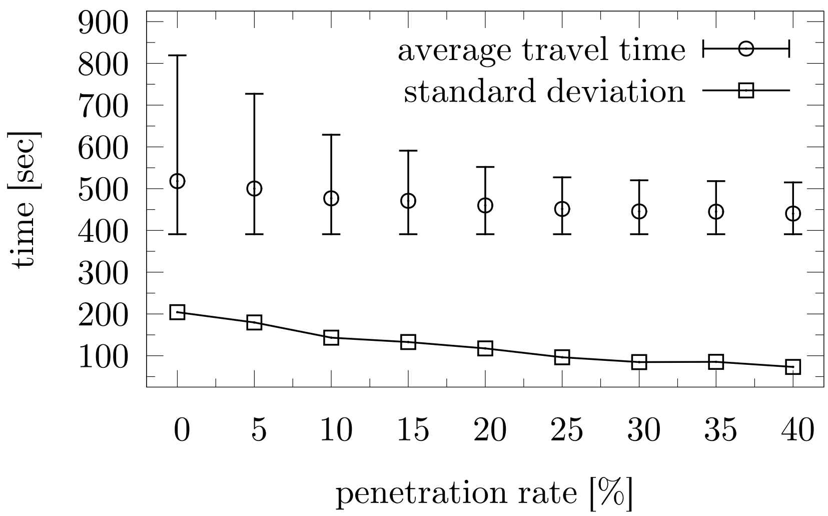


Fig. 5. Average travel times for different penetration rates: Error bars indicate the 0.1- and 0.9-quantiles.

Results were averaged over at least five independent simulation runs per penetration rate. The average travel time drops from 518 seconds without vehicle-to-vehicle communication to 440 seconds when 40 percent of all vehicles are equipped with communication devices. This corresponds to a travel time reduction of more than 15 percent. Error bars mark the positions of the 0.1- and 0.9-quantiles, respectively, which means 80 percent of all vehicles were able to cross the highway segment within the errorbars indicated interval. The lower boundary is mainly delimited by the minimal travel time following from vehicles' maximum velocity (see table II). The upper boundary, on the other hand, reflects the traffic dynamics and the existence of breakdowns. Here the benefits of vehicle-to-vehicle communication become more obvious; with one fourth of all vehicles being able to communicate the 0.9 quantile drops for more than 35 percent from 819 to 527 seconds. In addition, the lower curve in fig. 5 shows the standard deviation of observed travel times. The standard deviation of travel times can be understood as a measure

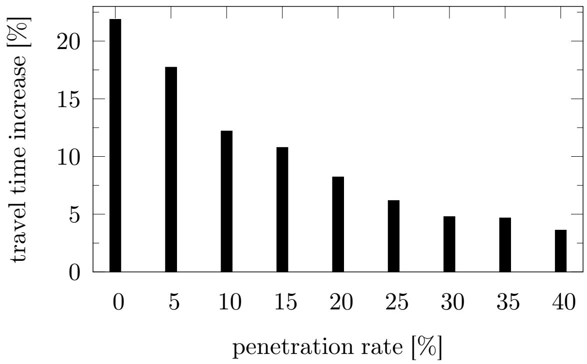


Fig. 6. Average travel times compared to an ideal travel time without vehicle interaction. This time is not expected to be reached because even in dilute traffic interactions between vehicles in the merging region the on-ramp casually causes braking maneuvers. Nevertheless, for a penetration rate of 40 percent the increase of average travel time is only 3.6 percent compared to the ideal travel time.

of travel time reliability and shows a similar dependence on penetration rate; with one in four vehicles being able to communicate standard deviation's value measures only 96 seconds compared to more than 200 seconds when communication is turned off.

To determine the average increase of time delay in each scenario we calculated an optimal travel time. To do so, we started a vehicle at each second of the simulated day on an empty road and recorded the corresponding travel time. Taking into account the share of trucks and trucks' increased travel time due to their reduced maximum velocity (see table II) one obtains an optimal average travel time of 425 seconds. This time serves as a reference value in fig. 6 which shows how much the scenarios deviate from the ideal condition without any interactions.

The temporal traffic dynamics is illustrated in fig. 7 where travel times of single vehicles are plotted against the hour of day. The application of vehicle communication reduces the duration and the severity of breakdown observed in the time from 6:30 a.m. to 9:30 a.m. significantly. This result is confirmed by the analysis of the stationary detector data.

In section IV the variables T_s and T_t were introduced to define an area of relevance for traffic information. Only vehicles within this spatiotemporal area change their driving behavior in response to received messages. To check the sensitivity of our results on the variables T_s and T_t we modified the original values of $T_s = 3$ km and $T_t = 30$ s and analyzed travel times in the interval from 6 a.m. to 9 a.m. where most fluctuations occur (see fig. 4(a)). As can be seen from fig. 9 the qualitative behavior of travel times is conserved when changing T_s and T_t for $\pm 1/3$ of the original value. Lee and Kim [35]

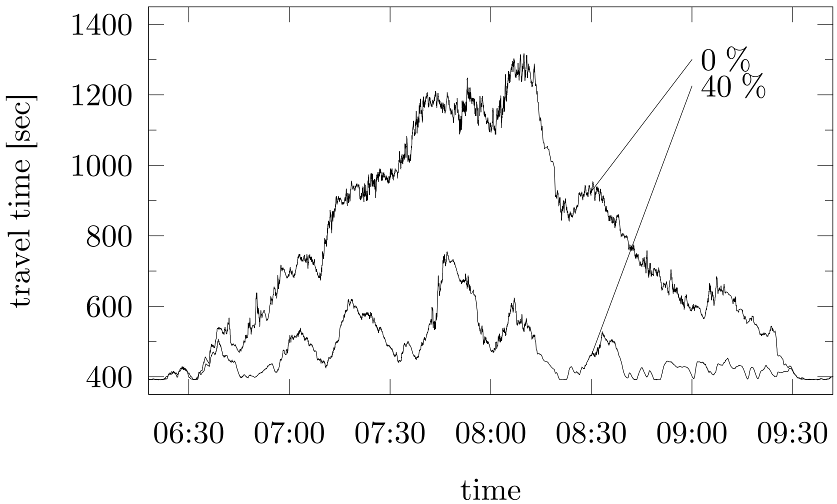


Fig. 7. The evolution of single vehicle travel times during the morning peak hour. For better readability the plot shows only data from vehicles of type car and a moving average over ten subsequent data points is applied.

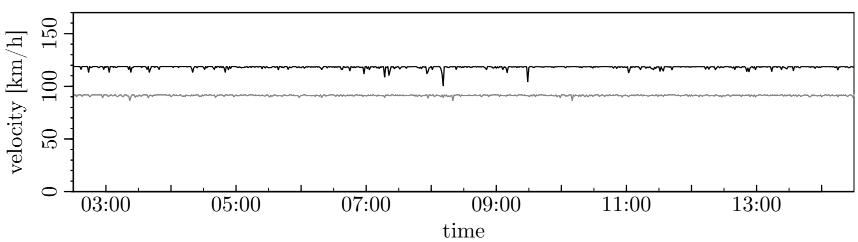


Fig. 8. The time series from the same detector as in fig. 4(b) after equipping 40 percent of vehicles with communication. In this case the breakdown which could be clearly observed in in fig. 4(b) has vanished

made a similar observation when studying the dissolution of traffic jams after introducing additional local interactions. For the local interactions they introduced each vehicle evaluated the velocity of a single downstream vehicle at distance d. Their results are independent from the distance d over a broad range.

Although we made no suggestion how the proposed strategy can be put into practice, we wanted to assess its success if some vehicles or drivers do not (or cannot) follow the recommended change of driving behavior. For this purpose we repeated the simulations and made half of the communicating vehicles ignore any recommendation on the driving behavior. However, these vehicles did correctly broadcast messages as described earlier. We compared the average travel times from these simulations to the previous simulation runs and found a very good agreement between the values for a given penetration rate (e.g., 40%) and the results obtained for half the given penetration rate (e.g., 20%) when all communicating vehicles do follow

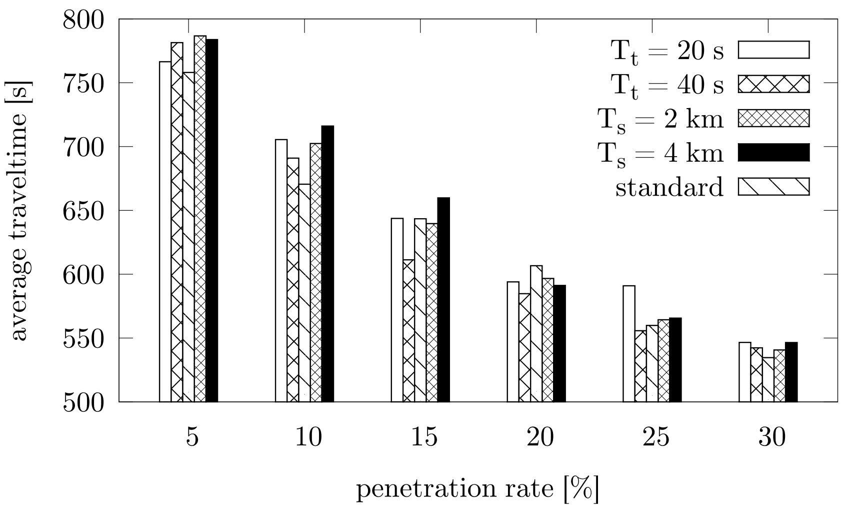


Fig. 9. Average travel times in the time from 6 a.m. to 9 a.m. for different values of T_s and T_t. The average travel time obtained with the original values of T_s and T_t serves as reference and is labeled 'standard'.

the recommendation. Hence, the success of our strategy depends crucially on the drivers' willingness (or capability) to follow the recommendation whereas the benefit from better connectivity in the latter case was found to be negligible.

VII. Conclusion

In this paper we presented a method to reduce congestion and improve traffic flow based on the use of vehicle-to-vehicle communication. Solely based on periodic beacon messages and using only velocity and position as a source of traffic state estimation the proposed method makes minimal requirements to the technical implementation.

The impact of the proposed strategy was evaluated by simulations employing a bidirectionally coupled simulator. The traffic simulator used empirical loop detector data which show a breakdown of traffic flow during the morning peak hour and which the simulator is able to reproduce.

In contrast to several previous studies (see Sec. III) where route choice was altered in response to an already existing jam, our approach becomes effective before a jam occurs. For this purpose our approach requires a traffic state analysis which does not only take into account vehicle density; by evaluating vehicles' position and velocity vehicles are able to decide when and where to change their driving behavior. The success of this approach can be seen by comparing figs. 4(b) and 8; with a sufficient number of vehicles applying our strategy the original traffic breakdown (fig. 4(b)) can no longer be observed (fig. 8).

Simulation showed even low penetration rates suffice to considerably improve traffic flow. With only one in ten vehicles being able to communicate the increase in travel time sinks from 22 to 12 percent compared to the case without communication. Only slight improvements were found for penetration rates of 30 percent and above.

All of the aforementioned points suggest VANETs are an adequate means to increase traffic efficiency and to improve traffic state estimation.

APPENDIX

The mobility model used for simulations is based on the comfortable driving model (CDM) by Knospe et al. [23]. It is a traffic cellular automaton where space is discretized in units of 1.5 meters and time in intervals of one second. The position and the velocity of a vehicle labeled as n are given by x_n and v_n, respectively. Vehicles are labeled downstream such that the vehicle in front of n is labeled $n+1$. For convenience, additional variables d_n and $t_h = d_n/v_n$ are introduced to denote the spatial and temporal headway between vehicles n and $n+1$. The model includes anticipatory effects by considering the status of the preceding vehicle's brake light l_{n+1}, by anticipating its velocity $v_{\mathrm{anti}} = \min(v_{n+1}, d_{n+1})$ and by calculating an effective distance d_n^{eff}:

$$d_n^{\mathrm{eff}} = d_n + \max(v_{\mathrm{anti}} - d_{\mathrm{safe}}, 0)$$

where d_{safe} governs the effectiveness of the anticipation (usually $d_{\mathrm{safe}} = 7$). According to the rules presented in section IV communicating vehicles are to keep a larger gap when they are notified about dense traffic. The additional gap is denoted as gap_n. The rules of motion in our modified model read as follows (The temporal discretization of one second allows to treat all magnitudes as dimensionless because conversions do not change a variable's numerical value):

1) acceleration:

   $l_n(t+1) \leftarrow$ false

   if $l_n(t) = l_{n+1}(t) =$ false OR $t_h \geq t_s$ then:

   $\quad v_n(t+1) \leftarrow \min(v_n^{\max}, v_n(t) + 1)$

2) adaptation of gap_n:

   if $(v_n(t+1) > d_n^{\mathrm{eff}} - \mathrm{gap}_n(t)$ AND $\mathrm{gap}_n(t) > 0)$ then:

   $\quad$ if$(v_n(t+1) > v_n(t))$ then:

   $\quad\quad v_n(t+1) \leftarrow v_n(t)$

   $\quad \mathrm{gap}_n(t+1) \leftarrow \max(d_n^{\mathrm{eff}} - v_n(t+1), 0)$

3) determination of randomization parameter p:

$$p \leftarrow \begin{cases} p_b, & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ & \text{AND } \mathrm{gap}_n \leq v_n t_r, \\ p_c, & \text{if } l_{n+1} = \text{true AND } t_h < t_s \\ & \text{AND } \mathrm{gap}_n > v_n t_r, \\ p_0, & \text{if } v_n = 0 \text{ AND NOT} \\ & (l_{n+1} = \text{true AND } t_h < t_s), \\ p_d, & \text{otherwise.} \end{cases}$$

4) braking:

$v_n(t+1) \leftarrow \min(d_n^{\mathrm{eff}} - \mathrm{gap}_n(t+1), v_n(t+1))$

$l_n(t+1) \leftarrow 1 - \Theta\left(v_n(t+1) - v_n(t)\right)$

5) dawdling:

if $(\texttt{rand()} < p)$ then:

$v_n(t+1) \leftarrow \max(v_n(t+1) - 1, 0)$

if $p = p_b$ then $l_n(t+1) \leftarrow$ true

6) reaction to warning message:

$$\mathrm{gap}_n(t+1) \leftarrow \begin{cases} \min(7 s_{\mathrm{car}}, d_n - v_n^{\max}), & \\ \quad \text{if } b_n = \text{ true} & \\ \quad \text{AND } d_n > v_n^{\max}, & \\ 0, & \\ \quad \text{if } b_n = \text{ false.} & \end{cases}$$

7) car motion:

$x_n(t+1) \leftarrow x_n(t) + v_n(t+1)$

In the first step a vehicle tries to accelerate to its maximum velocity. To avoid unnecessary acceleration it checks the status of its own and the preceding vehicle's brake light and compares its time headway t_h to a velocity dependent interaction horizon $t_s = \min(v_n, h)$ (with $h = 6$ seconds). In the next step the additional gap gap_n is adapted to avoid braking. After determining the randomization parameter p (see section IV) the vehicle checks whether it actually has to brake. The function $\Theta(\cdot)$ denotes the Heaviside step function. If a random number $\texttt{rand()}$ uniformly generated in $(0, 1)$ is smaller than the randomization parameter p velocity is reduced by one unit. The last two steps where the new value of gap_n is calculated and the vehicle moves are interchangeable. The length of gap_n is limited to a multiple of passenger car length s_{car} to avoid unrealistically large gaps in dense traffic.

Acknowledgments

The authors thank M. Boban for providing parts of his code used in [36].

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