

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 (ITS) in terms of ‘safety’ is one of the major challenges in vehicular networking research. We aim to provide a metric, an estimation of the vehicle collision probability at intersections, that can be used for evaluating Inter-Vehicle 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 like 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 CAM or a 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 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, can be used to develop more sophisticated beaconing solutions.

I. INTRODUCTION

Crash mitigation and crash avoidance are two of the major applications of Intelligent Transportation Systems (ITS) [1]. Most recent approaches for active safety also take Inter-Vehicle Communication (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, *safety*, adds further demands like 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 have been identified, from emergency braking systems for highways [9] to more radical innovations such as virtual traffic lights [10], [11].

One of these applications are Intersection Collision Warning Systems (ICWS), 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 ICWS 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 for each investigated type clearly indicates a substantial safety advantage. These early results show the potential of ICWS 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 ICWS at suburban intersections. 3G and 4G approaches are also considered for this application scenario [16], [17], but are out of 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 1Hz to 25Hz 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 the possible improvements using available relay nodes (e.g., parked vehicles [21] close to the intersection). In this paper, we focus on the possibility to estimate the collision probability when a beacon message is received. The approach is fully distributed and does not require external infrastructure. Our goal is gaining insight on the requirements of the communication platform, but (unlike earlier 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 (VANET) 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 – not delay, or packet loss. Therefore, we believe 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 like *How many crashes can be avoided?* and *Can the impact of crashes be*

significantly reduced? Accordingly, we developed 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, now expressed as a collision probability. This probability is a quantitative measure of the criticality of intersection approach situations (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 which selectively ignore traffic rules; we further integrated the possibility to detect the resulting crashes or near crashes (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 behavior (Sections V-B and V-C).
- *Implications on Vehicular Networking Concepts:* We study the impact of beaconing approaches 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 (Section V-D).

II. RELATED WORK

Our work is focusing on collision avoidance at intersections as one application of ITS and, hence, it touches on not only communications issues, but also research areas such as controller theory, transportation science and road traffic engineering, albeit we do not claim to be experts in these fields, too.

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 vehicles furthest 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 (ATB) [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 in the focus of this work.

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. had a look on busy time fraction of DSRC systems for intersection safety [26] using a simplified radio propagation model which 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 like 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 Intersection Collision Warning Systems (ICWS) with new safety metrics that are based on the collision probability of two approaching vehicles.

Tang et al. [28] investigated timings for collision avoidance systems assuming DSRC transmission delays of 25 ms 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 driver, and different deceleration rates) within this time interval. This metric is definitely a good possibility to compare 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 as well as 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 model 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 et al. [32] have explored the possibilities of future trajectory prediction for cooperative collision warning systems with 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 by 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 which 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, our work is focusing on the communication aspects and hence its goal is not designing 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 ICWS and it provides the potential to enhance 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 as well as 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 , d_B and the speeds v_A , 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 , but depend on each vehicle model. To simplify the notation in this paper, we omit the vehicle dependent indices for these two physical boundaries in the following.

For defining the 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. Figure 1). The axes' origins are at the center of where the vehicles' trajectories intersect. In the following we concentrate on the X-intersection shown Figure 1a. However, by considering the interdependence of the two distances also a Y-intersection as depicted in Figure 1b can be modeled similarly.

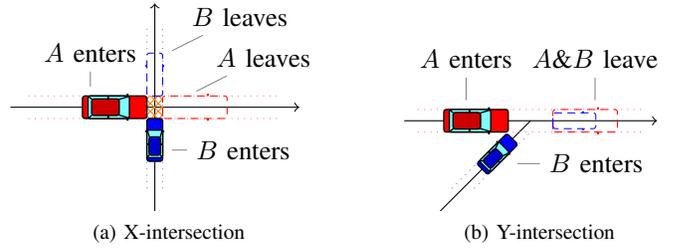


Figure 1. Coordinate space for vehicles A & B for different intersection types.

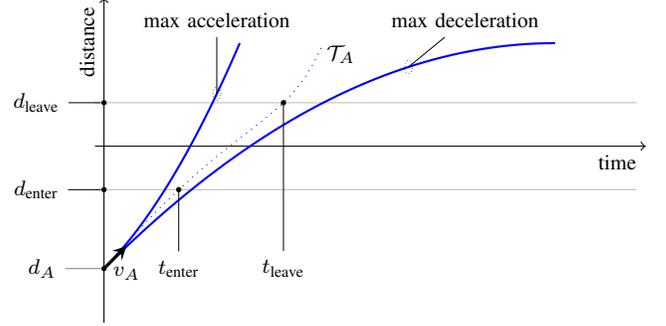


Figure 2. Sample trajectory of vehicle A dependent on its distance d_A and speed v_A . The distances d_{enter} , d_{leave} and times t_{enter} , t_{leave} are depicted for an orthogonal X-intersection.

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

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

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 depicted in Figure 2.

For determining 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 $\text{coll}(\mathcal{T}_A, \mathcal{T}_B)$ 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* to occur 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

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

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 to model 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 (called *bad set* in [34]) and a future crash is unavoidable (*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 for evaluating communication strategies for ICWS we do not need to model details like 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 Figure 1a 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} , t_{leave} when a vehicle enters and leaves the potential collision area of a given trajectory 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} , t_{leave} , and the distances d_{enter} , d_{leave} is depicted in Figure 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 insights 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 especially interested in situations where the drivers are not aware of each other and 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 $\text{coll}(\cdot, \cdot)$ analogous to Equation (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:

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

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.

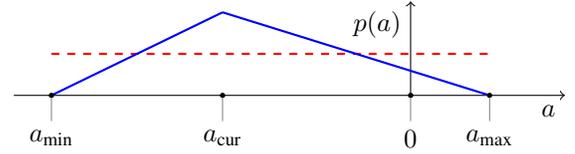


Figure 3. Example of a triangular acceleration probability distribution conditioned on the present acceleration (solid line), compared to a uniform distribution (dashed line).

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 Equation (3). The probability $p(a)$ can then be calculated as

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

resulting in

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

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 to represent such behavior is to employ a triangular acceleration probability distribution with lower limit a_{min} , mode a_{cur} , and upper limit a_{max} as depicted in Figure 3. When using this distribution, the collision probability \mathcal{P}_C can still be calculated using the simplified version shown in Equation (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 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, based on lane geometry imported from OpenStreetMap, and let two vehicles approach the intersection, then cross it without turning. For this study, we used the Intelligent-Driver Model (IDM) car-following model [37] (in order to reproduce realistic braking behavior [13]) as well as a modified version of SUMO that allows us to let selected vehicles ignore traffic rules [7]. We

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	$\sim U(0, v_{\text{max}})$

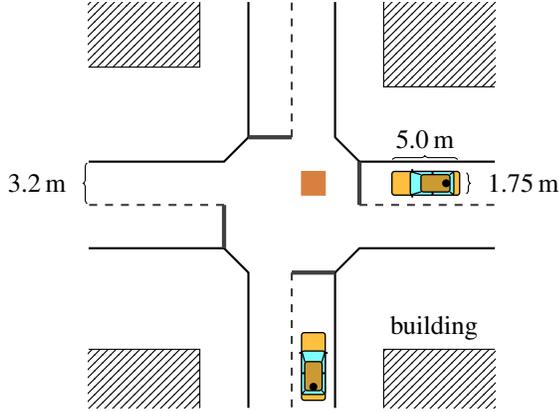


Figure 4. Map view of the simulated X-intersection showing the potential collision area, buildings, and two approaching vehicles.

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 Figure 4 the potential collision area of two approaching vehicles, the intersection and vehicle geometry are depicted 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} , a_{max}) of the vehicle, we can compute the maximum possible error ϵ introduced by deceleration and acceleration as

$$\epsilon_{\text{dec}} = \frac{1}{2} |a_{\text{min}}| t_{\text{step}}^2, \quad \epsilon_{\text{acc}} = \frac{1}{2} |a_{\text{max}}| t_{\text{step}}^2, \quad (7)$$

$$\epsilon = \max(\epsilon_{\text{dec}}, \epsilon_{\text{acc}}). \quad (8)$$

In our simulations we choose a 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

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
CW _{min} , CW _{max}	3, 7
AIFSN	2

braking with maximum deceleration). Moreover, the selected simulation time step results in a maximum step distance of $v_{\text{max}} \times t_{\text{step}} = 8.405$ 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 as well as comparability for future simulation studies. For the radio propagation, we use the obstacle model [39] which allows us to accurately model signal attenuation by buildings in a computationally efficient way. For simulating the physical and 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 which 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 s, 0.1 s, 0.5 s 1.0 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 which collided at the intersection. To be able to distinguish critical and non-critical situations better, we introduce a second group called NEAR CRASH which 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 which have not been detected due to simulation time step size and allows to detect 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.

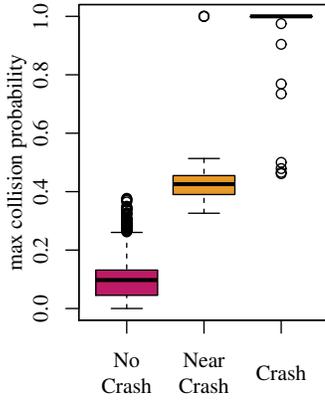


Figure 5. Maximum collision probability per approaching vehicle calculated using exact sensor data.

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

In 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 negatives*: 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 this data, we calculated the maximum collision probability for each approaching vehicle and present the distribution in box plots grouped by the different outcomes in Figure 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 towards the minimum and maximum of the data set, but no 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 geodata) and the perfect intersection layout assumed during probability calculation. To crosscheck, we simulated a perfect intersection with exact (down to the millimeter) layout depicted in Figure 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 idealized (best) case with respect to channel conditions and medium access delay.

Figure 6 shows the distribution of the maximum collision probability per vehicle for different beacon intervals (0.04 s, 0.1 s, 0.5 s, and 1.0 s) and 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 which do not reach a high collision probability is substantially increasing for larger beacon intervals. This can be seen by comparing Figure 6a, which shows a similar distribution as shown in the validation (cf. Figure 5), and Figure 6d, which reveals that already a major portion of the approaching vehicles has not reached a high collision probability before crashing.

For understanding the correlation between the vehicles’ distances and the resulting estimated collision probabilities, Figure 7 presents 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 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 Figure 7a, where the estimated mean collision probabilities of only CRASH approaches are plotted. As expected, all points close to the potential collision

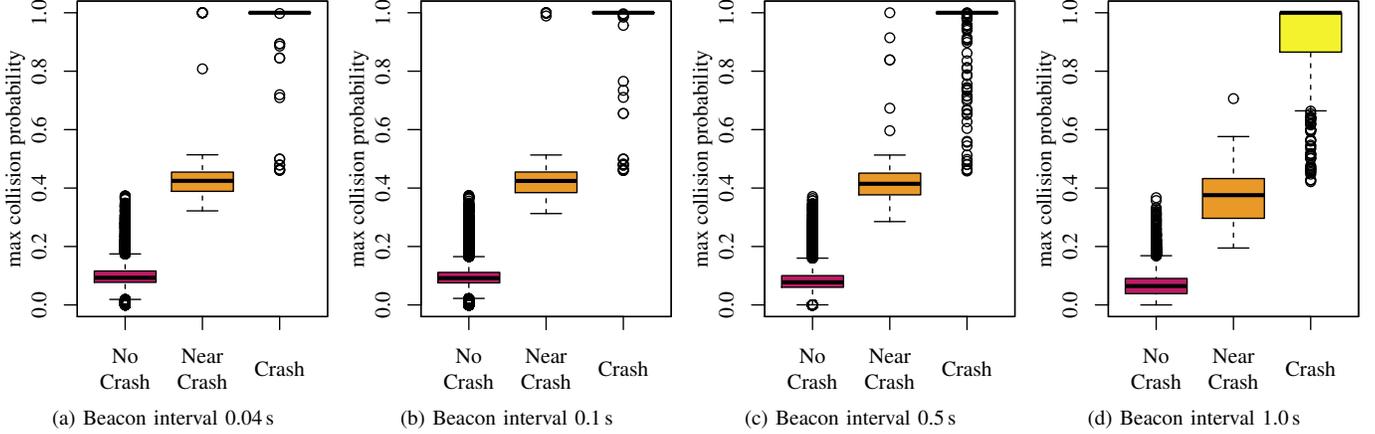


Figure 6. Maximum collision probability per approaching vehicle for all received beacons, grouped by the final outcome of the intersection approach.

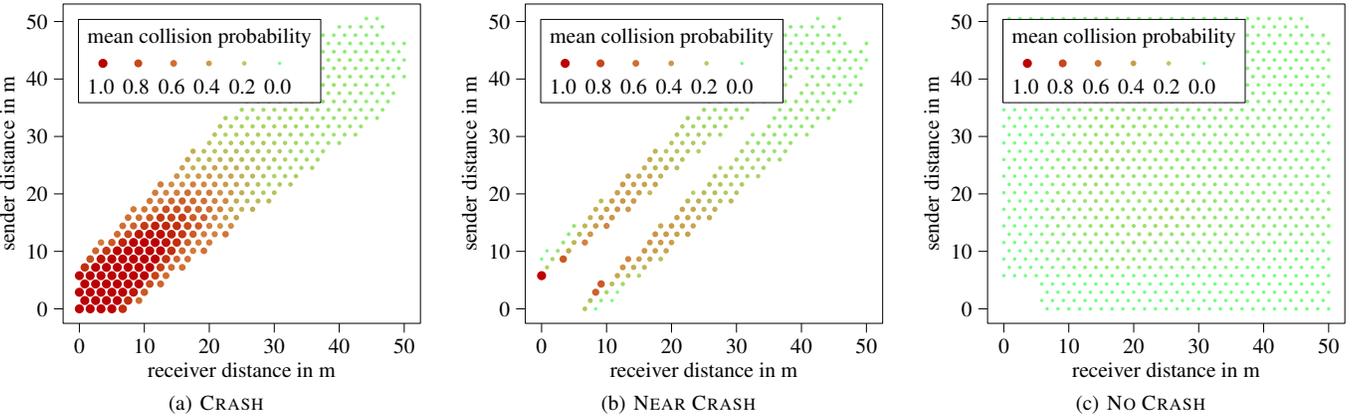


Figure 7. Mean estimated collision probability per bin calculated based on beacons received using a beacon interval of 0.04 s and assuming uniform distribution of possible trajectories; the dot size represents also the collision probability of the bin by showing large dots for high collision probabilities.

area show a very high mean collision probability which is steadily decreasing when looking at points further away from the intersection. For outcome NEAR CRASH (cf. Figure 7b), 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 towards the intersection. Additionally, the outliers, that have been already identified as not detected collisions, are visible as small high probability dots close to the intersection and diagonal. Figure 7c shows very low estimated collision probabilities for NO CRASH approaches.

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.

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

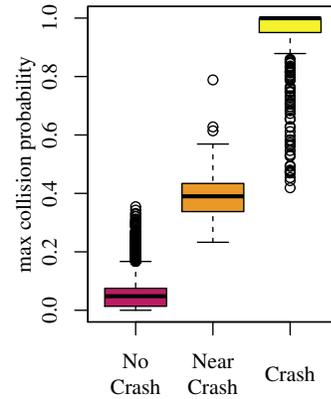


Figure 8. Maximum collision probability per approaching vehicle for all received beacons (beacon interval 1 s) using the triangular distribution.

Another positive aspect in a more realistic setup, i.e., using the triangular distribution, is shown in Figure 9. Here, again the correlation between sender/receiver distances and collision probabilities is depicted. When comparing Figure 9a and Figure 9b, 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 to intervene earlier in critical situations (we have already shown that there is no negative effect for the NO CRASH outcome either).

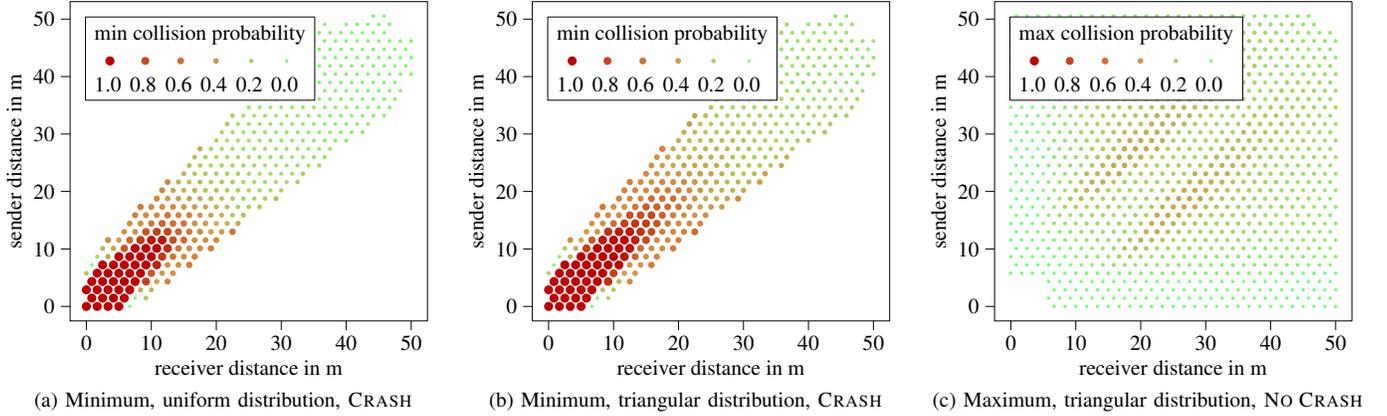


Figure 9. Worst case collision probabilities (per bin) when beaconing at an interval of 0.04 s.

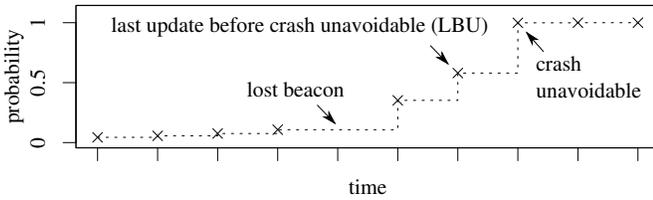


Figure 10. Evolution of the collision probability for a typical CRASH intersection approach.

We plotted the minimum reached collision probability per bin to demonstrate how the collision probability is behaving in the worst case, though 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 Figure 9a and Figure 9b). We verified that these outliers are again 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 Figure 9c. Although the collision probability values are higher compared to the mean (cf. Figure 7c), the plot confirms the trend that close to the intersection the collision probability is decreasing and showing really 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.

Figure 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 – it remains unchanged in case of lost beacons. Loss of beacons will, for example, occur if radio communication is obstructed or if the channel becomes overloaded. Both effects are considered in our simulation study as well. Also, the step

Table III
REACTION THRESHOLDS BASED ON LBU COLLISION PROBABILITY.

Probability distribution Success rate	Uniform		Triangular	
	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 %

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. Figure 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 Figure 11a, which shows the eCCDFs for uniform distribution of possible trajectories, it can be seen that the median LBU collision probability estimation was below 75% and 50% for slow beacon intervals of 0.5 s and 1.0 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 s 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 Figure 11b and Table III), the necessary reaction threshold might be chosen some percentage points higher (from 39% to 76%), but it still remains low.

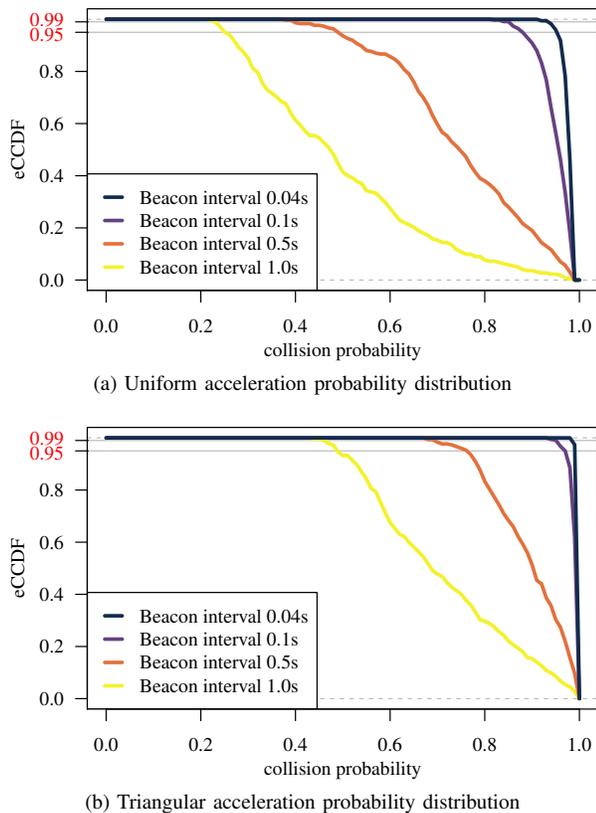


Figure 11. eCCDF of collision probability for Last Before Unavoidable (LBU) beacons and approaches in group CRASH.

For smaller beacon intervals (0.04s and 0.1s), 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 ICWS.

VI. CONCLUSION

In conclusion, it can be said that we were able to define a collision probability estimation scheme that allows to assess the criticality of an intersection approach based on exchanged beacons, like Cooperative Awareness Messages (CAMs) or Basic Safety Messages (BSMs). Given information about the two vehicles approaching (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 subsequently be exploited for warnings to the human driver, even though this is not the focus of this paper. Instead, we evaluated the impact of beaconing based Inter-Vehicle Communication (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 *Last Before Unavoidable (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 on how to properly design information dissemination for such applications.

Finally, we want to mention that the presented general approach of the intersection collision probability can be extended to capture more details like 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.

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