Inter-Vehicle Communication on Freeways: Statistical Properties of Information Propagation in Ad-Hoc Networks

Martin Schönhof[1], Arne Kesting[1], Martin Treiber[1], and Dirk Helbing[1,2]

[1] Technische Universität Dresden, Institute for Transport & Economics, Andreas-Schubert-Straße 23, D-01062 Dresden, Germany
[2] Collegium Budapest – Institute for Advanced Study, Szentháromság u. 2, H-1014 Budapest, Hungary

Abstract. The function of adaptive cruise control (ACC) systems can be enhanced by information flows between equipped cars, i.e., by upstream transmission of messages about the current traffic situation. Message transport within one driving direction is obviously rather restricted for small percentages of equipped cars due to the limited broadcast range. Thus, we consider vehicles in the opposite driving direction as possible relay stations. Analytical results based on a Poisson approximation, which are in accordance with empirical traffic data, show the efficiency and velocity of information propagation based on transversal message hopping. The obtained propability distributions of the transmission times are compared with numerical results of microscopic traffic simulations. By simulating the formation of a typical traffic jam, we show how information about distant bottlenecks and jam fronts reaches upstream equipped cars, which then can optimize their driving strategies.

1 Introduction

Inter-vehicle communication (IVC) is widely regarded as a powerful concept for the transmission of traffic-related information. In contrast to the common communication channels, which operate with a centralized broadcast concept via radio or mobile-phone services, IVC is designed as a local service based on ad-hoc networks. Vehicles equipped with a short-range radio device, broadcast messages which are received by all other equipped cars within the limited broadcast range. The message transmission is not controlled by a central station, and, therefore, no further infrastucture is needed. Supported by the technological progress and the falling prices for corresponding hardware, the market for short-range communication devices is growing, and wireless local-area networks (WLAN) spread more and more.

In this contribution, we will focus on the propagation of information via IVC equipped vehicles. Since IVC will start with a small equipment level, it is crucial to investigate the functionality and the statistical properties of the message hopping processes. Fast and reliable information spreading is a necessary precondition for a successful implementation of this technology. The traffic information of interest can be generated by the IVC equipped cars themselves, if each car reports about the traffic conditions it currently faces. This results in a completely decentralized, autonomous traffic surveillance and information system. While the information must be transported over distances of about 1 km in upstream direction, the broadcast range is only of the order of 250 m. We, therefore, also consider equipped vehicles in the opposite driving direction as transmitter cars.

Apart from the single drivers the whole traffic system may benefit from IVC as well [2]. *Adaptive cruise control* (ACC) automates the braking and accelerating of a car. While the objectives of the currently available ACC systems are to enhance the comfort and safety of driving, there has been no focus on their effect on the capacity of the freeway, except for the general positive effects of avoiding accidents. Transmission of traffic information via IVC could help ACC systems to recognize the traffic situation faster and more reliably. Moreover it could help ACC systems to increase road capacity by allowing it to reduce the time headway just when it is about to leave the downstream front of a traffic jam.

Our contribution is organized as follows: After a discussion of message transport strategies for freeways and their statistics (Section 2), we will present in Section 3 a simulation scenario, where information about a traffic jam is transported upstream by cars of the other driving direction. Afterwards, we will summarize our contribution and give a short outlook.

2 Statistics of Message Transport on Freeways

2.1 Message Transport Strategies

In the context of freeway traffic, messages normally have to travel upstream in order to be valuable for their receivers. In general, there are two strategies, how a message can be transported upstream via IVC (or mixtures of both): Either the message hops from an IVC car to a subsequent IVC car within the same driving direction – which will be called *longitudinal hopping*, or the message hops to an IVC car of the other driving direction which takes the message upstream and delivers it back to cars of the original driving direction. The second mechanism, where vehicles of the opposite direction act as relay stations, will be referred to as *transversal hopping* (cf. Fig. 1).

2.2 Spatial Distribution of Equipped Vehicles

If the market penetration is low, the encounter of an IVC equipped vehicle with another one is seldom. In good approximation, the positions of the IVC cars therefore can be assumed independent of each other, even for high traffic densities. With the additional assumption of a constant overall traffic density ρ on all lanes of the analyzed driving direction, and for a given percentage (equipment level, market penetration) α of IVC vehicles, it follows that the number of IVC vehicles on a given road section is Poisson distributed. Thus, the headways Δs between consecutive equipped vehicles are distributed exponentially:

$$f_{\Delta s}(x) = \lambda e^{-\lambda x} \quad \text{with} \quad \lambda = \alpha\rho. \tag{1}$$

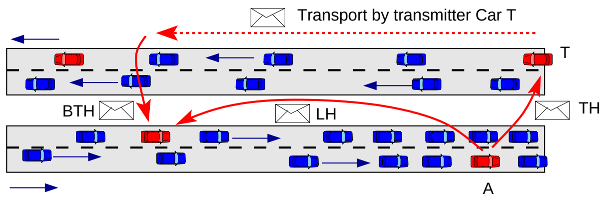


Fig. 1. Transport of a traffic information message on a freeway: When car "A" enters a traffic jam, it broadcasts a related message. This is received by a subsequent car via longitudinal hopping ("LH") and by an equipped transmitter car "T" of the other driving direction via transversal hopping ("TH"). The message can travel with the transmitter "T" upstream, until it is delivered back to the original driving direction by back transversal hopping ("BTH"). In the main text, we will discuss which message passing mechanism is more efficient

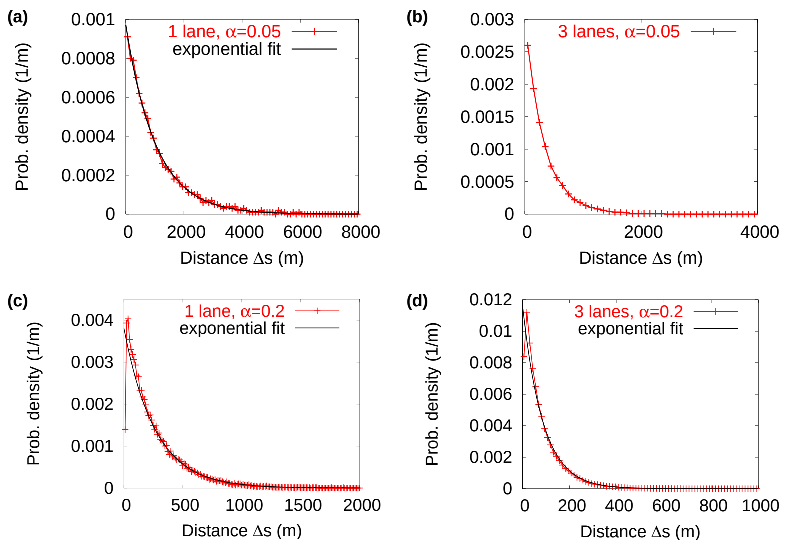


Fig. 2. Probability density of distances between IVC equipped vehicles based on single vehicle data for the freeway I-880. Each car entering the upstream boundary of the investigated freeway stretch have, with probability α randomly and independently, been chosen to be an 'equipped' car. The resulting fraction of α chosen cars corresponds to an IVC market penetration of α. Using the time headways Δt between consecutive equipped vehicles, we have obtained the distance Δs for every equipped car i via $\Delta s_i = \Delta t_i V_{i-1}$, where the equipped car $i-1$ is the predecessor of car i, and V_{i-1} its velocity. The single vehicle data were recorded in 1993 at cross section 6 (29300 feet distance from Mariana) of freeway I-880, Hayward, California, in direction north [13]. Data of congested or light traffic (velocity $<$ 60 km or flow $<$ 1000/h/lane) have been omitted. Only the right lane has been taken into account in **(a)** and **(c)**. In **(b)** and **(d)**, the three rightmost lanes from altogether five lanes have been considered

This assumption is very well supported by empirical data, cf. Fig. 2. Evaluating the data of single cars passing a freeway cross section, it is possible to obtain the distribution of distances between IVC equipped vehicles for scenarios of different equipment levels. Even for a single lane, this distance is exponentially distributed for small equipment levels. However, above a level of 20%, the form of the distribution gets more and more similar to the Erlang/Pearson III distribution of headways [5].

2.3 Longitudinal Message Hopping

Longitudinal hopping is only possible, if there is an upstream receiver in the broadcast range of the sending car. For message transport over a certain distance, there has to be a closed chain of IVC cars: Every single distance between two subsequent IVC equipped cars must be smaller than the broadcast range for a certain time span. This is very unlikely for a low equipment level. The following example presents a more detailed analysis.

For a given maximum broadcast range $r_{\max}$, the probability of finding an upstream receiver for longitudinal hopping is given by

$$P(\Delta s < r_{\max}) = \int_0^{r_{\max}} f_{\Delta s}(x)dx = 1 - \mathrm{e}^{-\lambda r_{\max}}. \tag{2}$$

Considering an overall density of $\rho = 30$ veh/km on two lanes, $\alpha = 0.05$, and $r_{\max} = 250\,\mathrm{m}$, we obtain a probability of 31% for a message hop. If we require that the information should be available at least $r_{\mathrm{u}} = 1000\,\mathrm{m}$ upstream of a detected traffic event, the information has to hop at least four times. Because of the statistical independence of the hopping processes, the probability for n successful hops is given by

$$P_n = \left(1 - e^{-\lambda r_{\max}}\right)^n. \tag{3}$$

That is, the probability for four successful hops is only $(0.31)^4 \approx 1\%$. Note that this is an upper limit for the transmission probability, as not every hop will bridge exactly 250 m. Thus, normally more than 4 hops will be necessay, which further reduces the transmission probability.

2.4 Transversal Message Hopping

With longitudinal hopping, a message either reaches its “destination” at once or never. Via transversal hopping, a message reaches *always* the destination point $r_{\mathrm{u}} = 1000$ m upstream of the position where it has been generated. The message is available at this point as soon as the first encountered equipped car of the other direction, the *transmitter*, has moved a distance $x^\star = r_{\mathrm{u}} - r_{\max}$ upstream from the place of message generation. The remaining distance can be bridged via wireless communication (cf. Fig. 3). The time t, when this is completed,

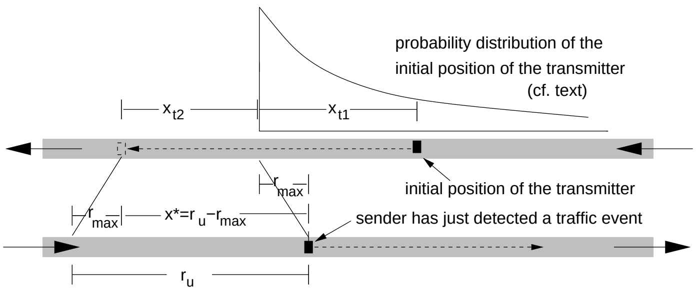


Fig. 3. Initial spatial configuration and labelling of the distances: The sender has just detected an event and broadcasts a corresponding message. The first encountered equipped car of the other direction, the transmitter, may be downstream or upstream (left) of the sender, but in the latter case within the broadcast range $r_{\max}$ (left cutoff of probability distribution). If the transmitter is out of the broadcast range (for large x_{t1}), the message will not be received immediately. The time, when the message is picked up by the transmitter does not directly affect the time t which is needed to deliver the message the distance r_{u} upstream of the initial sender position. However, both times depend, of cause, on x_{t1}

depends on the initial position of the transmitter at the time the message is generated and on its velocity v_{tr}. The initial distance of the transmitter from the "retransmission point" x^* consists of two parts, x_{t1} and x_{t2} (cf. Fig. 3). Thus, we obtain

$$t = \frac{x_{t1} + x_{t2}}{v_{\mathrm{tr}}}. \tag{4}$$

x_{t2} is given by

$$x_{t2} = r_u - 2r_{\max} \tag{5}$$

(cf. Fig. 3), while the stochastic quantity x_{t1} is determined by the gap distribution between two IVC cars, i.e., its probability density is given by

$$f_{x_{\mathrm{t1}}}(x) = f_{\Delta s}(x) = \lambda e^{-\lambda x} \Theta(x). \tag{6}$$

Here, the Theta-function $\Theta(x)$ is 1 for positive arguments x, and zero, otherwise.

Let us now calculate the cumulative distribution $P(t < \tau)$ of arrival times t. According to Eq. (4), the message arrives at a time $t < \tau$, if $x_{\mathrm{t1}} < \tau v_{\mathrm{tr}} - x_{\mathrm{t2}}$. Therefore, the probability that the information is succesfully transmitted until time τ can be calculated as

$$P(t < \tau) = P(x_{\mathrm{t1}} < \tau v_{\mathrm{tr}} - x_{\mathrm{t2}}) \tag{7}$$

$$= \int_0^{\tau v_{\mathrm{tr}} - x_{\mathrm{t2}}} f_{x_{\mathrm{t1}}}(x)\, dx \tag{8}$$

$$= \Theta\left(\tau - \frac{r_{\mathrm{u}} - 2r_{\max}}{v_{\mathrm{tr}}}\right)\left(1 - e^{-\lambda(2r_{\max} + v_{\mathrm{tr}}\tau - r_{\mathrm{u}})}\right) \tag{9}$$

Because $f_{x_{t1}}(x) = 0$ for $x < 0$ (see Eq. (6)), the probability distribution is zero if, in the case of a small value of τ, the upper bound of the integral in Eq. (8) becomes negative. This results in the Theta function $\Theta(\tau v_{\mathrm{tr}} - x_{\mathrm{t2}}) = \Theta\left(\tau - \frac{r_{\mathrm{u}} - 2r_{\mathrm{max}}}{v_{\mathrm{tr}}}\right)$ in Eq. (9). Since the probability of a transmission before the time $\frac{r_{\mathrm{u}} - 2r_{\mathrm{max}}}{v_{\mathrm{tr}}} = \frac{x_{\mathrm{t2}}}{v_{\mathrm{tr}}}$ is zero, this is the minimal possible transmission time. It occurs, when the transmitter only needs to pass the distance x_{t2}, i.e., if it is initially as far as possible upstream (corresponding to maximum of the distribution in Fig. 3).

In Figure 4, the information transport within the same driving direction is compared to the information transport via a transmitter of the opposite driving direction. In the first case, the message is instantaneously available a certain distance r_u upstream of a recognized traffic event (if we neglect the broadcasting time). However, because of the low equipment rate, the transmission succeeds only with a very small probability that does not change in time. Either the information reaches the destination more or less at once, or never. In the case of transversal hopping, the message needs at least 18 seconds, but after 36 seconds, the message is available with a probability of 50%. An 36-seconds old information 1000 m ahead of the event is still very valuable: For example, in 36 seconds a possible disturbance of the traffic flow may travel (with a characteristic speed of $\approx$ 15 km/h) 150 m upstream. Hence, for the receiver of this information, there are 850 m left to react to the traffic event (e.g. stop-and-go wave).

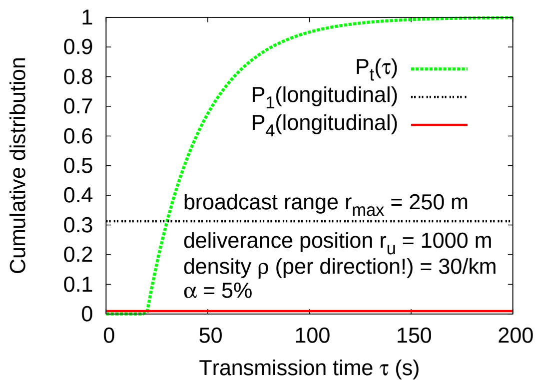


Fig. 4. Probability distribution of the time interval between the generation of a message and its availability 1 km upstream of the event for the two broadcast strategies. If only cars of the same driving direction are used for message transmission, at least 4 successful "hops" are necessary. The transmission probability is, therefore, $P_4 = P_1^4 = 0.01$ or less (cf. text). When transmitter cars of the opposite driving direction are used, the message needs at least 18 seconds, but after 36 seconds, the message is available with a probablilty of about 50%. The velocity of the transmitters has been assumed to be $v_{\mathrm{tr}} = 100$ km/h. The minimal time for the message transfer is $\frac{r_{\mathrm{u}} - 2r_{\mathrm{max}}}{v_{\mathrm{tr}}} = 18\,\mathrm{s}$

2.5 Microscopic Simulation of Inter-Vehicle Communication

In order to test these analytical results, we have carried out a multi-lane traffic simulation of a 10 km freeway stretch with two independent driving directions and altogether four lanes. We have used the *intelligent driver model* (IDM) [12] complemented by a lane changing algorithm [11] (see Fig. 5 below). The parameters have been selected as in Ref. [2], whereas the desired velocities have been chosen Gaussian distributed with an rms value of 18 km/h around $v_0 = 120\,\text{km/h}$. We have used open boundary conditions with a constant inflow at the upstream boundary of $Q = 1240/\text{h/lane}$.

The microscopic simulation approach allows for a detailed modeling of the message broadcast and receipt mechanisms of IVC equipped vehicles (colored vehicles in Fig. 5). To obtain the statistics of message propagation, the equipped vehicles have generated a "dummy" message while crossing the position $x =$ 5 km. In Fig. 6, the results of the simulation are compared to the analytical results based on the Poisson approximation (cf. Sec. 2.2). The percentage of vehicles equipped with the IVC device has been varied and the traffic density measured by 'virtual' detectors as in Ref. [2]. The results show a very good agreement with our analytical calculations (Eq. 9).

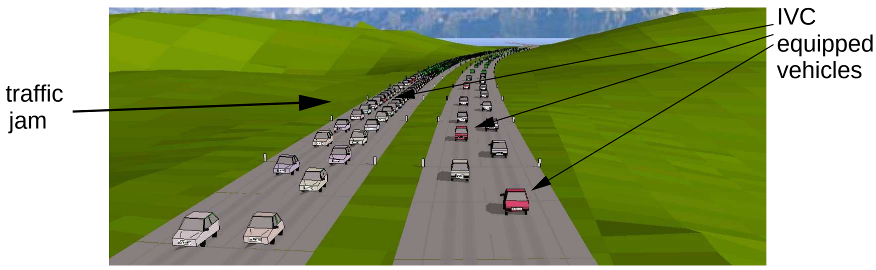


Fig. 5. Screenshot of the traffic scenario discussed in Sec. 3. The microscopic simulation approach allows one to combine traffic dynamics with the microscopic mechanisms of broadcasting and receiving messages via inter-vehicle communication (IVC). The colored cars are equipped with the functionality of generating, sending and receiving information. In the driving direction towards the reader, a stop-and-go wave propagates through the system. The equipped vehicles in the opposite driving direction are used as transmitter cars enabling a "transversal" message hopping. This process allows for a fast information propagation in upstream direction

3 Application: Upstream Transport of Traffic-Related Information via Transversal Hopping

Let us now demonstrate the message propagation mechanism with a microscopic traffic simulation. We have simulated the two driving directions of an altogether

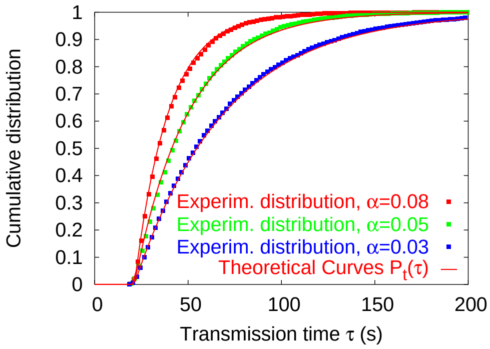


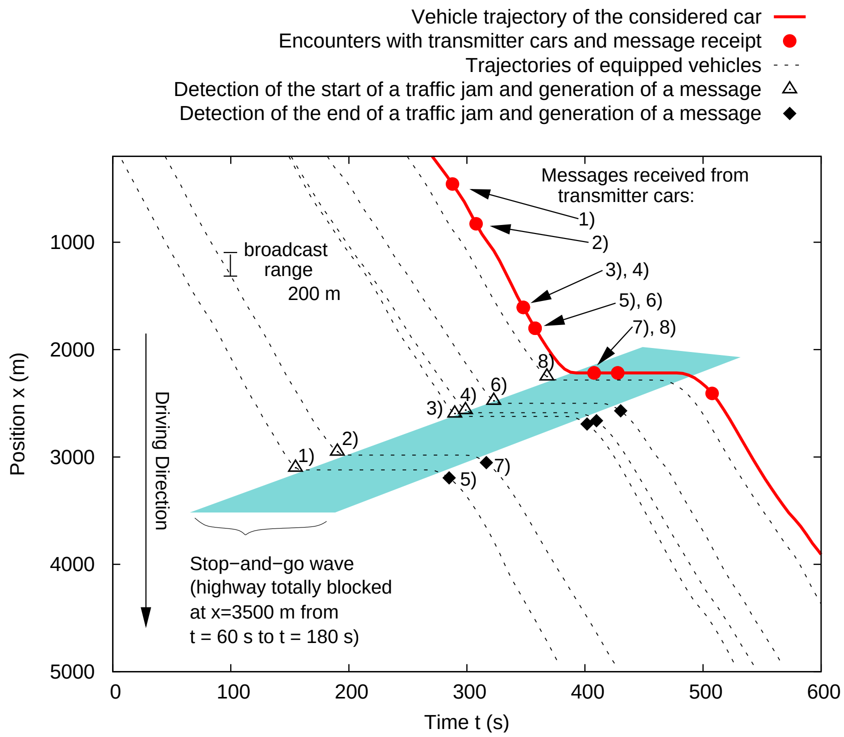
Fig. 6. Message transport via transmitter cars in the opposite driving direction: Comparison of Eq. (9) (solid lines) with the simulated distribution of the time intervals τ until a message is available 1000 m upstream of a traffic event (symbols). The assumed IVC parameters were the broadcast range $r_{\rm max} = 250$ m and the minimal delivery range $r_{\rm u} = 1000$ m. Applying the vehicle parameters in Ref. [2] and choosing an inflow of $Q = 1240$veh/h/lane, we have a transmitter velocity of $v_{\rm tr} = 85$ km/h and an overall density of $\rho = 29$/km in each direction. The simulations have been carried out with equipment rates of $\alpha = 3\%$, $\alpha = 5\%$, and $\alpha = 8\%$

four-lane freeway. In one driving direction, we have triggered a wide moving cluster (also called a "Moving Localized Cluster" [3,8]), while traffic was freely flowing in the other driving direction (see Fig. 5). Two types of messages have been generated: (i) If the velocity of a vehicle equipped with an IVC device dropped below 30 km/h, the car started to broadcast the message "start of traffic jam" with the time and position of its detection. (ii) If the velocity exceeded the velocity 45 km/h, the message "end of traffic jam" was being broadcasted.

The spatiotemporal traffic dynamics and the processes of sending and receiving messages are shown in Fig. 7. Due to the low equipment rate of $\alpha = 3\%$, the equipped vehicles have an average distance to each other that exceeds the broadcast range of the IVC device. An upstream message propagation only within one driving direction would, therefore, lead to a fast breakdown of the information chain (see Fig. 7) as stated in Sec. 2.3. Thus, we have used IVC-equipped vehicles as transmitters in the other driving direction. Fig. 7 numbers the generated messages and shows their delivery to a specific vehicle. Remarkably, the considered vehicle gets the first information about the traffic congestion already 2 km before encountering the stop-wave. The information is confirmed and updated by subsequent messages provided by other vehicles. The up-to-date information about the expected traffic situation could be used to warn drivers or to set-up a strategically operating adaptive cruise control (ACC) system [2].

4 Summary and Outlook

The market penetration of adaptive cruise control (ACC) is steadily growing. By means of inter-vehicle communication, (IVC), the performance of these systems



Messages:

1) Jam begins at x=3100 m, t=155 s
2) Jam begins at x=2950 m, t=190 s
3) Jam begins at x=2595 m, t=290 s
4) Jam begins at x=2563 m, t=299 s
5) Jam ends at x=3195 m, t=285 s
6) Jam begins at x=2477 m, t=33 s
7) Jam ends at x=3053 m, t=317 s
8) Jam begins at x=2250 m, t=368 s

Fig. 7. Spatiotemporal diagram of a traffic simulation, for which the trajectories of vehicles equipped with inter-vehicle communication (IVC) devices are displayed by dashed lines. The equipment level is 3%. While the cars encounter a propagating stop-and-go wave, they start to broadcast messages about the begin and the position of the stop-wave and the following start-wave as labeled by numbers in the diagram. Since the broadcast range of 200 m does not allow for a reliable message propagation only in the driving direction (see scale in the diagram), the messages are transported by equipped (transmitter) cars of the opposite driving direction (trajectories not shown). Finally, the receipt of the propagating messages is marked for a specific vehicle (solid trajectory). This considered car gets the information about the position of the traffic jam, and, additionally, the expected travel time, for the first time 2 km upstream. The reliability of the information increases by the receipt of additional messages, which confirm and update the reconstruction of the expected traffic situation for the individual driver

can be increased by accurate and up-to-date messages about the traffic situation ahead. For receiving and transmitting up-to-date information on a short timescale, it is promising to use an entirely decentralized system like an adhoc-network of vehicles equipped with inter-vehicle communication technology – especially if these equipped cars on the road also gather the traffic information that is transmitted.

A problem of such a short-range communication system is that it may not work properly for a low equipment rate. In this contribution, we have, therefore, presented a communication strategy for inter-vehicle communication that operates well for low equipment rates by using cars on the opposite driving direction as relay stations. For example, even for an equipment rate of 5% only, a traffic-information message will be passed 1 km upstream with a probability of 50% within 36 seconds. The simulations of Fig. 7 showed that even lower equipment rates enable effective communication in realistic situations. A further step is to develop and implement traffic-state dependent strategies for ACC [2] that react to IVC information in a situation-specific way.

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