Autonomous Detection and Anticipation of Jam Fronts from Messages Propagated by Intervehicle Communication

Martin Schönhof, Martin Treiber, Arne Kesting, and Dirk Helbing

A minimalist, completely distributed freeway traffic information system is introduced. It involves autonomous, vehicle-based jam-front detection, information transmission via intervehicle communication, and forecast of the spatial position of jam fronts by reconstructing the spatiotemporal traffic situation on the basis of the transmitted information. The whole system is simulated with an integrated traffic simulator, which is based on a realistic microscopic traffic model for longitudinal movements and lane changes. The function of its communication module has been explicitly validated by comparing the simulation results with analytical calculations. By means of simulations, it is shown that the algorithms for congestion-front recognition, message transmission, and processing reliably predict the existence and position of jam fronts for vehicle equipment rates as low as 3%. A reliable mode of operation for small market penetrations is crucial for successful introduction of intervehicle communication. The short-term prediction of jam fronts is not only useful for the driver but also essential for enhancing road safety and road capacity by intelligent adaptive cruise control systems.

Intervehicle communication (IVC) is widely regarded as a promising concept for transmitting traffic-related information. There are essentially two types of future applications that inspire the research on IVC. First, those in traffic safety such as automated reaction to an emergency incident; cooperative, autonomous driving; and platoon formation on freeways rely on fast communication and information transmission between single vehicles (*1–5*). In contrast, applications for advanced traveler information systems, dynamic routing, or entertainment do not depend critically on information transmission times.

Recently, another application field of IVC was proposed in the context of strategically operating adaptive cruise control (ACC) systems, which change their driving characteristics automatically on an intermediate time scale according to the local traffic situation (*6*). Although currently available ACC systems aim to enhance the comfort and safety of driving, their impact on the capacity and the stability of traffic flow on freeways has moved into the focus of traffic research (*7–11*). Receiving traffic-related messages via IVC could help ACC systems to recognize relevant traffic situations faster and more reliably. This assistance allows ACC-equipped vehicles to drive with an intelligent driving strategy that adapts the ACC parameters to the current traffic situation and thereby changes the driving style. For example, if the positions of jam fronts were known in advance, an ACC system could brake earlier and more smoothly when the vehicle approached the upstream jam front, to increase traffic safety. In contrast, it could keep smaller time gaps to the lead vehicle when it left the jam at the downstream jam front, to increase the jam outflow (discharge rate) while it stayed at normal operating characteristics in all other situations. Furthermore, ACC-equipped cars acting as floating cars are also able to detect the position of jam fronts and consequently may spread such information via IVC. However, since IVC will be implemented on a small number of equipped vehicles, it is crucial to investigate the functionality and the statistical properties of the message-hopping processes under such conditions. These questions were investigated recently within the German research project Intelligent Traffic and User-Friendly Technology (INVENT) (*12*).

Fast and reliable information spreading is a necessary precondition for successful implementation of all these IVC-based applications. Assuming sufficient market penetration, IVC offers the possibility of a decentralized and robust traffic information system, in which the data are collected, evaluated, and distributed autonomously by each single car. It should be noted that estimation of the necessary market penetration for IVC depends on the application, which means on the type of information transmitted and how this information is used. The transmission of messages within a dynamic ad hoc network of vehicles has been investigated on different levels of abstraction with respect to protocol design (*13, 14*) and message propagation efficiency. The latter aspect, which is also addressed here, has been investigated by simulations and by analytical calculations in different studies (*15–19*). Yang and Recker (*20*) published a short and thorough literature overview.

An IVC-based application of vehicle-based jam-front detection and prediction is presented here. By means of microscopic traffic simulation, the whole chain of information generation, transmission, and interpretation based on a small fraction of vehicles equipped with IVC is simulated. Single vehicles in the traffic simulation detect jam fronts and generate traffic-related messages based on their locally available floating-car data. These messages are propagated further upstream via IVC mainly by cars traveling in the opposite driving direction. Finally, the received information is used for reconstruction and short-term prediction of the expected traffic situation further downstream, which can serve as the basis for determining the appropriate ACC strategy as discussed by Kesting et al. (*6*). The prediction error for an equipped car is investigated as a function of the distance to the predicted jam front. It should be noted that this individual short-term traffic forecast is of general interest to the driver.

Institute for Transport and Economics, Technische Universität Dresden, Andreas-Schubert-Strasse 23, D-01062 Dresden, Germany. Corresponding author: M. Schönhof, martin@vwi.tu-dresden.de.

Transportation Research Record: Journal of the Transportation Research Board, No. 1999, Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 3–12.
DOI: 10.3141/1999-01

MICROSCOPIC MODELING OF IVC AND MESSAGE GENERATION

Characteristics of IVC and Its Implementation

In the model of IVC introduced here, in the context of freeway traffic, messages have to travel upstream in order to be valuable for their receivers. In general, there are two strategies for transporting a message upstream via IVC (Figure 1): either the message hops from one IVC car to a subsequent IVC car in the same driving direction (longitudinal hopping) or the message hops to an IVC-equipped vehicle in the other driving direction, which takes the message upstream and delivers it back to cars in the original driving direction (transverse hopping). The sender (e.g., having recognized an upstream jam front) generates a message at time t_1 and starts broadcasting it. The message may be received by a subsequent car via a longitudinal hop. At time t_2, the message is received by an equipped transmitter car via a transverse hop. The characteristic quantity of the communication process is the time $\tau = t_3 - t_1$ from the message generation until it is available for the first time at a user distance r_u upstream of the position where the message has been generated. The minimal time τ for communication via transverse hopping is realized for a configuration as shown in the bottom diagram of Figure 1. The transmitter (velocity v_{tr}) must be at the optimal position at $t = 0$, that is, a distance R upstream of the sender. The message is available when the transmitter has covered the distance $r_u - 2R$, or after a time $\tau_{min} = (r_u - 2R)/v_{tr}$.

For a low density of equipped cars (i.e., for a small market penetration), instantaneous multiple longitudinal hopping is not very likely because of gaps that are larger than a given limited broadcast range (*21*). It has been argued that the gaps in multilane traffic may be bridged after a while because of different velocities of the equipped cars. However, this effect is a minor one. For low densities of equipped vehicles, a message propagates in the driving direction with a velocity not greater than the velocity of the fastest cars (*17*). Therefore, it is concluded that longitudinal hopping against the driving direction does not work for low densities of equipped vehicles because the mechanism for bridging gaps is too slow for a real backward propagation of the messages—the normal downstream movement of messages inside the cars cannot be exceeded by the wireless communication in the upstream direction. Thus, longitudinal hopping will only have some impact in combination with transverse hopping in order to enhance the message propagation in the traffic stream of the opposite driving direction. However, in the case of dense traffic conditions (which is to be distinguished from a high density of IVC-equipped vehicles), the variation in the velocities of the vehicles is limited. As a consequence, even in the limit of long time scales, the obtained propagation velocity is similar to the mean velocity of the transmitter vehicles (*17*).

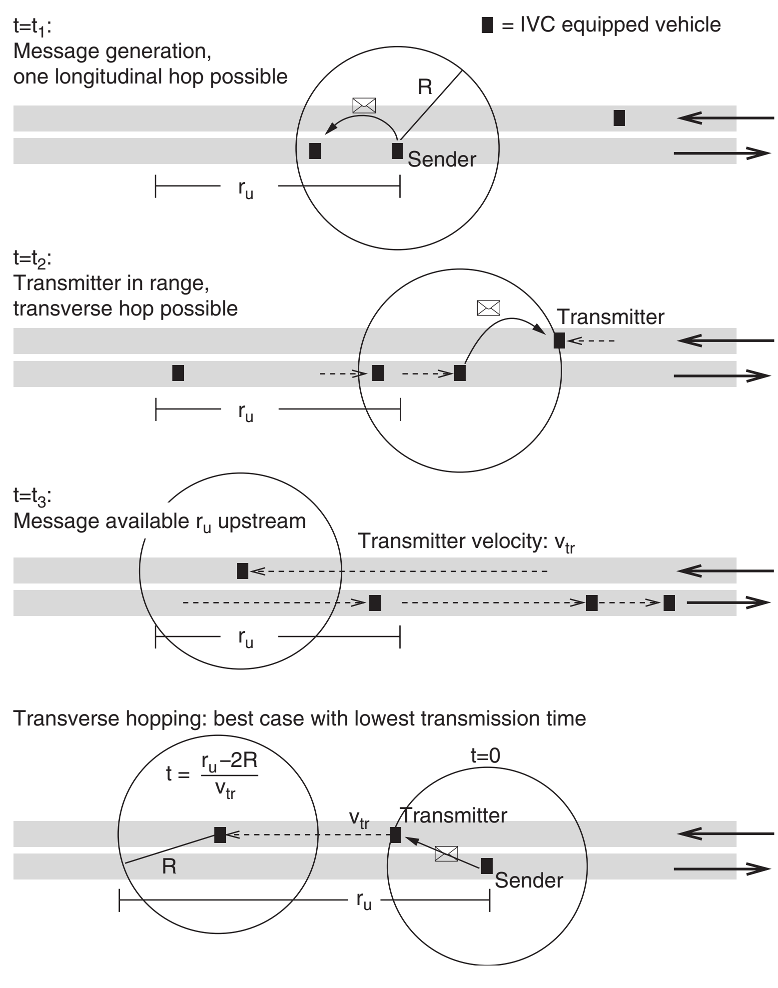

FIGURE 1 Basic mechanisms for transport of traffic-related message on freeway (only IVC-equipped vehicles are shown).

In the following, the microscopic model used for the IVC-related processes is outlined. Every 2 s, messages are exchanged between IVC-equipped vehicles within a limited broadcast range *R*. Each car sends all its stored messages, and the default broadcast range is set to 250 m. These assumptions are well justified with regard to the current technological possibilities of data exchange between vehicles (discussed in the next subsection). Furthermore, the width of the road is neglected in the calculations and simulations; that is, the broadcast range *R* refers to longitudinal distances.

Because of the low efficiency of longitudinal hopping, the discussion is restricted to transverse hopping processes. Each car accepts only messages from the other driving direction, either as a transmitter vehicle (after the first transverse hop) or as a user that receives information about its own driving direction (after a second transverse hop). All other messages will be discarded directly after reception. Furthermore, messages related to events at an already passed position and messages that are older than 10 min are deleted as well. Since the routing in this system is obviously given by the two traffic streams in opposite directions, no further rule is necessary for modeling the message exchange process.

Technological Basis for IVC

The assumptions about the exchange of small traffic-related data packages are justified by the experimentally proved possibilities of data transmission between vehicles on the freeway within IEEE Standard 802.11b. Operation of wireless local-area network equipment on a freeway with an external antenna in a broadcastlike mode—that is, by using Internet protocol (IP)–user datagram protocol—allows a data throughput of about 1 Mb/s. This throughput holds for distances of about 300 m and even for cars moving in different driving directions with a relative speed difference of 200 km/h (*22*). Despite high relative velocity differences between two vehicles, the total transmission of more than 3-MB data within one encounter has been reported (*23*), although the available time within the broadcast range decreases with the relative velocity and some time is needed to associate to the communication channel.

Without giving quantitative values, Günter and Grossmann (*24*) predict for a high vehicle density and a high market penetration rate a breakdown of communication because of too many users on the available bandwidth. Such scenarios indeed have not yet been investigated empirically. Reducing transmission power or simply sending messages less often may avoid breakdown of the communication channel. For jam-front prediction, it is not necessary to receive a message from every car that has detected the front. In addition, the new pending IEEE Standard 802.11p (Wireless Access for the Vehicular Environment) comes with a much quicker and more efficient protocol than IP: dedicated short-range communications is a concept specifically designed for automotive use. According to Xu et al. (*14*), in normal freeway traffic (four lanes, 33 vehicles/km/lane) it is no problem to transmit small data packages of 400 bytes from each car to each other car within a broadcast range of 150 m within a fraction of a second and with a loss rate of less than 1%. It should be noted that a message containing traffic-related information (e.g., about a jam front) has a size on the order of a few hundred bytes rather than kilobytes.

Congestion Fronts: Recognition and Generation of Traffic-Related Messages

Since the focus here is to use traffic information as input for traffic-adaptive ACC systems, the crucial events to be detected and transmitted are the jam-front positions.

There are cases in which an (expected) jam-front position may be anticipated—for example, if a car gets stuck in a traffic-jam upstream bottleneck—which are well known for causing congestion. In many cases, jam-front positions can only be exactly detected by cars passing the location. Figure 2 shows a traffic jam on German Freeway A5 between Kassel and Frankfurt in the south direction. The jam was caused by blockage of the rightmost three lanes after an accident occurred, as noted in the sketch of the freeway. One-minute averaged data of the velocity were recorded by double loop detectors with an average distance of 1 km, and the velocity field shown was obtained by using an adaptive smoothing method for interpolation of macroscopic traffic data between the detectors (*25*). This jam illustrates three examples of different congestion fronts:

- A downstream jam front pinned at some bottleneck, for example, at the location of an incident, as shown by the dashed line in Figure 2;
- A downstream jam front (a dissolution front of congested traffic) propagating against the traffic flow with a characteristic speed of about −15 km/h (*26–28*); and

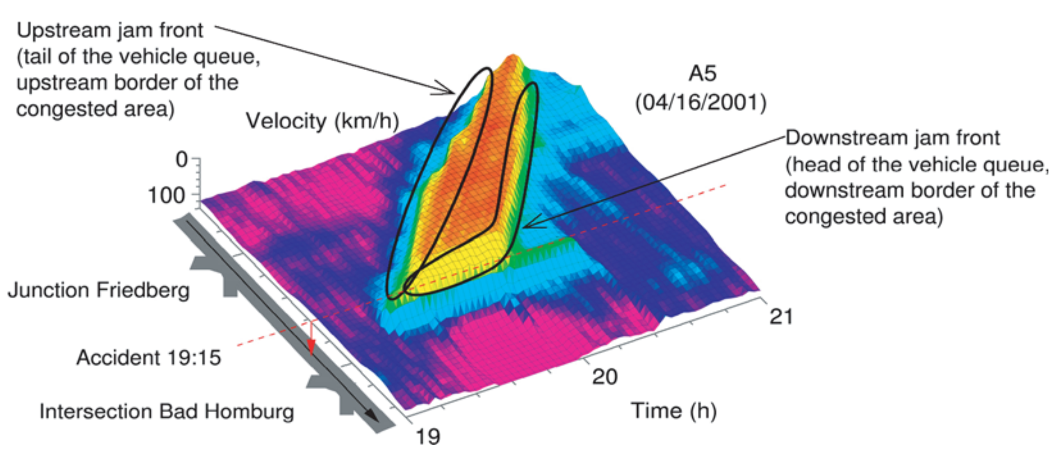

FIGURE 2 Example for spatiotemporal dynamics of freeway jams to illustrate different types of jam fronts (see text); driving direction of cars is indicated by black arrow (vertical axis inverted for better illustration).

• An upstream jam front moving with a propagation speed that depends on the traffic flow upstream of the jam and the flow in the jam.

Downstream jam fronts are normally straight lines in the spatiotemporal plane. These fronts are either fixed at a bottleneck or move with a constant velocity of approximately −15 km/h, apart from a few cases of a moving bottleneck, in which the propagation velocity can assume other values but is constant as well. This fundamental feature of traffic flow dynamics is found in most of the empirical work and was also reflected in traffic models from the very beginning (*29*). The velocity of downstream jam fronts can even be constant for hours. For stationary inflow conditions, upstream jam fronts also have a constant velocity. It may vary between −25 km/h [the high value of −40 km/h reported by Bertini and Malik (*30*) has not been observed in other studies] and the velocity of freely driving vehicles (if the inflow is vanishing and a cluster of vehicles is accelerating). In most cases, the approximation of a constant front velocity is justified because the traffic demand normally does not change significantly on time scales of 5 to 10 min.

For the detection and prediction of jam fronts, their spatial extension has to be considered (*31*). Because of the discrete nature of traffic, the jam-front position as a continuous line in time and space can only be thought of as an abstract result of an averaging process based on vehicle trajectories.

In the following, a model for jam-front detection based on floating-car data is presented. The jam front is characterized by the time and the location at which a passing car starts to brake or to accelerate. In order to reliably detect these acceleration and deceleration processes and to minimize the number of false alarms, each car smoothes its floating-car data [i.e., its velocity $v(t)$ using an exponential moving average (EMA)]:

$$v_{\text{EMA}}(t) = \frac{1}{\tau}\int_{-\infty}^{t} dt' e^{-(t-t')/\tau} v(t') \tag{1}$$

with a relaxation time $\tau = 10$ s. The EMA allows for an efficient real-time update by using an explicit integration scheme for the corresponding ordinary differential equation:

$$\frac{d}{dt} v_{\text{EMA}} = \frac{v - v_{\text{EMA}}}{\tau} \tag{2}$$

The detection of an upstream or downstream jam front relies on a change in speed compared with the exponentially averaged past speed. An upstream jam front is therefore given when, for the first time, the following holds:

$$v(t) - v_{\text{EMA}}(t) < -\Delta v_{\text{up}} \tag{3}$$

with $\Delta v_{\text{up}} = 15$ km/h. A downstream jam front is identified by the first notice of an acceleration period,

$$v(t) - v_{\text{EMA}}(t) > \Delta v_{\text{down}} \tag{4}$$

with $\Delta v_{\text{down}} = 10$ km/h. When a congestion front is detected, a corresponding message containing position, time, and jam-front type is generated. This message is repeatedly broadcast until it is discarded after 10 min.

STATISTICS OF MESSAGE PROPAGATION VIA OPPOSITE DRIVING DIRECTION

In this section simulation results for the efficiency of IVC via transverse hopping are compared with analytical results (*32*). In addition, the parameters of the system are briefly discussed.

When the proportion α of vehicles equipped with IVC is low, the positions of the IVC-equipped cars can be assumed to be statistically independent of each other. Therefore, the arrival process of an equipped vehicle at a given cross section is a Poisson process. This characteristic holds even for high traffic densities, where the positions of neighboring vehicles are highly correlated. The density of equipped cars λ in one driving direction is defined as $\lambda = \rho a$, where ρ is the traffic density over all lanes. As a consequence of the Poisson process, the longitudinal distances Δ between consecutive equipped cars are exponentially distributed with the probability density

$$f(\Delta) = \lambda e^{-\Delta} \tag{5}$$

which is well supported by empirical data (*32*).

Particularly, given the full density λ_{tr} of equipped cars on all lanes for the opposite driving direction, the cumulative probability distribution of the time τ may be calculated, after which the message is available at the distance r_u upstream from the position of message generation:

$$P(\tau < t) = \Theta\left(t - \frac{r_u - 2R}{v_{\text{tr}}}\right)\left[1 - e^{-\lambda_{\text{tr}}(2R + v_{\text{tr}}t - r_u)}\right] \tag{6}$$

where

R = broadcast range of sender–receiver unit,
v_{tr} = (average) velocity on opposite lanes, and
$\Theta(x)$ = heavyside function, defined by $\Theta(x) = 1$ for $x > 0$ and $\Theta(x) = 0$ otherwise.

Figure 3 (*a*) shows the distributions of τ for several values of α. The assumed IVC parameters are the broadcast range $r_{\max} = 250$ m and the minimal delivery range $r_u = 1{,}000$ m. A chosen moderate inflow of $Q = 1{,}240$ vehicles/h/lane resulted in a transmitter-vehicle velocity of $v_{\text{tr}} = 85$ km/h and an overall traffic density of $\rho = 29$ vehicles/km in each direction. The simulations were carried out with equipment rates of $\alpha = 3\%$, $\alpha = 5\%$, and $\alpha = 8\%$. With rising market penetration rate α, message transport becomes faster. Time $\tau_{0.95}$ indicates when 95% of the messages are available $r_u = 1{,}000$ m upstream.

The microscopic simulation approach allows for a detailed modeling of the message broadcast and receipt mechanisms of IVC-equipped vehicles (see Figure 4). The section on the traffic simulation scenario describes the traffic simulation setup. To obtain the statistics of message propagation, the equipped vehicles have generated a dummy message while crossing the position $x = 5$ km in a freeway stretch of 10-km length, and the cycle time for the communication has been set to 0.5 s. The results show good agreement with the analytical calculations (Equation 6). The lower limit for τ,

$$\tau_{\min} = \frac{r_u - 2R}{v_{\text{tr}}} \tag{7}$$

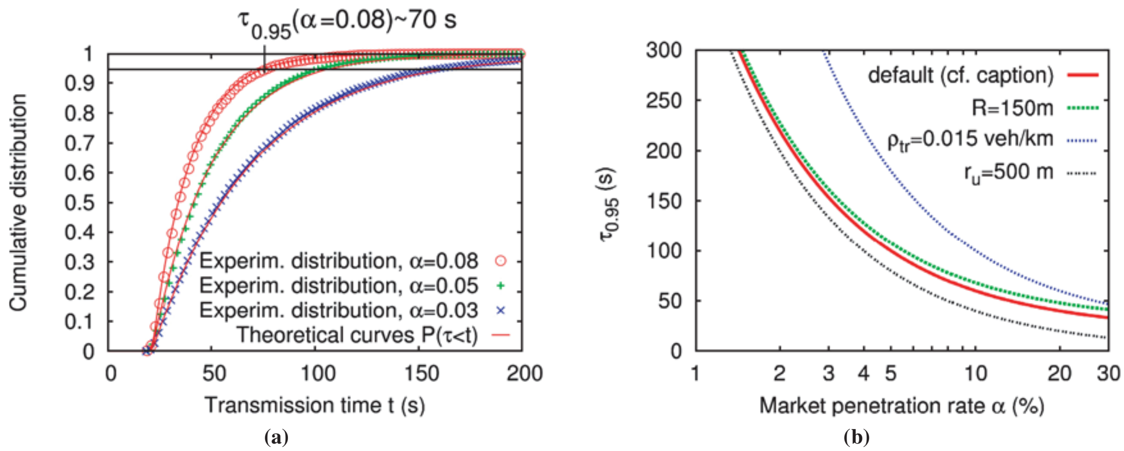

FIGURE 3 Statistics for opposite driving directions: (*a*) cumulative distribution of transmission times if messages are transmitted via cars in opposite driving direction (symbols correspond to simulation results and solid curves to analytical result of Equation 10) and (*b*) investigation of efficiency of message propagation in terms of $\tau_{0.95}$, depending on parameters by evaluating Equation 10 (default parameters: r_{max} = 250 m, r_u = 1,000 m, ρ = 0.03/m, and v_{tr} = 90 km/h; other curves result by variation of only one parameter, which reveals its impact).

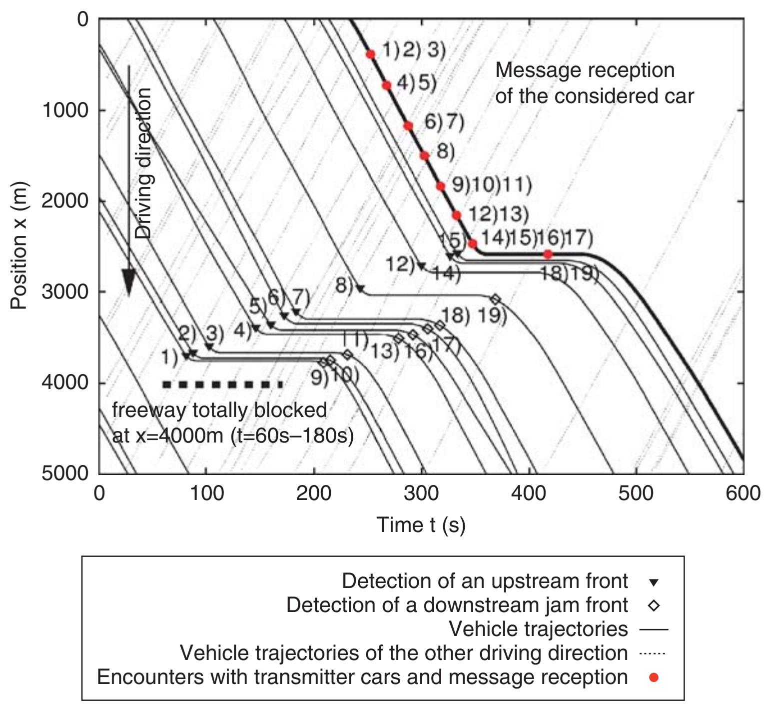

FIGURE 4 Space–time diagram of traffic scenario considered; trajectories of IVC-equipped vehicles (only 3% of all vehicles) are displayed by solid and dotted lines, depending on driving direction. Trajectories of subsequent vehicles of the considered car are not shown (crossing trajectories of equipped vehicles in upper left corner of diagram refer to passing maneuver due to different desired velocities).

is realized if the transmitter has an optimal position at $t = 0$ (see Figure 1).

Apart from this lower limit, which depends on R, r_u, and v_{tr}, the value of $P(\tau < t)$ is strongly influenced by the density of equipped vehicles in the opposite driving direction. This attribute becomes obvious if one looks at the expectation value $\langle\tau\rangle$:

$$\langle\tau\rangle = \frac{r_u - 2R}{v_{tr}} + \frac{1}{\lambda_{tr} v_{tr}} \tag{8}$$

The higher the market penetration level α, the higher the values are for $\lambda_{tr} = \alpha\rho_{tr}$ and the earlier a message arrives upstream because of the decreasing second part of the expression for $\langle\tau\rangle$ (the average waiting time for a transmitter car).

Now, the 95th percentile of the IVC transmission time is considered as a quantity for the IVC efficiency. The definition

$$P\left(\tau \leq \tau_{0.95}\right) = 0.95 \tag{9}$$

leads to the result

$$\tau_{0.95} = \frac{r_u - 2R}{v_{tr}} + \frac{\ln\left(\frac{1}{0.05}\right)}{\lambda_{tr} v_{tr}} \tag{10}$$

This quantity is shown in Figure 3*b* for four different scenarios. For a low equipment rate α, it depends only weakly on the broadcast range R and the minimal propagation distance r_u, because the second term in Equation 10 dominates: the traffic density ρ_{tr} on the opposite lanes has a high impact.

In the limit of the upstream distance $r_u \to \infty$, the mean IVC propagation velocity $\langle v\rangle = \langle r_u/\tau\rangle$ converges to v_{tr}, that is, to the average speed of the vehicles. So, at least in the long term, messages can propagate faster via the transverse hopping mechanism than any congestion front because the maximum upstream propagation of jam fronts is much less than v_{tr} (*30*).

SIMULATION OF JAM-FRONT DETECTION AND PREDICTION

Traffic Simulation Scenario

For illustration, the proposed congestion-front recognition and message propagation via IVC (see the previous section) are applied to a specific traffic scenario. As the simulation scenario, a homogeneous freeway section 5 km long with two independent driving directions and four lanes is considered. The longitudinal movement of the vehicles is described by the Intelligent Driver Model (IDM) (*33*), which is a simple and realistic car-following model. The lane-changing decisions are based on the recently proposed model MOBIL (*34*). Heterogeneity is introduced by distributing the desired velocities of the vehicle–driver units according to a Gaussian distribution with a standard deviation of 18 km/h around a mean speed of $v_0 = 120$ km/h. The other parameter values were chosen according to Kesting et al. (*7*). The details of the traffic model do not influence the dynamics of message propagation via IVC, which is the main focus here.

A given fraction α of the cars is randomly chosen to be equipped with an IVC module. In the simulation, these vehicles in addition determine their position by a satellite positioning system and feed their jam-front detection device by their own velocity time series as pointed out in the subsection on congestion fronts: recognition and generation of traffic-related messages.

In one driving direction, a stop-and-go wave was triggered (the moving localized cluster) (*27, 28*), whereas traffic is free in the other driving direction. The inflow at both upstream boundaries of the simulated freeway stretch is set to 1,800 vehicles/h/lane. It should be noted that the outflow (discharge rate) at the downstream jam front is of the same order, so that the upstream and the downstream jam fronts propagate with the characteristic speed of about 15 km/h in the upstream direction through the system.

An IVC equipment rate of $\alpha = 3\%$ is considered. The resulting trajectories and the sending and receiving events via transverse hopping are illustrated in Figure 4. As pointed out earlier, the distance of the equipped vehicles often exceeds the broadcast range of $R = 250$ m, even in the region of congested traffic. As shown in Figure 4, the considered vehicle receives the first message about the upcoming traffic congestion 2 km before encountering the traffic jam. Further received messages from other equipped vehicles are used to confirm and update the predicted downstream traffic situation. The vehicles in the other driving direction serve as transmitter cars for the transverse hopping mechanism. A temporary road blockage triggers a stop-and-go wave, indicated by horizontal trajectory curves in one driving direction. When cars encounter the propagating moving localized cluster, they broadcast messages about the detected position and time of the upstream jam front and the following downstream jam front. These message generations are represented in Figure 4 by numbers. Reception of these messages by the considered vehicle (thick solid line) is indicated by the same numbers.

Jam-Front Prediction Algorithm

After the generation and propagation of traffic-related messages, the received messages are finally used for vehicle-based reconstruction and prediction of the downstream traffic situation. Each car in the microscopic simulation sorts the incoming messages according to the reported jam-front type for a separate evaluation. Within each message group, all messages that are not older than 120 s (compared with the most recently received message) are considered for the prediction. If this selection process yields two or more relevant messages, the prediction for the jam front is based on linear regression in the space–time plane, since the assumption of a constant jam-front velocity is well justified for the time scale of several minutes (see section on recognition and generation of traffic-related messages). In the case of only one valid message, the reported position in this message is regarded as the prediction of the jam-front position.

In order to analyze the quality of the jam-front prediction, an error measure is defined that compares the prediction calculated at a time t_{pr} with the actual realization of the jam front. It should be noted that this error can only be calculated a posteriori since the considered vehicle will pass the real jam front at some time in the future. Since the forecast is carried out autonomously by each equipped vehicle, a single car c with its trajectory $x^c(t)$ is now considered. At a considered time $t_{pr} < t$, the car is located at $x^c(t_{pr})$ and predicts the position of the jam front at time t by the linear regression function $X_{fr}^{c,t_{pr}}(t)$. The prediction quality is evaluated after the fact when vehicle c itself detects the jam front at a time t_{fr}^c and at a position $x^c(t_{fr}^c)$. Thus, the difference between the real jam-front position $x^c(t_{fr}^c)$ and the predicted one for the time t_{fr}^c defines the error e by

$$e^c\left(t_{pr}\right) = x^c\left(t_{fr}^c\right) - X_{fr}^{c,t_{pr}}\left(t_{fr}^c\right) \quad (11)$$

Figure 5 illustrates the error e for two snapshots at the prediction times $t_{pr} = 260$ s and 340 s, respectively. As shown in the diagrams, e decreases when it approaches the jam front as measured by the distance D.

Each equipped car predicts the jam fronts every 2 s according to the communication cycle described earlier, in the section on characteristics of IVC. If no messages arrive in one update cycle, no new prediction will be estimated. After the simulation run, the prediction error e is determined offline. The prediction error e (Equation 11) depends on the time t_{pr} and should, on average, decrease when the considered car approaches the predicted jam front because of the

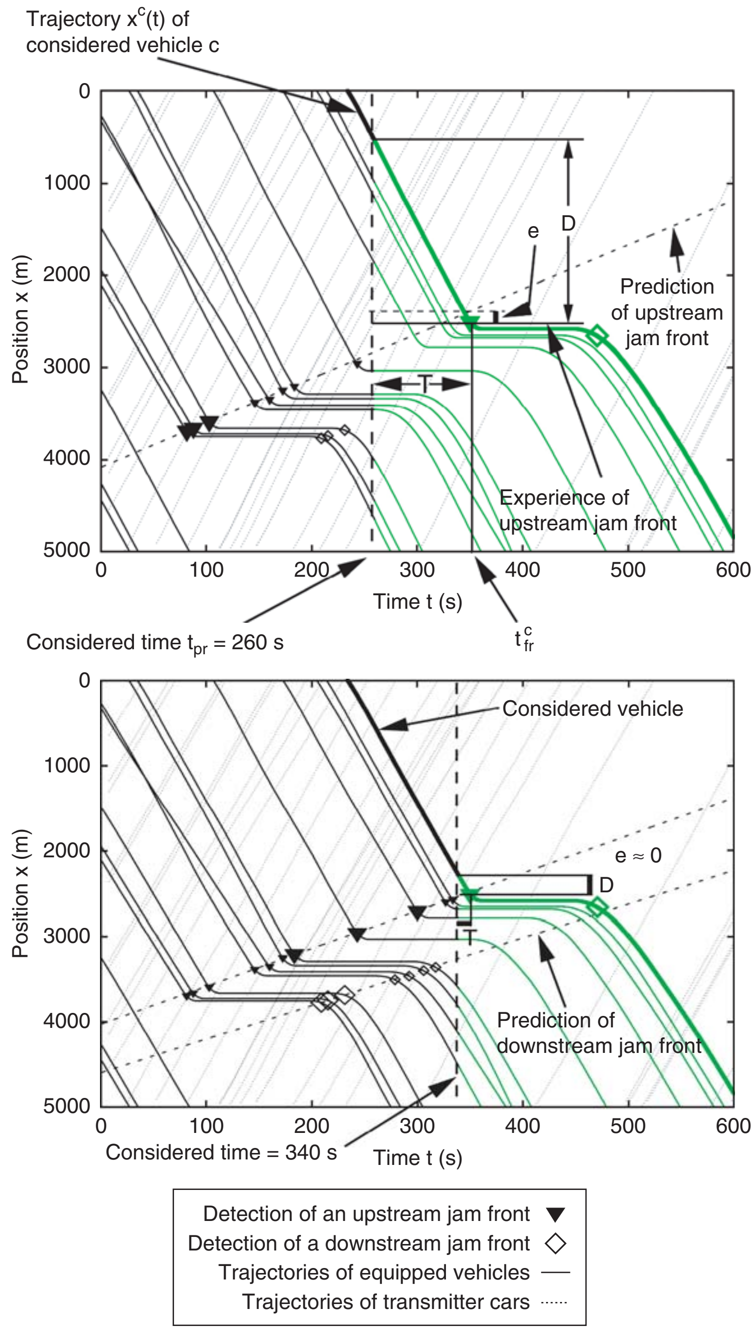

FIGURE 5 Two subsequent snapshots of congestion-front prediction as considered vehicle (thick solid line) approaches jam front (symbols denote generation of messages when vehicle detects jam front: large symbols are actual jam-front prediction by considered car, small symbols are outdated messages or messages that have not yet reached considered car via IVC).

reception of new messages, which allow for a better forecast. By a simple time shift transformation,

$$T \equiv t^{c}_{\mathrm{fr}} - t_{\mathrm{pr}} \qquad (12)$$

e depends on the time interval T between the prediction time and the time when the traffic-jam front is reached.

Figure 6 shows all single predictions in each car for the scenario of Figure 5. For illustration, the subsequent predictions of a single car are connected by dotted lines. Figure 6*a* and *b* show how the error e for the upstream jam-front prediction depends on D and T. In the case when $D \rightarrow 0$ corresponds to $T \rightarrow 0$, the final deviations e of the considered vehicles do not exceed an interval of about ±50 m. Figure 6*a* and *b* show similar characteristics because the velocity of the cars does not vary significantly, so D is essentially proportional to T.

This feature no longer holds when a downstream jam front is approached, as shown in Figure 6*c* and *d*. A considered car spends approximately 120 s in the jam and, as a consequence, is already close to the downstream jam front. Therefore, the car receives several messages and updates predictions for $D \approx 50$ m. This aspect explains the clustering of the symbols in Figure 6*c*, whereas this effect is not relevant in the representation of Figure 6*d*. In the latter diagram, it can be seen that for a car in the congestion zone ($T < 120$ s) the mean frequency of prediction changes is decreased compared with the situation in the free-flow state because a vehicle that is not moving encounters transmitter cars from the other driving direction less frequently and thus receives fewer new messages per time than a moving vehicle does. For $T \rightarrow 0$, the errors for predicting the downstream jam front are restricted to values of the order of ±100 m. It turns out that the reason is given by the characteristics of the downstream jam front.

As shown in Figures 4 and 5, the downstream jam front becomes smoother after some time: the cars spend more time (and space) in the acceleration process. This result is due to the traffic dynamics in this special situation. The first car leaving the jam has no leader car in front, and thus its acceleration is higher compared with that of subsequent cars leaving the jam. This attribute affects the detection of the front, which gets more and more delayed compared with the first detection processes at $t = 200$ s. Thus the prediction of the front position is likely to be further upstream than the actual position detected according to Equation 4, which leads to prediction errors of $e > 0$ according to the applied definition of e. The second clustering of e in the interval between 50 and 100 m seems to be a result of this spatiotemporal curvature of the jam front.

In summary, it has to be stated that prediction errors are also caused by uncertainties in determining the actual position of the downstream front by Equation 4.

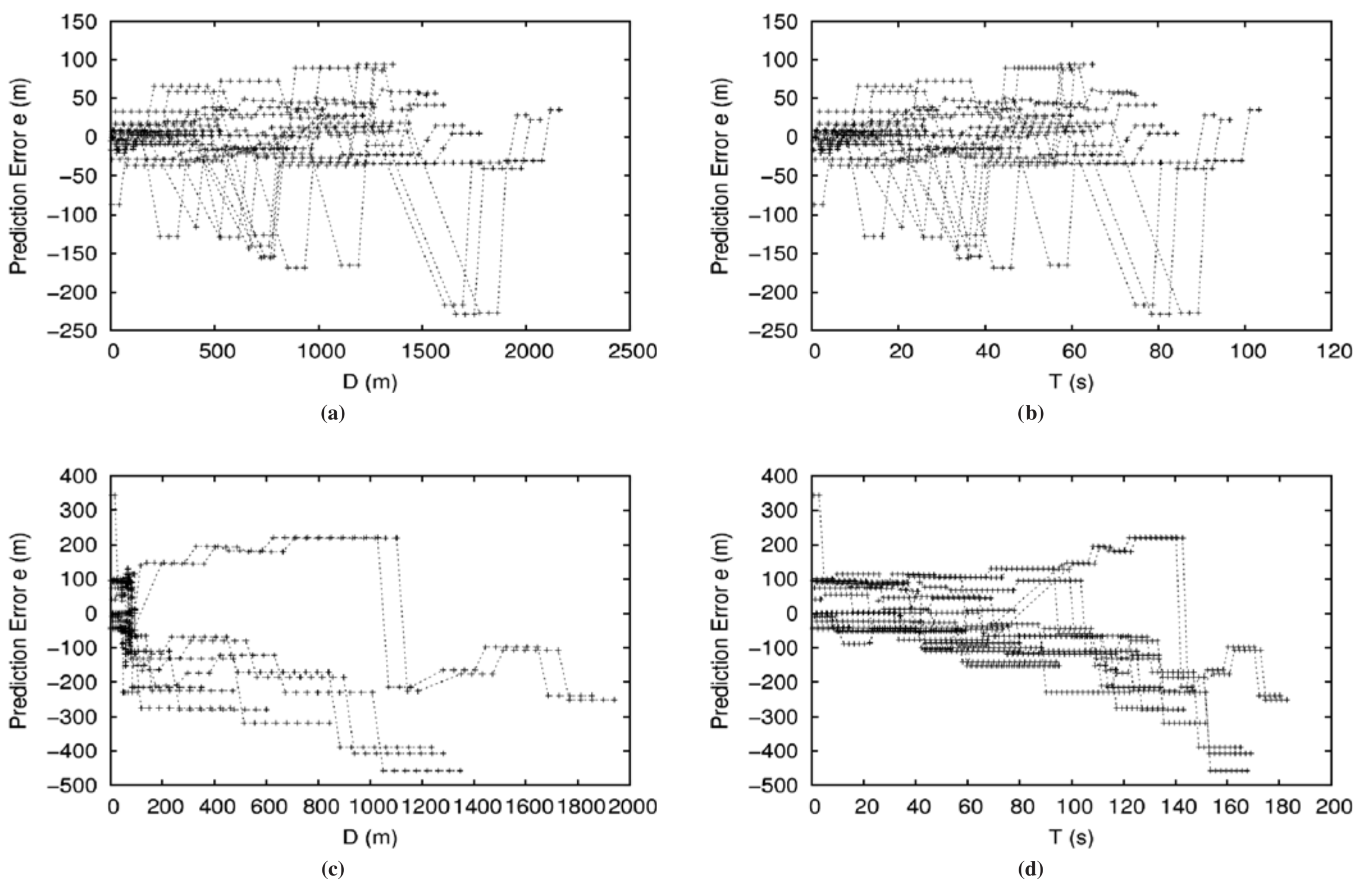

FIGURE 6 Prediction errors e of several equipped cars for traffic scenario shown in Figure 5: (*a*, *b*) upstream jam front and (*c*, *d*) downstream jam front. Subsequent predictions of equipped car are connected by dotted line. Prediction and thus prediction error are updated when car gets new messages via IVC. Diagrams show errors as function of spatial distance D to real jam-front position (*a*, *c*) in future and (*b*, *d*) as function of remaining time T. Errors decrease with decreasing D and T as vehicles approach jam fronts. For $e > 0$, predicted jam-front position is further upstream than real jam front (see Figure 5).

SUMMARY, CRITICAL DISCUSSION, AND OUTLOOK

In this contribution, a completely distributed freeway traffic information system based on IVC was introduced. It involves autonomous, vehicle-based jam-front detection, information transmission via IVC, and prediction of the spatial position of jam fronts by reconstruction of the spatiotemporal traffic situation based on the transmitted information. The whole system is simulated within an integrated microscopic traffic simulation framework. The function of its communication module was explicitly validated by comparing the simulation results with analytical calculations for message propagation.

By means of simulations, it was shown that the algorithms for congestion front recognition and message transmission and processing predict the existence and position of jam fronts reliably for vehicle equipment rates as low as 3%. The prediction error decreases when a car is approaching the front but does not go to zero because of uncertainties in determining the exact positions of a jam front. It should be noted that a reliable mode of operation for small market penetrations is crucial for successful introduction of the technology proposed here. The accurate prediction results obtained can be used as (nonlocal) input for a traffic-adaptive ACC system that changes its driving characteristics according to the local traffic situation, as recently proposed by Kesting et al. (*6*). Furthermore, timely knowledge about the upcoming traffic situation on a scale of minutes and a few kilometers offers new possibilities for vehicle-based advanced driver information systems.

This feasibility study was based on the following main assumptions and mechanisms:

1. IVC allows for a reliable exchange of small data packages between vehicles in different driving directions with speed differences of up to 300 km/h. The broadcast range is limited, for example, to 250 m.
2. Traffic in the opposite driving direction is free. In the traffic simulations, stationary traffic flow conditions were assumed, but this assumption is not a precondition for the functionality of the proposed concept.
3. The propagation speed of the dynamic jam fronts changes little on time scales of several minutes.

A few brief remarks concerning the presented approach may summarize the limitations of the current study. The existing communications technology and the future standards of wireless data transmission between vehicles allow for fast and reliable dissemination of small traffic-related messages (as needed for the concept presented here), even for a high density of equipped vehicles. However, it should be mentioned that other applications may use the provided bandwidth as well. It is assumed that there will be a balanced distribution of the resources needed for traffic safety, traffic information, and other applications.

For a small market penetration of IVC-equipped vehicles, the characteristics and efficiency of the message transport rely to a large extent on the density of equipped vehicles in the opposite driving direction and their driving speed. It should be noted that in peak traffic hours, often only one of the driving directions is congested. The same characteristic applies for traffic congestion caused by accidents. Thus in most of the cases, free traffic flow in the opposite driving direction can be assumed. With respect to the considered application in traffic-adaptive ACC systems, it is essential to predict traffic-jam fronts. Within short time scales of 5 to 10 min, the velocity of the traffic-jam fronts can be assumed to be constant in most cases, in particular for downstream jam fronts. Further research is necessary to improve the proposed prediction model and to reduce the prediction error. In particular, this research applies to traffic situations with several traffic-jam fronts of the same type and to special situations, in which the jam-front velocity may change, for example, because of clearance after an accident.

ACKNOWLEDGMENTS

The authors thank Hans-Jürgen Stauss for the excellent collaboration and Volkswagen AG for partial financial support within the German Federal Ministry of Education and Research project INVENT.

REFERENCES

1. Varaiya, P. Smart Cars on Smart Roads: Problems of Control. *IEEE Transactions on Automatic Control,* Vol. 38, No. 2, 1993, pp. 195–207.
2. Rao, B. S. Y., P. Varaiya, and F. Eskafi. Investigations into Achievable Capacities and Stream Stability with Coordinated Intelligent Vehicles. In *Transportation Research Record 1408,* TRB, National Research Council, Washington, D.C., 1993, pp. 27–35.
3. Rao, B. S. Y., and P. Varaiya. Flow Benefits of Autonomous Intelligent Cruise Control in Mixed Manual and Automated Traffic. In *Transportation Research Record 1408,* TRB, National Research Council, Washington, D.C., 1993, pp. 35–43.
4. Aoki, M., and H. Fujii. Inter-vehicle Communication: Technical Issues on Vehicle Control Application. *IEEE Communications Magazine,* Vol. 34, 1996, pp. 90–93.
5. Tank, T., and J.-P. M. G. Linnartz. Vehicle-to-Vehicle Communications for AVCS Platooning. *IEEE Transactions on Vehicular Technology,* Vol. 46, No. 2, 1997, pp. 528–536.
6. Kesting, A., M. Treiber, M. Schönhof, and D. Helbing. Extending Adaptive Cruise Control to Adaptive Driving Strategies. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2000,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 16–24.
7. Kesting, A., M. Treiber, M. Schönhof, F. Kranke, and D. Helbing. Jam-Avoiding Adaptive Cruise Control (ACC) and Its Impact on Traffic Dynamics. In *Traffic and Granular Flow '05* (A. Schadschneider, T. Pöschel, R. Kühne, M. Schreckenberg, and D. E. Wolf, eds.), Springer, Berlin, 2007, pp. 633–643.
8. Davis, L. Effect of Adaptive Cruise Control Systems on Traffic Flow. *Physical Review E,* Vol. 69, No. 6, 2004.
9. VanderWerf, J., S. Shladover, N. Kourjanskaia, M. Miller, and H. Krishnan. Modeling Effects of Driver Control Assistance Systems on Traffic. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1748,* TRB, National Research Council, Washington, D.C., 2001, pp. 167–174.
10. Treiber, M., and D. Helbing. Microsimulations of Freeway Traffic Including Control Measures. *Automatisierungstechnik,* Vol. 49, 2001, pp. 478–484.
11. Marsden, G., M. McDonald, and M. Brackstone. Towards an Understanding of Adaptive Cruise Control. *Transportation Research C,* Vol. 9, 2001, pp. 33–51.
12. Research Project INVENT—Intelligent Traffic and User-Friendly Technology. German Federal Ministry of Education and Research, 2005. www.invent-online.de.
13. Kim, Y., and M. Nakagawa. R-Aloha Protocol for SS for Inter-Vehicle Communication Network Using Head Spacing Information. *Institute of Electronics, Information and Communication Transactions on Communications,* Vol. E79-B, No. 9, 1996, pp. 1309–1315.
14. Xu, Q., T. Mak, J. Ko, and R. Sengupta. Vehicle-to-Vehicle Safety Messaging in DSRC. In *Mobicom 2004: International Conference on Mobile Computing and Networking,* IEEE and Association for Computing Machinery, Philadelphia, Pa., 2004, pp. 19–28.
15. Briesemeister, L., L. Schäfers, and G. Hommel. Disseminating Messages Among Highly Mobile Hosts Based on Inter-Vehicle Communication. In *Intelligent Vehicles Symposium,* IEEE, 2000, pp. 522–527.

16. Wischhof, L., A. Ebner, and H. Rohling. Information Dissemination in Self-Organizing Intervehicle Networks. *IEEE Transactions on Intelligent Transportation Systems,* Vol. 6, 2005, pp. 90–101.
17. Wu, H., R. Fujimoto, and G. Riley. Analytical Models for Information Propagation in Vehicle-To-Vehicle Networks. In *60th Vehicular Technology Conference,* IEEE, 2004, pp. 4548–4552.
18. Wu, H., J. Lee, M. Hunter, R. Fujimoto, R. L. Guensler, and J. Ko. Efficiency of Simulated Vehicle-to-Vehicle Message Propagation in Atlanta, Georgia, I-75 Corridor. In *Transportation Research Record: Journal of the Transportation Research Board, Vol. 1910,* TRB, National Research Council, Washington, D.C., 2005, pp. 82–89.
19. Jin, W.-L., and W. W. Recker. Instantaneous Information Propagation in a Traffic Stream Through Inter-Vehicle Communication. *Transportation Research B: Methodological,* Vol. 40, 2006, pp. 230–250.
20. Yang, X., and W. W. Recker. Simulation Studies of Information Propagation in a Self-Organizing Distributed Traffic Information System. *Transportation Research C: Emerging Technologies,* Vol. 13, 2005, pp. 370–390.
21. Dousse, O., P. Thiran, and M. Hasler. Connectivity in Ad-Hoc and Hybrid Networks. In *Proc., IEEE Infocom 2002, Annual Joint Conference of the IEEE Computer and Communications Societies,* 2002, pp. 1079–1088.
22. Singh, J. P., N. Bambos, B. Srinivasan, and D. Clawin. Wireless LAN Performance Under Varied Stress Conditions in Vehicular Traffic Scenarios. In *58th Vehicular Technology Conference,* IEEE, 2002, pp. 743–747.
23. Ott, J., and D. Kutscher. Drive-Thru Internet: IEEE 802.11b for "Automobile" Users. In *Proceedings of Infocom 2004, Twenty-third Annual Joint Conference of the IEEE Computer and Communications Societies,* 2004, pp. 362–373.
24. Günter, Y., and H. P. Grossmann. Usage of Wireless LAN for Inter-Vehicle Communication. In *Intelligent Transportation Systems Conference,* IEEE, 2005, pp. 408–413.
25. Treiber, M., and D. Helbing. Reconstructing the Spatio-Temporal Traffic Dynamics from Stationary Detector Data. *Cooper@tive Tr@nsport@tion Dyn@mics,* Vol. 1, 2002, pp. 3.1–3.24. www.TrafficForum.org/journal.
26. Kerner, B., and H. Rehborn. Experimental Features and Characteristics of Traffic Jams. *Physical Review E,* Vol. 53, 1996, pp. R1297–R1300.
27. Helbing, D., A. Hennecke, and M. Treiber. Phase Diagram of Traffic States in the Presence of Inhomogeneities. *Physical Review Letters,* Vol. 82, 1999, pp. 4360–4363.
28. Schönhof, M., and D. Helbing. Empirical Features of Congested Traffic States and Their Implications for Traffic Modeling. *Transportation Science,* Vol. 41, No. 2, 2007, pp. 1–32.
29. Lighthill, M. J., and G. B. Whitham. On Kinematic Waves: II. A Theory of Traffic Flow on Long Crowded Roads. *Proceedings of the Royal Society of London, Series A,* No. 229, 1955, pp. 317–345.
30. Bertini, R. L., and S. Malik. Observed Dynamic Traffic Features on Freeway Section with Merges and Diverges. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1867,* Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 25–35.
31. Muñoz, J., and C. Daganzo. Structure of the Transition Zone Behind Freeway Queues. *Transportation Science,* Vol. 37, No. 3, 2003, pp. 312–329.
32. Schönhof, M., A. Kesting, M. Treiber, and D. Helbing. Coupled Vehicle and Information flows: Message Transport on a Dynamic Vehicle Network. *Physica A,* Vol. 363, 2006, pp. 73–81.
33. Treiber, M., A. Hennecke, and D. Helbing. Congested Traffic States in Empirical Observations and Microscopic Simulations. *Physical Review E,* Vol. 62, 2000, pp. 1805–1824.
34. Kesting, A., M. Treiber, and D. Helbing. General Lane-Changing Model MOBIL for Car-Following Models. In *Transportation Research Record: Journal of the Transportation Research Board, No. 1999,* Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 86–94.

The Traffic Flow Theory and Characteristics Committee sponsored publication of this paper.