A Vehicular Networking Perspective on Estimating Vehicle Collision Probability at Intersections

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***Abstract*—Finding viable metrics to assess the effectiveness of intelligent transportation systems (ITSs) in terms of safety is one of the major challenges in vehicular networking research. We aim to provide a metric, i.e., an estimation of the vehicle collision probability at intersections, that can be used for evaluating intervehicle communication (IVC) concepts. In the last years, the vehicular networking community reported in several studies that safety-enhancing protocols and applications cannot be evaluated based only on networking metrics such as delays and packet loss rates. We present an evaluation scheme that addresses this need by quantifying the probability of a future crash, depending on the situation in which a vehicle is receiving a beacon message [e.g., a cooperative awareness message (CAM) or a basic safety message (BSM)]. Thus, our criticality metric also allows for fully distributed situation assessment. We investigate the impact of safety messaging between cars approaching an intersection using a modified road traffic simulator that allows selected vehicles to disregard traffic rules. As a direct result, we show that simple beaconing is not as effective as anticipated in suburban environments. More profoundly, however, our simulation results reveal more details about the timeliness (regarding the criticality assessment) of beacon messages, and as such, they can be used to develop more sophisticated beaconing solutions.**

***Index Terms*—Vehicle safety, vehicular ad hoc networks, wireless communication.**

I. Introduction

CRASH mitigation and crash avoidance are two of the major applications of intelligent transportation systems (ITSs) [1]. Most recent approaches for active safety also take intervehicle communications (IVC) into consideration [2]. In general, research on IVC is mainly motivated by two classes of applications: *safety* and *efficiency*. Both require proper management of the wireless communication channel [1], [3]–[5], but the first application type, i.e., *safety*, adds further demands such as extremely low transmission latencies combined with high communication reliability [6], [7].

With the development and standardization of dedicated short-range communication (DSRC) using IEEE 802.11p at the access level [8], short-range radio broadcast became a viable complement to cellular communications and one of the preferred technologies for low-latency communications between vehicles in close vicinity. DSRC promises to reduce accidents by enabling novel support systems. Within this scope, a wide range of applications has been identified, from emergency braking systems for highways [9] to more radical innovations such as virtual traffic lights [10], [11].

One of these applications is intersection collision warning systems (ICWSs), which can offer real-time warnings up to fully automated reactions [12]–[14]. The benefit of such systems has already been investigated thoroughly using *driving simulators*. In 2009, Chang *et al.* have shown that audio-based ICWSs are able to reduce drivers' reaction time and hence reduce the accident rate [12], e.g., for young inexperienced drivers. The impact of different warning systems has been studied in [15], and each investigated type clearly indicates a substantial safety advantage. These early results show the potential of ICWSs as the number of intersection crashes could be reduced by 40% to 50%. However, these results should be seen as a baseline as they neither address how ICWS can be implemented nor consider the involved networking issues.

In this paper, we employ simple beaconing, i.e., one-hop broadcasts, for exchanging safety critical information via DSRC in the context of ICWSs at suburban intersections. Third- and fourth-generation approaches are also considered for this application scenario [16], [17] but are outside the scope of this paper. Beaconing has been identified in the literature as a communication strategy suitable for many challenging vehicular networking applications [3], [9], [18], [19]. It is being standardized for the dissemination of safety critical information to be broadcast periodically at 1 to 25 Hz in the form of cooperative awareness messages (CAMs) [4] and basic safety messages (BSMs) [20] in Europe and in the U.S., respectively. In previous work [7], we also explored possible improvements using available relay nodes (e.g., parked vehicles [21] close to the intersection). In this paper, we focus on the possibility of estimating the collision probability when a beacon message is received. The approach is fully distributed and does not require external infrastructure. Our goal is to gain insight into the requirements of the communication platform, but (unlike earlier

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work) we approach this problem from the wireless networking perspective.

Two issues have routinely been overlooked in the past. First, networking-related metrics often do not reveal the quality of ITS-based solutions [2]. Second, the gap between application requirements and networking concepts needs to be closed [22].

In particular, in most vehicular ad hoc network studies on safety and safety applications, the performance of the applications was not measured through *safety metrics*, although the final goal of these applications is to investigate the benefit that they are able to provide for the driver and not delay or packet loss. Therefore, we believe that it is important that future proposals are not analyzed with network metrics such as latency, goodput, or dissemination area, but that studies concentrate on safety metrics [2], answering more relevant questions such as *how many crashes can be avoided*, and *can the impact of crashes be significantly reduced?* Accordingly, we develop new safety metrics and show in this paper, which extends earlier work presented in [7], how these reflect the performance of simple beaconing based communications.

Our main contributions can be summarized as follows.

- *Collision probability estimation*. We built upon the initial coarse-risk classification that we presented in [7] to develop a more comprehensive estimation of criticality, which is now expressed as collision probability. This probability is a quantitative measure of the criticality of intersection approach situations (see Section III).
- *Integration into a road traffic simulator*. We developed a simulation environment that enables the (collision-free) road traffic simulator SUMO to support vehicles that selectively ignore traffic rules; we further integrated the possibility of detecting the resulting crashes or near crashes (see Section IV).
- *Validation of the probability estimation*. We carefully evaluated our collision probability using measurements from a high number of simulated intersection approaches, using lane geometry imported from OpenStreetMap (presented in Section V-A). Using two simple example models, we show how our mathematical approach can be adapted to capture different driver behaviors (see Section V-B and C).
- *Implications on vehicular networking concepts*: We study the impact of beaconing for the transmission of safety messages in non-line-of-sight scenarios, investigating the timeliness (regarding the criticality assessment) of beacon messages. Our results indicate that simple beaconing is not as effective as anticipated in suburban environments; further insights can be used to develop more sophisticated CAM/BSM beaconing solutions (see Section V-D).

II. Related Work

This paper focuses on collision avoidance at intersections as one application of ITS; hence, it touches on not only communications issues but also on research areas such as control theory, transportation science, and road traffic engineering.

Starting with the communication perspective, we investigate the possibilities of intersection safety applications using simple beaconing strategies as currently proposed in standards [4], [20]. In the vehicular networking community, approaches clearly outperforming simple beaconing in terms of channel load or information dissemination range have been proposed. DV-Cast [23] aims at mitigating the broadcast storm problem by rebroadcasting first (and hopefully only) from the vehicles farthest from the original sender. The protocol can also switch between relaying and opportunistic forwarding depending on the estimated advantages. An initial work on adaptive beaconing is Adaptive Traffic Beacon [3], which continuously adapts to the available channel capacity by modifying the beaconing interval. Beaconing and adaptive changes of the beaconing interval have also been investigated in many other publications [18], [19].

Based on these studies, decentralized congestion control (DCC) has been suggested in ETSI ITS-G5 to cope with congestion problems [24], [25], and more advanced dynamic beaconing approaches have been proposed [5]. Nevertheless, optimizations in this network-specific domain are not the focus of this paper.

When looking at the communication perspective of intersection applications, most approaches did not evaluate their communication systems using safety metrics [10], [11], [26]. Le *et al.* looked at the busy time fraction of DSRC systems for intersection safety [26] using a simplified radio propagation model that uses only a fixed unit-disk communication range. A detailed study on communication requirements for crash avoidance applications has been published in [27]. The authors changed collision-free vehicle traces by artificially injecting collisions with constant velocity to evaluate their protocol in terms of crash mitigation possibilities. However, simplifying assumptions such as idealistic radio signal propagation and not considering low-speed collisions (< 7 m/s) limit the contribution for intersection safety applications. We go one step further and evaluate the ICWS with new safety metrics that are based on the collision probability of two approaching vehicles.

Tang and Yip [28] investigated timings for collision avoidance systems assuming DSRC transmission delays of 25 and 300 ms in normal and poorer channel conditions, respectively. They introduced the *time-to-avoid collision* metric, which represents the time from detecting a potential collision to the point of barely avoiding a collision and concentrated on the events (when to warn a driver early and latest, reaction of the driver, and different deceleration rates) within this time interval. This metric is definitely a good possibility for comparing information dissemination protocols for intersection safety; however, the point in time for detecting a potential collision has not been defined explicitly, and their analysis is limited to two fixed transmission delays, which in reality will vary.

Research that focuses on estimating, predicting, and/or reducing the likelihood of crashes at an intersection provides various approaches to model intersection approaching vehicles. This research goes as far as to include threat assessment for avoiding arbitrary collisions with bicycles. For this, lateral and longitudinal movements and vehicle dynamics have been modeled [29], yet communication aspects have not been investigated. Lefèvre *et al.* [30] point out that risk assessment at intersections is possible by comparing intention and expectation. Liebner *et al.* [31] also used drivers' intent inference at intersections.

In our opinion, an approach that restricts the analysis of communication protocols to one particular estimated driver behavior is not applicable. Therefore, we decided to use another approach to modeling safety aspects for intersection-approaching vehicles: model the probability of all possible future trajectories, and exploit their likelihood to estimate collision probabilities. In this area, Tan and Huang [32] have explored the possibilities of future trajectory prediction for cooperative collision warning systems with a focus on the engineering feasibility using simple GPS receivers and motion sensors.

Verma and Del Vecchio [33] presented a hybrid control approach for cooperative active safety systems, which was evaluated in the laboratory using robots. However, even under laboratory conditions, it becomes clear that the communication delay is critical for the controller and even caused failures. Hafner *et al.* [34] have built an automated vehicle-to-vehicle (V2V) collision avoidance application that avoids collisions by automatically controlling the longitudinal movements of both vehicles. The decision whether the system needs to control the brake and throttle is based on the calculation of the *capture set*, which is the set of all situations where no control input is able to prevent a collision [35] and the prevention of such situations. They showed that the controller is able to avoid collisions under favorable communication conditions with a two-car real testbed.

In contrast, this paper focuses on the communication aspects; hence, its goal is not to design a novel vehicle controller. Thus, we abstract the aspects (i.e., lateral and longitudinal vehicle dynamics, sensor errors, and feedback control) that would be needed in this case, focusing instead on the identification of communication conditions that would hamper any control system.

Our approach uses a probabilistic model for trajectories to represent all possible future driver behaviors and to derive collision probabilities, but we do not attempt to take decisions that influence their future evolution (triggering an automated reaction or warning a driver), leaving these aspects for future works. We use the presented intersection collision probability to evaluate the communication aspects of ICWSs, and it provides the potential for enhancing future communication strategies for intersection safety applications.

III. Intersection Collision Probability

Our goal in establishing a criticality metric is to calculate the probability of a possible collision whenever we have new information about two potentially colliding vehicles available, i.e., every time a car receives a beacon message (which includes position information speed, heading, etc., of the sender). In our case, the needed information for two approaching vehicles A and B consists of the distances from their trajectories' intersection d_A and d_B and the speeds v_A and v_B, as well as the maximum acceleration $a_{\max}$ and the maximum deceleration (in terms of a minimum, negative acceleration) $a_{\min}$. Notably, $a_{\min}$ and $a_{\max}$ are not necessarily the same for vehicles A and B

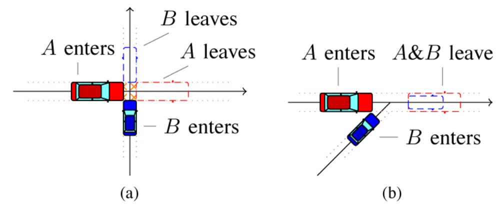

Fig. 1. Coordinate space for vehicles A and B for different intersection types. (a) X-intersection. (b) Y-intersection.

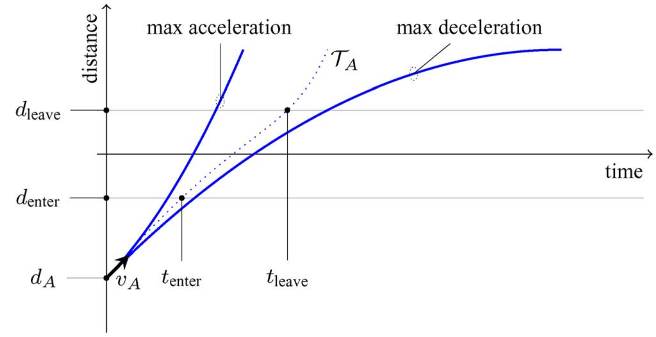

Fig. 2. Sample trajectory of vehicle A dependent on its distance d_A and speed v_A. Distances d_{enter} and d_{leave}, and times t_{enter} and t_{leave} are shown for an orthogonal X-intersection.

but depend on each vehicle model. To simplify the notation in this paper, we omit the vehicle-dependent indexes for these two physical boundaries in the following.

For defining distances d_A and d_B, the intersection is modeled as a simple coordinate space, where the axes are defined by the future driving path of the vehicles and are not necessarily orthogonal (cf. Fig. 1). The axes' origins are at the center of where the vehicles' trajectories intersect. In the following, we concentrate on the X-intersection shown in Fig. 1(a). However, by considering the interdependence of the two distances, a Y-intersection, as shown in Fig. 1(b), can be modeled similarly.

A. Trajectories

To define the intersection collision probability, we first need to mathematically model all possible driver behaviors of a single vehicle.

Depending on the current distance d_A and speed v_A of vehicle A, an unlimited number of future trajectories $\mathcal{T}_A$ (i.e., different intersection approaches) are possible. With current time being t_0, a trajectory is a feasible function of time that describes the vehicle's distance from the intersection center respecting the initial conditions and acceleration limits, i.e.,

$$\mathcal{T}_A(t_0)=d_A \quad \dot{\mathcal{T}}_A(t_0)=v_A, \qquad a_{\min}\leq\ddot{\mathcal{T}}_A(t)\leq a_{\max}. \quad (1)$$

Given the current distance d_A and speed v_A of vehicle A, we call the measurable set of all possible future trajectories $\mathbb{T}_A=\bigcup\mathcal{T}_A$. This set is limited by the maximum acceleration $a_{\max}$ and maximum deceleration $a_{\min}$, as shown in Fig. 2.

To determine whether a collision happens for two trajectories $\mathcal{T}_A\in\mathbb{T}_A$ and $\mathcal{T}_B\in\mathbb{T}_B$, we define the function coll $(\mathcal{T}_A,\mathcal{T}_B)$ as

$$\text{coll}\,(\mathcal{T}_A,\mathcal{T}_B)=\begin{cases}1, & \text{if there is a collision}\\ 0, & \text{otherwise}\end{cases} \quad (2)$$

where we define a *collision* as occuring if the bounding boxes of the vehicles are overlapping at some point in time during the intersection approach.

B. Definition of Collision Probability

If we integrate over all possible trajectories $\mathbb{T}_A$ and $\mathbb{T}_B$ of two approaching vehicles, we can define the probability $\mathcal{P}_C$ of a collision at an intersection as

$$\mathcal{P}_C = \int_{\mathbb{T}_B}\int_{\mathbb{T}_A} p(\mathcal{T}_A, \mathcal{T}_B)\,\mathrm{coll}\,(\mathcal{T}_A, \mathcal{T}_B)\, d\mathcal{T}_A\, d\mathcal{T}_B. \tag{3}$$

The function $p(\mathcal{T}_A, \mathcal{T}_B)$ gives the probability that the trajectories $\mathcal{T}_A$ and $\mathcal{T}_B$ are chosen and hence provides the possibility of modeling different kinds of driver behavior. In particular, this general definition of the collision probability does not assume the two chosen trajectories to be independent of each other. Moreover, our calculated collision probability does not distinguish situations where a crash has happened already (which is called a *bad set* in [34]) and a future crash is unavoidable (which is called a *capture set* in [34]); $\mathcal{P}_C$ will in both situations be 100%. In the following, we continue with a simplified version of this general approach because, to evaluate communication strategies for ICWSs, we do not need to model details such as lateral movements and/or longitudinal vehicle dynamics, for example.

C. General Assumptions

The formulation presented is very general and has high expressive power. However, without some additional assumptions, it is hardly tractable. Thus, we now introduce several simplifying assumptions that can be selectively relaxed when additional insight on a specific issue is needed. As a first simplification, in the following, we consider only orthogonal X-intersection crossings without turning maneuvers. In this case, a collision happens for two given trajectories if both vehicles are in the potential collision area, i.e., where the vehicles might hit/touch each other [shown in Fig. 1(a) as orange crosshatched area] at the same time. The size of the potential collision area depends only on the vehicles widths. Thus, the times t_{enter} and t_{leave}, i.e., when a vehicle enters and leaves the potential collision area of a given trajectory, respectively, can be calculated using the trajectory and the distances d_{enter} and d_{leave}. The relationship between a sample trajectory $\mathcal{T}_A$, the times t_{enter} and t_{leave}, and the distances d_{enter} and d_{leave} is shown in Fig. 2.

As a second simplification, we assume that the probabilities for the two trajectories $\mathcal{T}_A$ and $\mathcal{T}_B$ are independent. Currently, the literature does not give insight into whether and to what degree two approaching vehicles might influence the behavior of each other (causing a driver to accelerate, decelerate, or swerve). Moreover, we are particularly interested in situations where the drivers are not aware of each other; hence, the probability of choosing a certain trajectory does not depend on the other one. Furthermore, we consider only trajectories with a constant acceleration between $a_{\min}$ and $a_{\max}$. Under this constraint, every trajectory $\mathcal{T}$ can be identified by a tuple (a, v, d), and we can define a new function $\mathrm{coll}(\cdot,\cdot)$ analogous to (2) but only depending on these values. Hence, we can calculate $\mathcal{P}_C$ by integrating over the interval $a_{\min}$ and $a_{\max}$ for both vehicles as follows:

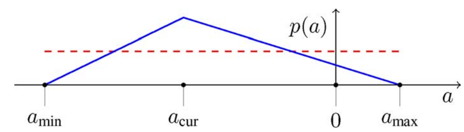

Fig. 3. Example of a triangular acceleration probability distribution conditioned on the present acceleration (solid line) compared with a uniform distribution (dashed line).

$$\mathcal{P}_C = \int_{a_{\min}}^{a_{\max}} p(a_B) \int_{a_{\min}}^{a_{\max}} p(a_A)\,\mathrm{coll}\left(\begin{bmatrix} a_A \\ v_A \\ d_A \end{bmatrix}, \begin{bmatrix} a_B \\ v_B \\ d_B \end{bmatrix}\right) da_A\, da_B. \tag{4}$$

The behavior of drivers, i.e., how likely it is that a driver chooses a certain acceleration, can now be modeled by defining the distribution of accelerations. In the following, we present two possible simple distributions to give an idea of their impact on collision probability.

D. Uniform Acceleration Probability Distribution

One simple example is a uniform distribution of all possible accelerations between $a_{\min}$ and $a_{\max}$. We will use this distribution to demonstrate the applicability of the collision probability defined in (3). Probability $p(a)$ can be then calculated as

$$p(a) = \begin{cases} \frac{1}{a_{\max}-a_{\min}}, & \text{if } a_{\min} \le a \le a_{\max} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

resulting in

$$\mathcal{P}_C = \frac{1}{(a_{\max}-a_{\min})^2} \int_{a_{\min}}^{a_{\max}}\int_{a_{\min}}^{a_{\max}} \mathrm{coll}\left(\begin{bmatrix} a_A \\ v_A \\ d_A \end{bmatrix}, \begin{bmatrix} a_B \\ v_B \\ d_B \end{bmatrix}\right) da_A\, da_B. \tag{6}$$

E. Towards More Realistic Driver Behavior

As a uniform acceleration distribution does not account for the current acceleration of the car, it might not represent typical human driver behavior well. It might be considered more likely that the driver continues to drive with the current acceleration; similarly, extreme accelerations could be very unlikely. One possibility for representing such behavior is to employ a triangular acceleration probability distribution with lower limit $a_{\min}$, mode a_{cur}, and upper limit $a_{\max}$, as shown in Fig. 3. When using this distribution, the collision probability $\mathcal{P}_C$ can still be calculated using (4).

IV. Simulation Model and Setup

We conducted an extensive simulation study to validate and evaluate the proposed collision probability estimation. For this, we used version 2.0 of the vehicular network simulator

TABLE I
ROAD TRAFFIC SIMULATION PARAMETERS, INCLUDING CAR-FOLLOWING PARAMETERS FOR IDM

Parameter	Value
Road traffic simulator time step t_{step}	5 ms
Safety boundary for near crash	0.4 m
Vehicle length	5.0 m
Vehicle width	1.75 m
Maximum speed $v_{\max}$ [15, Tab. IV]	$\sim N(13.89, 2.92)$ m/s
Maximum acceleration $a_{\max}$	2.1 m/s^2
Desired deceleration a_{des} [15, Tab. IV]	$\sim N(3.47, 2.76)$ m/s^2
Maximum deceleration $a_{\min}$ [38]	9.55 m/s^2
Starting speed v_0	$\sim U(0, v_{\max})$

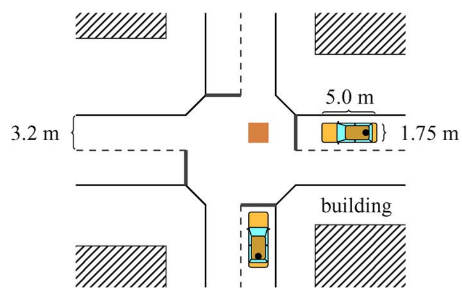

Fig. 4. Map view of the simulated X-intersection showing the potential collision area, buildings, and two approaching vehicles.

Veins [36], which bidirectionally couples the road traffic simulator SUMO and the network simulator OMNeT++. It extends the MiXiM physical-layer simulation framework and provides a rich set of simulation models for realistic simulation of IVC protocols and applications.

A. Modeling Road Traffic and Crash Situations

We simulated a typical suburban X-intersection, which is based on lane geometry imported from OpenStreetMap, and let two vehicles approach the intersection, then cross it without turning. For this paper, we used the intelligent driver model (IDM), the car-following model [37] (to reproduce realistic braking behavior [13]), and a modified version of SUMO that allows us to let selected vehicles ignore traffic rules [7]. We randomly selected 50% of approaching vehicles to ignore traffic rules. For inducing situations of different criticality at the intersection, the two vehicles used random initial speeds, maximum speeds, and desired deceleration values as listed in Table I. The variation of IDM parameters resembles different driver behaviors. Since we want to evaluate intersection warning applications regarding their communication requirements, our simulated intersection approaches do not resemble lateral and longitudinal vehicle dynamics.

In Fig. 4, the potential collision area of two approaching vehicles, the intersection, and vehicle geometry are shown in detail, Since vehicles in this simulation study cross the intersection without turning, this yields a rectangular potential collision area of size 1.75 m $\times$ 1.75 m.

Since our simulation study is based on the discrete road traffic simulator SUMO and the linearly interpolating mobility model of Veins, we assessed the necessary simulation granularity for the vehicle movements. Considering the maximum possible speed $v_{\max}$ and the maximum deceleration and acceleration $a_{\min}$ and $a_{\max}$, respectively, of the vehicle, we can compute the maximum possible error ϵ introduced by deceleration and acceleration as

TABLE II
COMMUNICATION SIMULATION PARAMETERS FOR SIGNAL ATTENUATION, PHYSICAL LAYER, AND MAC

Parameter	Value
Frequency	5.89 GHz
Channel bandwidth	10 MHz
Bitrate	18 Mbit/s
Transmit power	20 mW
Sensitivity	–94 dBm
Building shadowing model β, γ	9 dB, 0.4 dB/m
$\text{CW}_{\min}$, $\text{CW}_{\max}$	3, 7
AIFSN	2

$$\varepsilon_{\text{dec}} = \frac{1}{2}|a_{\min}|t_{\text{step}}^2, \varepsilon_{\text{acc}} = \frac{1}{2}|a_{\max}|t_{\text{step}}^2 \tag{7}$$

$$\varepsilon = \max(\varepsilon_{\text{dec}}, \varepsilon_{\text{acc}}). \tag{8}$$

In our simulations, we choose time step $t_{\text{step}} = 5$ ms for simulating the longitudinal movements within SUMO, which leads to a maximum error $\epsilon = 0.12$ mm (i.e., the vehicle is braking with maximum deceleration). Moreover, the selected simulation time step results in a maximum step distance of $v_{\max} \times t_{\text{step}} = 8.405$ cm and allows us to detect vehicle collisions very accurately. Still, with a low probability, we might fail to detect slightly "touching" vehicles; how we account for these inaccuracies is detailed in Section V.

B. Modeling Communication

All communication-relevant parameters are summarized in Table II to ensure reproducibility and comparability for future simulation studies. For the radio propagation, we use the obstacle model [39] that allows us to accurately model signal attenuation by buildings in a computationally efficient way. For simulating the physical and medium access control (MAC) layers, we make use of the well-validated IEEE 802.11p model [40], configuring it to represent a single-radio/single-channel DSRC system with parameters as listed in Table II.

The exchange of CAMs/BSMs is implemented as a static beaconing application that generates a beacon containing the needed information for calculating the collision probability every beacon interval and passes the message down to the MAC. We simulate four different beacon intervals (every 0.04, 0.1, 0.5, and 1 s) in the range of the DCC defined in ETSI standard [25],

V. EVALUATION

The presented results are based on a simulation study, as described in Section IV, and we want to emphasize that the vehicle movements are controlled by IDM with varying input parameters and hence result in different driver behaviors and a wide variety of intersection approaches. In the following, we investigate the intersection collision probability estimation based on three different outcomes of intersection approaches; we distinguish the outcomes as follows. The first group CRASH includes only intersection approaches of vehicles that collided at the intersection. To be able to distinguish critical and non-critical situations better, we introduce a second group called NEAR CRASH that includes all approaches where a vehicle's safety boundary of 0.4 m has been violated by the other one. This group covers also crash situations that have not been detected due to simulation time step size and allows for the detection of situations in which a driver would already feel quite unsafe. The third group NO CRASH contains only intersection approaches where the vehicles did not collide nor violate the safety boundary of each other.

For each simulation parameter set, we simulate 5000 intersection approaches using the parameters in Table I and record the successfully received beacons, the exact movements of the approaching vehicles, and the outcome of each approach at the intersection. The distribution of all simulation runs across these groups has been as follows: 3.76% of runs resulted in CRASH, 0.84% NEAR CRASH, and 95.4% NO CRASH.

A. Validation of Collision Probability

As a first step, we investigate whether the defined collision probability is behaving as intended for both the most general form of acceleration probability distribution (uniform) and the more realistic distribution (triangular). The collision probability should have the following two properties essential for vehicular safety application.

- *No false positives*. During NO CRASH approaches, the collision probability estimation should never exceed a certain threshold.
- *No false negative.* During CRASH approaches, the collision probability estimation should exceed at least a certain threshold (ideally close to 100%).

To validate the collision probability, we recorded the exact position, speed, and acceleration for each time step and vehicle without considering any communication delay (referred to as *sensor* data). Based on these data, we calculated the maximum collision probability for each approaching vehicle and present the distribution in box plots grouped by the different outcomes in Fig. 5. For each data set, a box is drawn from the first quartile to the third quartile, and the median is marked with a thick line; additional whiskers extend from the edges of the box toward the minimum and maximum of the data set but not further than 1.5 times the interquartile range. Data points outside the range of box and whiskers are considered "outliers" and drawn singularly as circles.

When looking at the NO CRASH group, we see that the median probability value is approximately 10%, and even the highest value is clearly smaller than 40%.

For the CRASH group, we see that almost all approaching vehicles have reached a maximum collision probability of 100%. We carefully checked all the vehicles for which a percentage smaller than 100% has been recorded and observed that these false negatives occur due to a mismatch of the simulated intersection layout (which is based on the mentioned real-world

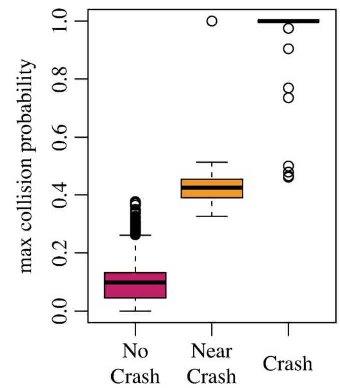

Fig. 5. Boxplot showing the maximum collision probability per approaching vehicle calculated using exact sensor data and grouped by the outcome.

geodata) and the perfect intersection layout assumed during probability calculation. To cross-check, we simulated a perfect intersection with the exact (down to the millimeter) layout shown in Fig. 4. In this perfect intersection scenario, every approaching vehicle reached a maximum collision probability of 100% (data not shown).

Finally, we can observe that, in group NEAR CRASH, probabilities are at a median value of 42%, with some interesting outliers at 100%. We analyzed the outliers and found that all of them depict vehicle collisions that went undetected due to simulation time step size.

We can conclude that, under the given assumptions and with perfect knowledge, the algorithm shows no false positives and no false negatives.

B. Bringing Networking Into the Picture

We now go one step further and calculate the collision probability based on the CAM/BSM information received from the other vehicle. The calculation is carried out using exact local information together with delayed CAM/BSM data received from the other vehicle. Please note that our scenario with only two approaching vehicles periodically sending CAM/BSM messages represents an ideal (best) case with respect to channel conditions and medium access delay.

Fig. 6 shows the distribution of the maximum collision probability per vehicle for different beacon intervals (0.04, 0.1, 0.5, and 1 s), which are grouped by the three different outcomes of an intersection approach. Basically, we can observe that, for the group NO CRASH, the distribution of maximum collision probability does not significantly change for the different beacon intervals. Hence, we can conclude that the beacon frequency has no effect on false positives when using a warning threshold of 40%. However, for the group CRASH, we see that the number of vehicles that do not reach a high collision probability is substantially increasing for larger beacon intervals. This is shown by comparing Fig. 6(a), which shows a similar distribution as shown in the validation (cf. Fig. 5), and Fig. 6(d), which reveals that already a major portion of the approaching vehicles has not reached a high collision probability before crashing.

To understand the correlation between the vehicles' distances and the resulting estimated collision probabilities, Fig. 7 shows

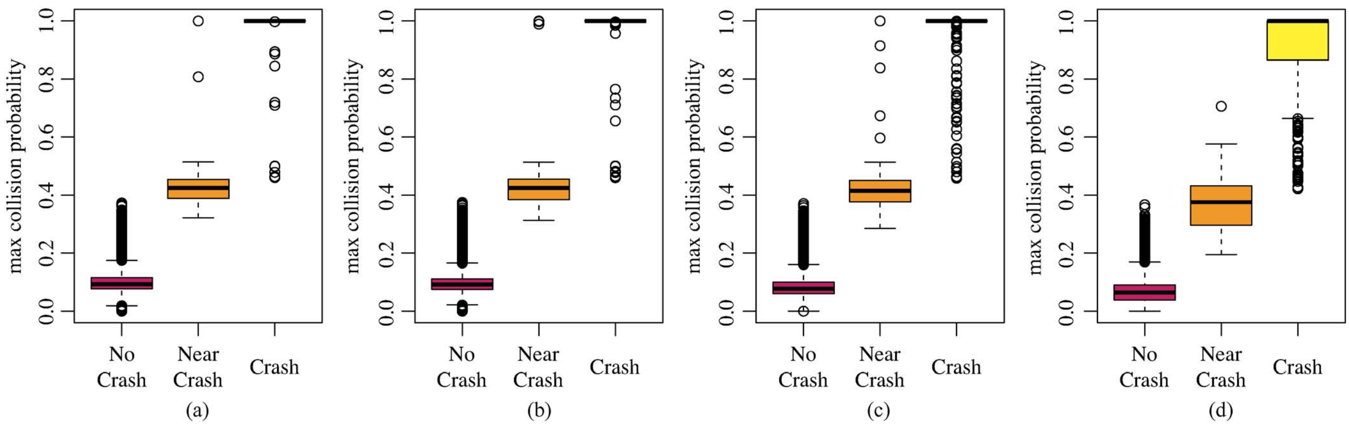

Fig. 6. Comparison of the maximum collision probability per approaching vehicle for all received beacons, which are grouped by the final outcome of the intersection approach. The results for different beacon intervals are shown. (a) Beacon interval of 0.04 s. (b) Beacon interval of 0.1 s. (c) Beacon interval of 0.5 s. (d) Beacon interval of 1 s.

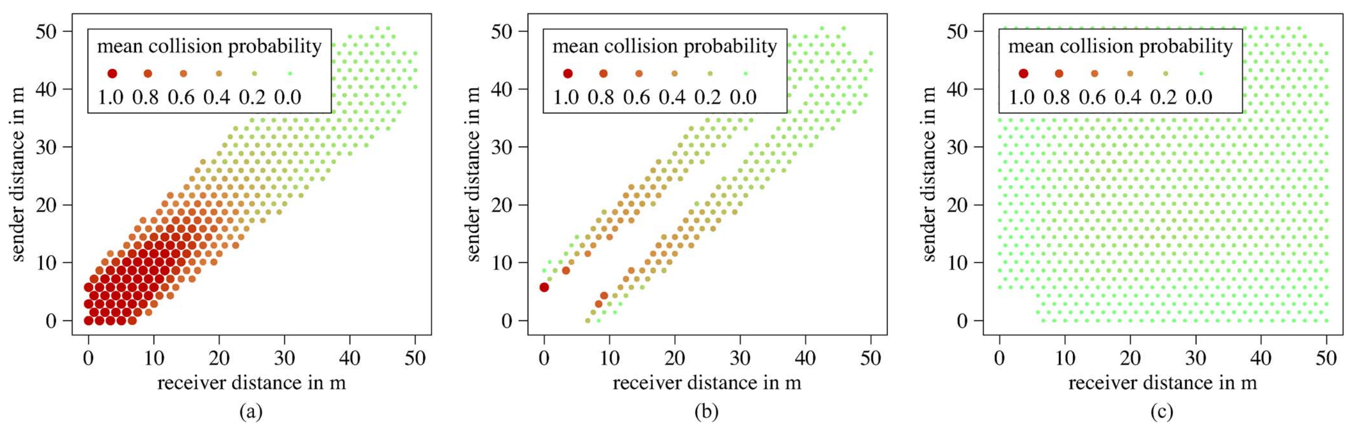

Fig. 7. Mean estimated collision probability per bin calculated based on beacons received using a beacon interval of 0.04 s and assuming uniform distribution of possible trajectories; the dot size represents also the collision probability of the bin by showing large dots for high collision probabilities. (a) CRASH. (b) NEAR CRASH. (c) NO CRASH.

the mean collision probability that has been reached for the vehicles' positions at the time a beacon was received. We binned all received beacons by the distance of the sender and the receiver to the intersection; the mean collision probability is calculated for each of the resulting bins and is depicted by the color and the size of the dots in the plot. The presented plots are separated for the three outcomes CRASH, NEAR CRASH, and NO CRASH, and show the calculated collision probabilities for a beacon interval of 0.04 s.

Let us first concentrate on Fig. 7(a), where the estimated mean collision probabilities of only CRASH approaches are plotted. As expected, all points close to the potential collision area show a very high mean collision probability, which is steadily decreasing when looking at points farther away from the intersection. For outcome NEAR CRASH [cf. Fig. 7(b)], no beacons have been received close to the diagonal, and the estimated collision probabilities reach a medium level (about 50%) at a distance of 20 m, but they decrease again toward the intersection. Additionally, the outliers, which have been already identified as not detected collisions, are visible as high probability dots close to the intersection and diagonal. Fig. 7(c) shows very low estimated collision probabilities for NO CRASH approaches.

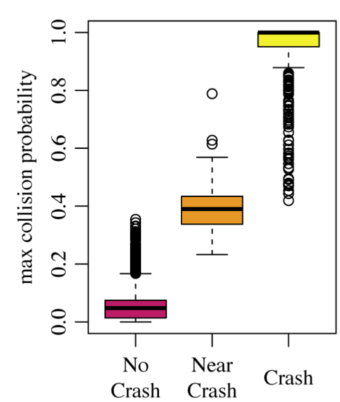

Fig. 8. Maximum collision probability per approaching vehicle for all received beacons (beacon interval 1 s) using the triangular distribution.

C. More Realistic Driver Behavior

As mentioned in Section III-E, we use a triangular acceleration probability distribution as an example for modeling a more realistic (but certainly not the real) driver behavior.

Fig. 8 shows again the maximum reached collision probability per approaching vehicle. When comparing these distributions in different situations for the beacon interval of 1 s

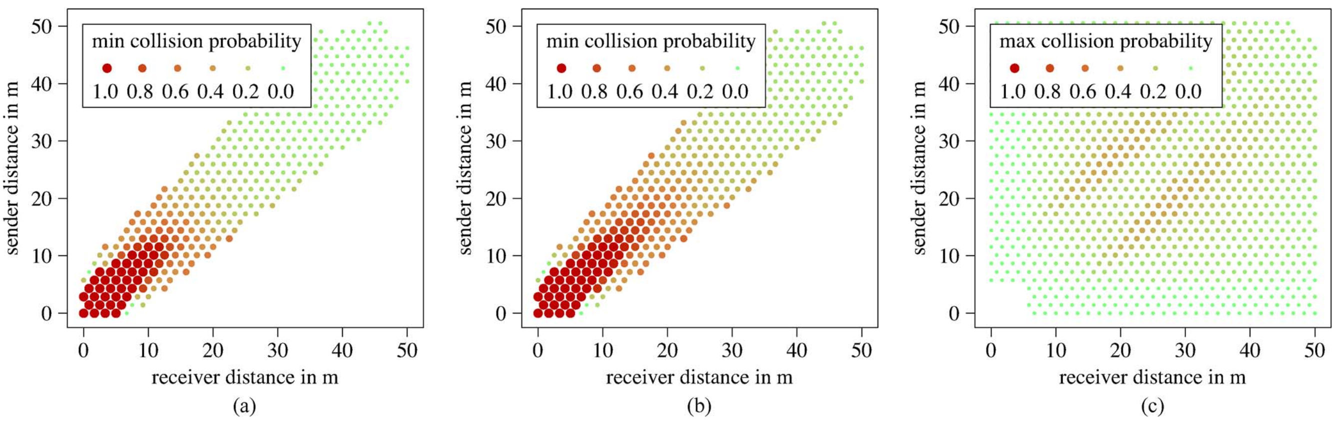

Fig. 9. Worst case collision probabilities per bin calculated based on beacons received using a beaconing interval of 0.04 s; the dot size and color represent the collision probability of the bin by showing large dots for high collision probabilities. (a) Minimum, uniform distribution, CRASH. (b) Minimum, triangular distribution, CRASH. (c) Maximum, triangular distribution, NO CRASH.

with Fig. 6(d), we notice that the distribution of the triangular distribution is more compact for the outcome CRASH, whereas the other two outcomes have similar distributions. Therefore, with a more realistic behavior (triangular distribution), we see fewer false negatives.

Another positive aspect in a more realistic setup, i.e., using the triangular distribution, is shown in Fig. 9. Here, again, the correlation between sender/receiver distances and collision probabilities is depicted. When comparing Fig. 9(a) and (b), it turns out that the collision probability estimation allows the prediction of a future crash already at larger distances from the intersection. This would allow earlier intervention in critical situations. (We have already shown that there is no negative effect for the NO CRASH outcome either.)

We plotted the minimum reached collision probability per bin to demonstrate how the collision probability is behaving in the worst case, although the same effects are also visible when plotting the mean (data not shown). Plotting this minimum collision probability reveals some low collision probabilities close to the borders [in Fig. 9(a) and (b)]. We verified that the outliers are caused by intersection layout inaccuracies.

To analyze the worst case results for outcome NO CRASH, the maximum reached collision probability per bin for the triangular distribution is plotted in Fig. 9(c). Although the collision probability values are higher compared with the mean [cf. Fig. 7(c)], the plot confirms the trend that, close to the intersection, the collision probability is decreasing and showing very low probabilities of around 5%.

D. Implications on Vehicular Networking Concepts

After showing the applicability and validity of our collision probability estimation, we are ready to draw first conclusions related to vehicular networking concepts.

Fig. 10 shows a typical evolution of the collision probability over time for a CRASH approach, i.e., for one vehicle approaching an intersection and finally colliding with another vehicle. Two effects are immediately apparent. The collision probability can only be updated when a beacon has been received; and it remains unchanged in the case of lost beacons. Loss of beacons will, for example, occur if radio communication is obstructed or

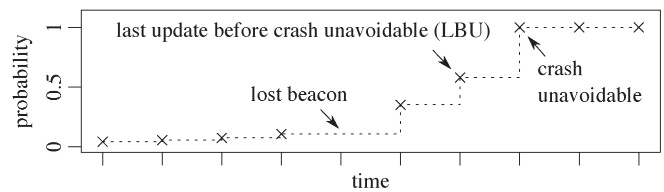

Fig. 10. Evolution of the collision probability for a typical CRASH intersection approach.

if the channel becomes overloaded. Both effects are considered in our simulation study as well. Moreover, the step height of the collision probability strongly depends on the interval at which new information is being received.

Assuming that an approach has been identified as *unavoidable crash*, i.e., the collision probability reached 100%, all future beacons will also yield a collision probability of 100%. Therefore, any action to prevent a crash needs to be triggered at least one beacon prior to receiving one yielding 100%. We call this the *Last Before Unavoidable (LBU)* beacon.

In the following, we investigate the collision probability estimation that has been calculated for LBU beacons. Fig. 11 shows the empirical complementary cumulative distribution function (eCCDF) of the calculated collision probability for LBU beacons, depending on the configured beacon interval.

Looking at Fig. 11(a), which shows the eCCDF for uniform distribution of possible trajectories, it is shown that the median LBU collision probability estimation was below 75% and 50% for slow beacon intervals of 0.5 and 1 s, respectively. This would already necessitate a fairly small threshold for automated reactions. Even worse, considering safety applications, it is necessary to cover almost all possible situations; thus, the 95th and 99th success percentiles (also listed in Table III) are a better indication of how a reaction threshold would need to be chosen. Here, it becomes clear that slow beacon intervals (1 and 0.5 s) are not suitable because the implied reaction thresholds for these beacon intervals are as low as 21% and 48%, thus leading to many false positives. Depending on the driver behavior (as illustrated by the triangular acceleration probability distribution chosen for Fig. 11(b) and Table III), the necessary reaction threshold might be chosen some percentage points higher (from 39% to 76%), but it still remains low.

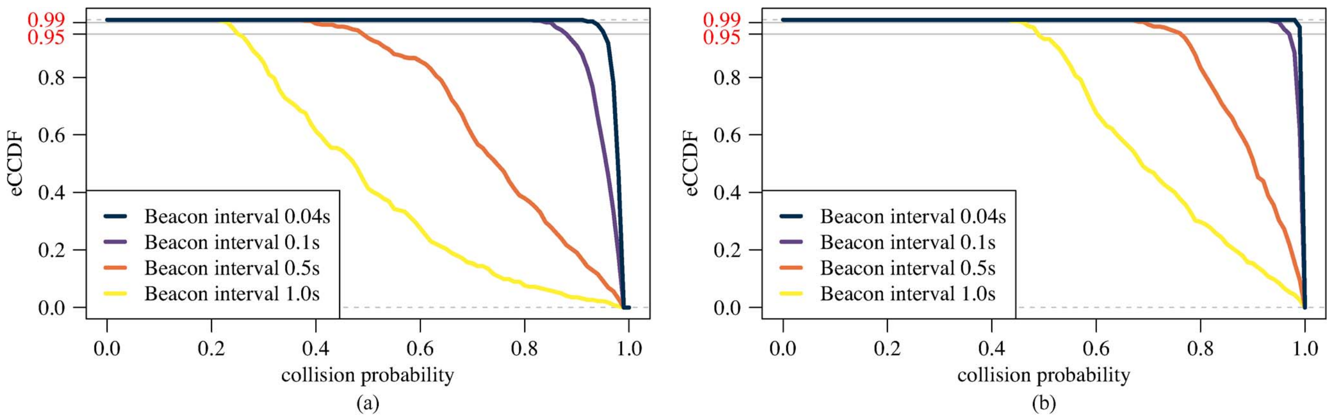

Fig. 11. eCCDF of collision probability for LBU beacons and approaches in group CRASH. (a) Uniform acceleration probability distribution. (b) Triangular acceleration probability distribution.

TABLE III
REACTION THRESHOLDS BASED ON LBU COLLISION PROBABILITY

Probability distribution	Uniform		Triangular	
Success rate	99 %	95 %	99 %	95 %
Beacon interval 1.0 s	21 %	25 %	39 %	49 %
Beacon interval 0.5 s	45 %	48 %	69 %	76 %
Beacon interval 0.1 s	83 %	87 %	94 %	96.5 %
Beacon interval 0.04 s	93 %	95 %	98.5 %	99.3 %

For smaller beacon intervals (0.04 and 0.1 s), we see that the necessary reaction thresholds are appreciably high (up to 99.3% assuming a triangular acceleration probability distribution, when targeting a 95th percentile success rate and using the fastest beaconing interval). However, these values are only applicable for the highly idealistic network conditions assumed in the simulation. In earlier work [3], we were able to show that fixed rate beaconing with such high rates would overload the network, leading to excessive packet loss, which, as discussed earlier, would have fatal implications for ICWSs.

VI. CONCLUSION

In conclusion, we were able to define a collision probability estimation scheme that allows assessment of the criticality of an intersection approach based on exchanged beacons, such as CAMs or BSMs. Given information about two approaching vehicles (such as their current position and speed), we are able to derive potential future trajectories and calculate the probability of a crash. In general, this value can be subsequently exploited for warnings to the human driver, although this is not the focus of this paper. Instead, we evaluated the impact of beaconing-based IVC on whether the calculated collision probability can be used for assessing the criticality of situations. In an extensive number of simulation experiments, we validated the proposed criticality metric and carefully evaluated the collision probability estimation.

Our findings show that our metric clearly reveals the criticality of an intersection approach. We also show, using periodic beaconing as an example, how the metric can be applied for evaluating IVC solutions and how simple periodic beaconing is not as effective as anticipated in suburban environments. The presented LBU collision probability can be used to further examine the behavior of information dissemination protocols for intersection safety applications. Moreover, the analysis of the maximum change of the collision probability between two consecutive beacons can give new insights into how to properly design information dissemination for such applications.

Finally, the presented general approach of the intersection collision probability can be extended to capture more details such as lateral movements of vehicles or longitudinal vehicle dynamics. Additional future work includes the investigation of more realistic (maybe even dependent) probability distribution functions for trajectories of two approaching vehicles. These probability distributions might also make use of machine learning and hence might be able to predict possible future trajectories more accurately on a per driver basis.

REFERENCES

[1] G. Karagiannis, O. Altintas, E. Ekici, G. Heijenk, B. Jarupan, K. Lin, and T. Weil, "Vehicular networking: A survey and tutorial on requirements, architectures, challenges, standards and solutions," *IEEE Commun. Surveys Tuts.*, vol. 13, no. 4, pp. 584–616, Jul. 2011.

[2] F. Dressler, F. Kargl, J. Ott, O. K. Tonguz, and L. Wischhof, "Research challenges in inter-vehicular communication—Lessons of the 2010 Dagstuhl seminar," *IEEE Commun. Mag.*, vol. 49, no. 5, pp. 158–164, May 2011.

[3] C. Sommer, O. K. Tonguz, and F. Dressler, "Traffic information systems: Efficient message dissemination via adaptive beaconing," *IEEE Commun. Mag.*, vol. 49, no. 5, pp. 173–179, May 2011.

[4] *Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Part 2: Specification of Cooperative Awareness Basic Service*, ETSI, TS 102 637-2 V1.1.1, Apr. 2010.

[5] C. Sommer, S. Joerer, M. Segata, O. K. Tonguz, R. Lo Cigno, and F. Dressler, "How shadowing hurts vehicular communications and how dynamic beaconing can help," in *Proc. 32nd IEEE INFOCOM*, Turin, Italy, Apr. 2013, pp. 110–114.

[6] S. Biswas and F. Dion, "Vehicle-to-vehicle wireless communication protocols for enhancing highway traffic safety," *IEEE Commun. Mag.*, vol. 44, no. 1, pp. 74–82, Jan. 2006.

[7] S. Joerer, M. Segata, B. Bloessl, R. Lo Cigno, C. Sommer, and F. Dressler, "To crash or not to crash: Estimating its likelihood and potentials of beacon-based IVC systems," in *Proc. 4th IEEE VNC*, Seoul, Korea, Nov. 2012, pp. 25–32.

[8] *Wireless Access in Vehicular Environments*, IEEE Std. 802.11p-2010, Jul. 2010.

[9] M. Segata and R. Lo Cigno, "Emergency braking: A study of network and application performance," in *Proc. 8th ACM Int. Workshop VANET*, Las Vegas, NV, USA, Sep. 2011, pp. 1–10.
[10] M. Ferreira, R. Fernandes, H. Conceição, W. Viriyasitavat, and O. K. Tonguz, "Self-organized traffic control," in *Proc. 7th ACM Int. Workshop VANET*, Chicago, IL, USA, Sep. 2010, pp. 85–90.
[11] T. Neudecker, N. An, O. K. Tonguz, T. Gaugel, and J. Mittag, "Feasibility of virtual traffic lights in non-line-of-sight environments," in *Proc. 9th ACM Int. Workshop VANET*, Low Wood Bay, U.K., Jun. 2012, pp. 103–106.
[12] S.-H. Chang, C.-Y. Lin, C.-C. Hsu, C.-P. Fung, and J.-R. Hwang, "The effect of a collision warning system on the driving performance of young drivers at intersections," *Transp. Res. F, Traffic Psychol. Behav.*, vol. 12, no. 5, pp. 371–380, Sep. 2009.
[13] H. Berndt, S. Wender, and K. Dietmayer, "Driver braking behavior during intersection approaches and implications for warning strategies for driver assistant systems," in *Proc. IEEE IV Symp.*, Istanbul, Turkey, Jun. 2007, pp. 245–251.
[14] T. Mangel, F. Schweizer, T. Kosch, and H. Hartenstein, "Vehicular safety communication at intersections: Buildings, non-line-of-sight and representative scenarios," in *Proc. 8th Int. Conf. WONS Services*, Bardonecchia, Italy, Jan. 2011, pp. 35–41.
[15] H. Chen, L. Cao, and D. B. Logan, "Investigation into the effect of an intersection crash warning system on driving performance in a simulator," *Traffic Inj. Prev.*, vol. 12, no. 5, pp. 529–537, Oct. 2011.
[16] D. Valerio, F. Ricciato, P. Belanovic, and T. Zemen, "UMTS on the road: Broadcasting intelligent road safety information via MBMS," in *Proc. 67th IEEE VTC-Spring*, May 2008, pp. 3026–3030.
[17] C. Sommer, A. Schmidt, Y. Chen, R. German, W. Koch, and F. Dressler, "On the feasibility of UMTS-based traffic information systems," *Ad Hoc Netw.*, vol. 8, no. 5, pp. 506–517, Jul. 2010.
[18] R. K. Schmidt, T. Leinmüller, E. Schoch, F. Kargl, and G. Schäfer, "Exploration of adaptive beaconing for efficient intervehicle safety communication," *IEEE Netw. Mag.*, vol. 24, no. 1, pp. 14–19, Jan./Feb. 2010.
[19] D. Rossi, R. Fracchia, and M. Meo, "VANETs: Why use beaconing at all?" in *Proc. IEEE ICC*, May 2008, pp. 2745–2751.
[20] *DSRC Message Communication Minimum Performance Requirements: Basic Safety Message for Vehicle Safety Applications*, SAE, Draft Std. J2945.1 Revision 2.2, Apr. 2011, SAE Int. DSRC Committee.
[21] D. Eckhoff, C. Sommer, R. German, and F. Dressler, "Cooperative awareness at low vehicle densities: How parked cars can help see through buildings," in *Proc. IEEE GLOBECOM*, Houston, TX, USA, Dec. 2011, pp. 1–6.
[22] N. An, M. Maile, D. Jiang, J. Mittag, and H. Hartenstein, "Balancing the requirements for a zero false positive/negative forward collision warnings," in *Proc. 10th Int. Conf. WONS Services*, Banff, Canada, Mar. 2013, pp. 191–195.
[23] O. K. Tonguz, N. Wisitpongphan, and F. Bai, "DV-CAST: A distributed vehicular broadcast protocol for vehicular ad hoc networks," *IEEE Wireless Commun.*, vol. 17, no. 2, pp. 47–57, Apr. 2010.
[24] M. Werner, R. Lupoaie, S. Subramanian, and J. Jose, "MAC layer performance of ITS G5—Optimized DCC and advanced transmitter coordination," in *4th ETSI TC ITS Workshop*, Doha, Qatar, Feb. 2012, pp. 1–21.
[25] *Intelligent Transport Systems (ITS); Decentralized Congestion Control Mechanisms for Intelligent Transport Systems Operating in the 5 GHz Range; Access Layer Part*, ETSI, Std. TS 102 687 V1.1.1, Jul. 2011.
[26] L. Le, A. Festag, R. Baldessari, and W. Zhang, "Vehicular wireless short-range communication for improving intersection safety," *IEEE Commun. Mag.*, vol. 47, no. 11, pp. 104–110, Nov. 2009.
[27] J. J. Haas and Y.-C. Hu, "Communication requirements for crash avoidance," in *Proc. 7th ACM Int. Workshop VANET*, Chicago, IL, USA, Sep. 2010, pp. 1–10.
[28] A. Tang and A. Yip, "Collision avoidance timing analysis of DSRC-based vehicles," *Accid. Anal. Prev.*, vol. 42, no. 1, pp. 182–195, Jan. 2010.
[29] M. Brannstrom, E. Coelingh, and J. Sjoberg, "Model-based threat assessment for avoiding arbitrary vehicle collisions," *IEEE Trans. Intell. Transp. Syst.*, vol. 11, no. 3, pp. 658–669, Sep. 2010.
[30] S. Lefèvre, C. Laugier, and J. Ibañez-Guzmán, "Risk assessment at road intersections: Comparing intention and expectation," in *Proc. IEEE IV Symp.*, Alcalá de Henares, Spain, Jun. 2012, pp. 165–171.
[31] M. Liebner, M. Baumann, F. Klanner, and C. Stiller, "Driver intent inference at urban intersections using the intelligent driver model," in *Proc. IEEE IV Symp.*, Alcalá de Henares, Spain, Jun. 2012, pp. 1162–1167.
[32] H.-S. Tan and J. Huang, "DGPS-based vehicle-to-vehicle cooperative collision warning: Engineering feasibility viewpoints," *IEEE Trans. Intell. Transp. Syst.*, vol. 7, no. 4, pp. 415–428, Dec. 2006.
[33] R. Verma and D. Del Vecchio, "Safety in semi-autonomous multi-vehicle systems: A hybrid control approach," *IEEE Robot. Autom. Mag.*, vol. 18, no. 3, pp. 44–54, Sep. 2011.
[34] M. Hafner, D. Cunningham, L. Caminiti, and D. Del Vecchio, "Cooperative collision avoidance at intersections: Algorithms and experiments," *IEEE Trans. Intell. Transp. Syst.*, vol. 14, no. 3, pp. 1162–1175, Sep. 2013.
[35] M. Hafner, D. Cunningham, L. Caminiti, and D. Del Vecchio, "Automated vehicle-to-vehicle collision avoidance at intersections," presented at the 18th ITS World Congress, Orlando, FL, USA, Oct. 2011, Paper 1314.
[36] C. Sommer, R. German, and F. Dressler, "Bidirectionally coupled network and road traffic simulation for improved IVC analysis," *IEEE Trans. Mobile Comput.*, vol. 10, no. 1, pp. 3–15, Jan. 2011.
[37] M. Treiber, A. Hennecke, and D. Helbing, "Congested traffic states in empirical observations and microscopic simulations," *Phys. Rev. E, Stat. Nonlin. Soft Matter Phys.*, vol. 62, no. 2, pp. 1805–1824, Aug. 2000.
[38] D. Schrauben and J. Flegel, "Police vehicle evaluation model year 2013," Michigan State Police, Precision Driving Unit, Lansing, MI, USA, Tech. Rep., Dec. 2012.
[39] C. Sommer, D. Eckhoff, R. German, and F. Dressler, "A computationally inexpensive empirical model of IEEE 802.11p radio shadowing in urban environments," in *Proc. 8th Int. Conf. WONS Services*, Bardonecchia, Italy, Jan. 2011, pp. 84–90.
[40] D. Eckhoff, C. Sommer, and F. Dressler, "On the necessity of accurate IEEE 802.11p models for IVC protocol simulation," in *Proc. 75th IEEE VTC-Spring*, Yokohama, Japan, May 2012, pp. 1–5.

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