# To Crash or Not to Crash: Estimating its Likelihood and Potentials of Beacon-based IVC Systems

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***Abstract*—Is it possible to estimate some 'safety' metric to assess the effectiveness of Intelligent Transportation Systems? In particular, we are interested in using Inter-Vehicle Communication (IVC) beaconing for increasing drivers' safety at intersections. In the last couple of years, the vehicular networking community reported in several studies that simple network metrics are not sufficient to evaluate safety enhancing protocols and applications. We present a classification scheme that allows the quantification of such improvements by determining how many potential crashes happen or can be avoided by a specific IVC approach. Using a modified road traffic simulator that allowed selected vehicles to disregard traffic rules, we investigated the impact of safety messaging between cars approaching an intersection. We show that in suburban environments simple beaconing is not as effective as anticipated. Yet, simple one-hop-relaying, e.g., by vehicles parked close to an intersection, can improve drivers' safety substantially. Since the key purpose of IVC is safety, the paper closes the loop in the evaluation of the effectiveness of vehicular networks as defined today.**

## I. INTRODUCTION

Research on Inter-Vehicle Communication (IVC) is mainly motivated by safety and efficiency applications, both requiring efficient management of the wireless communication channel [1]. In this paper, we focus on the first application type, safety, which in addition demands extremely low transmission latencies [2]. With the development and standardization of Dedicated Short-Range Communication (DSRC) using IEEE 802.11p at the access level [3], short range radio broadcast became the leading technology for low-latency communications between vehicles in close vicinity. 3G and 4G approaches are of course still investigated for this application scenario [4], [5], but out of scope for this work.

DSRC promises to reduce accidents by enabling support systems such as cross-traffic assistance [6]. Within this scope, a wide range of applications have been identified, from emergency braking systems for highways [7] to radical innovations such as virtual traffic lights [8], [9]. We are looking at a very specific application that is also part of much larger assistance concepts: Intersection Collision Warning Systems (ICWS) [10], [11].

The benefit of such systems has already been investigated thoroughly using *driving simulators*. In 2009, Chang et al. have shown that audio ICWS are able to reduce drivers' reaction time and hence reduce the accident rate [10], e.g., for young inexperienced drivers. The impact of different warning systems has been studied in [12] and for each investigated type clearly indicates a substantial safety advantage.

These early results indicate that intersection crashes could be reduced by 40 %–50 % using ICWS, but these works address neither how ICWS can be implemented, nor the involved networking issues.

In this paper, we study the feasibility of using simple beaconing for exchanging safety critical information in the context of ICWS at suburban intersections such as the one depicted in Figure 1. Beaconing has been identified in a couple of studies as a communication principle suitable for many challenging vehicular networking applications [7], [13]–[16]. Furthermore, ETSI standardized simple Cooperative Awareness Message (CAM) messages for the exchange also of safety critical information to be broadcasted periodically every 1 Hz–10 Hz. We not only estimate the quality of one-hop experiments, but also assess possible improvements using available relay nodes. In particular, we follow the ideas in [17] to use parked vehicles as relays, which can be expected to be positioned at suitable positions close to an intersection. This concept can of course also be replaced using Road Side Units (RSUs) installed at the traffic light but at much higher operational costs.

Another open question is to what extent this can be achieved and what metrics can be used to measure success in the design of protocols and applications [18]. So far, 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 the benefit that they are able to provide for

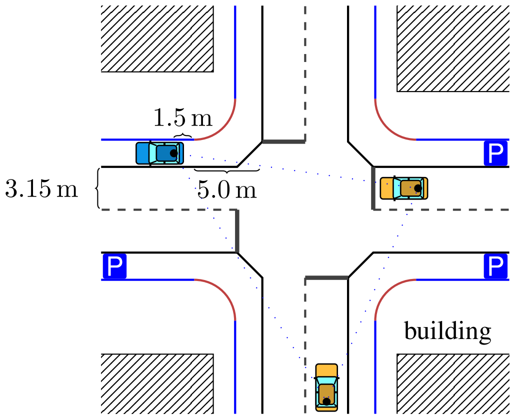

Fig. 1. Schematic view of the X intersection scenario.

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the driver and not delays and losses of packets. 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 like: "How many crashes can (theoretically) be mitigated?" and "Can the impact of crashes be significantly reduced?" Accordingly, we developed new safety metrics and show in this paper how these reflect the performance of simple beaconing based communications.

Our main contributions can be summarized as follows:

- *Risk classification*: We investigate safety measures for Intersection Collision Warning Systems (ICWS) based on which each vehicle can derive how critical the current situation is (Section III).
- *Integration into the 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 and to detect the resulting crashes and/or near misses (Section IV).
- *Evaluation of beaconing warning messages*: We study the impact of static beaconing approaches in non-line-of-sight scenarios for the transmission of safety messages and show in which situations (corresponding to risk classes) beacons can actually be exchanged between the endangered vehicles. In addition we show the substantial benefit of one-hop relays, which in our case are parked vehicles close to the intersection (Section V).

## II. RELATED WORK

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

From a communications perspective, we investigate the possibilities of safety applications using simple beaconing strategies combined with one-hop relaying. In the vehicular networking community, approaches clearly outperforming simple beaconing in terms of channel load or information dissemination range have been proposed. DV-Cast [19] aims at mitigating the broadcast storm problem by rebroadcasting first (and hopefully only) from vehicles with largest distance from the original sender. The protocol can also switch between relaying and opportunistic forwarding depending on the estimated advantages. Adaptive Traffic Beacon (ATB) [16] 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 [13], [14]. Nevertheless, optimizations in this domain are not the key focus of this work.

Instead, we focus on safety aspects of Intersection Collision Warning Systems (ICWS). Tang et al. investigated timings for collision avoidance systems [20] assuming DSRC transmission delays of $25\,\mathrm{ms}$ and $300\,\mathrm{ms}$ in normal and poorer 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. Our work is not having a look at reaction times and when to warn a driver at all, because we are presenting fundamental results which might be used by any kind of collision mitigation application, including those that do not require explicit cooperation between vehicles.

The results and implications of real-world traces of driver braking behavior during intersection approaches have been published in [11]. This work shows that detecting real warning situations is not trivial, because avoiding false positives is essential for the success of ICWS. We have also adjusted our simulation models as described in Section IV to use similar braking behavior when approaching the intersection.

Networking conditions, scenarios, and their implications are analyzed in [6], where the authors broadly discuss the requirements from the communication point of view of ICWS. Conceptually, the next step towards safety message exchange at intersections is the use of adequate relays. Eckhoff et al. investigated the use of parked vehicles in such scenarios [17]. We adopted this concept in our study by also checking the advantages of 1-hop-relays to improve drivers' safety.

## III. MODELING SAFETY AT INTERSECTIONS

The focus of this paper is on classifying situations' criticality, and providing sound building blocks for research on safety enhancement systems through Vehicle-to-Vehicle (V2V) communications. Thus, we do not investigate crash avoidance or impact reduction strategies and leave such investigations for future research. We need to emphasize, however, that future VANET safety applications must be able to avoid crashes while generating minimum disturbance to drivers, and a negligible level of false alarms. The analysis of different situations, of how beacons diffuse in these situations, whether relaying of beacons is needed, and of how simple models can pre-filter the number of situations that require further attention are fundamental preliminary steps for sound investigation and design.

### *A. Potential Crash Interval*

A key issue for a collision prevention application is understanding the risk of collisions in order to take the correct countermeasures without generating excessive false alarms. To classify the severity of a potential collision between two vehicles, we first determine the time interval in which they can cross the intersection (earliest and latest), given their initial speed $v_0$, their distance from the intersection $d_0 > 0$, and assuming a maximum possible acceleration of $a_{\text{acc}} > 0$ and deceleration of $a_{\text{dec}} < 0$. We can then calculate the time $t_{\text{brake}}$ and distance $d_{\text{brake}}$ needed in order to come to a full stop as follows:

$$t_{\text{brake}} = \frac{v_0}{-a_{\text{dec}}} \tag{1}$$

$$d_{\text{brake}} = \frac{v_0 t_{\text{brake}}}{2} = \frac{v_0^2}{-2a_{\text{dec}}}. \tag{2}$$

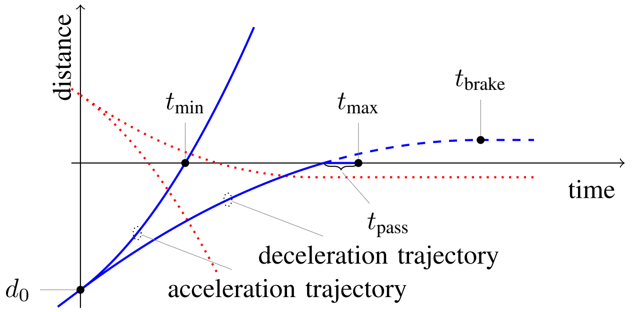

Fig. 2. Graphical derivation of $t_{\text{min}}$ and $t_{\text{max}}$. All labels and variables refer to solid blue line (first car), mirrored w.r.t. $x$ axis for clarity. The second car is represented by the dotted red line.

We are further interested in the earliest possible time a crash can happen, given a certain situation. For that reason, we calculate the time interval $\mathcal{I} = [t_{\text{min}}, t_{\text{max}}[$, during which a car may pass the intersection.

The earliest time $t_{\text{min}}$ a vehicle can reach the intersection, given the maximum acceleration $a_{\text{acc}}$, and the initial position $d_0$ and speed $v_0$:

$$t_{\text{min}} = \frac{-v_0 + \sqrt{v_0^2 + 2a_{\text{acc}}d_0}}{a_{\text{acc}}}. \tag{3}$$

For our purposes, a maximum time $t_{\text{max}}$ exists only if the car is not able to stop before arriving at the intersection, thus it is unavoidable that the car will enter the intersection, and it depends on the maximum deceleration $a_{\text{dec}}$. The time $t_{\text{max}}$ is defined only if the space equation admits a positive solution; otherwise, $t_{\text{max}}$ is infinite. If $t_{\text{max}}$ is not infinite, we have to account for the time $t_{\text{pass}}$ that a vehicle needs to pass through the lane it crosses:

$$t_{\text{max}} = \begin{cases} \frac{-v_0+\sqrt{v_0^2+2a_{\text{dec}}d_0}}{a_{\text{dec}}} + t_{\text{pass}} & \text{if } v_0^2 + 2a_{\text{dec}}d_0 \geq 0 \\ \infty & \text{otherwise.} \end{cases} \tag{4}$$

$t_{\text{pass}}$ depends on the length of the vehicle $l_{\text{vehicle}}$, the lane width $w_{\text{lane}}$, and the vehicle speed $v_{\text{pass}}$ when entering the intersection. For the sake of simplicity we assume that $v_{\text{pass}}$ is constant, and that each vehicle takes a maximum of 5 s to cross[1]:

$$t_{\text{pass}} = \min\left(\frac{l_{\text{vehicle}} + w_{\text{lane}}}{v_{\text{pass}}}, 5\,\text{s}\right). \tag{5}$$

We can calculate this interval for each car at any given time. Assuming we have two cars approaching the intersection, their time intervals are denoted as $\mathcal{I}_1$ and $\mathcal{I}_2$. The earliest time $t_c$ a crash can happen is then

$$t_c = \min\left(\mathcal{I}_1 \cap \mathcal{I}_2\right). \tag{6}$$

A graphical example is shown in Figure 2. At time $t = 0$, the first vehicle has a distance $d_0$ from the intersection. By accelerating at a constant rate of $a_{\text{acc}}$, it follows the solid blue trajectory on the left, crossing the intersection at time $t_{\text{min}}$. By constantly decelerating at $a_{\text{dec}}$, instead, it leaves the intersection at time $t_{\text{max}}$. Since the vehicle is not able to stop before the intersection, $t_{\text{max}}$ exists and hence $t_{\text{brake}} > t_{\text{max}}$. The dotted red lines represent how the second vehicle might approach the intersection. The two vehicles can collide in the overlapping interval $\mathcal{I}_1 \cap \mathcal{I}_2$.

### B. *Risk Classification*

By analyzing the intervals $\mathcal{I}_1$ and $\mathcal{I}_2$ of two approaching vehicles, we can classify situations at any point in time during an intersection approach. We define four classes in order to categorize the severity of the intersection approaches: NO-CRASH, SAFE, ATTENTION, and CRITICAL.

If both vehicles can stop before the intersection (meaning that $t_{\text{max}}$ is undefined for both) we consider the situation SAFE.

NO-CRASH represents situations when no collision can happen at all, meaning that the two intervals $\mathcal{I}_1$ and $\mathcal{I}_2$ do not overlap. Note that NO-CRASH implies that at least one of the two vehicles is already so close to the intersection that it cannot stop before the intersection anymore. Thus, from the vehicles dynamics point of view this situation is very different from SAFE, where both $t_{\text{max}}$ are infinite.

If only one vehicle can stop and the intervals do overlap, we classify the situation as ATTENTION, meaning that there might be a crash, but it can still be avoided by braking one vehicle so that it comes to a complete stop before the intersection.

CRITICAL is used when none of the two can stop before reaching the intersection: in this case *crash avoidance strategies* may require coordination between the two vehicles, whereas *crash impact reduction strategies* might still react on their own to reduce the consequences of crashes if not avoid them.

## IV. INTEGRATION INTO SUMO

We used the road traffic simulator Simulation of Urban Mobility (SUMO), because it already provides a set of car following models including the Krauss model [21] and the Intelligent-Driver Model (IDM) [22]. We first investigated the applicability of these car following models as driver models for intersection approaches. However, all of the implemented models do not consider the possibility of collisions between vehicles, i.e., they are designed to be *collision free*. We therefore extended SUMO to support driving situations which in reality would result in a crash. Finally, we implemented a crash detection scheme and CAM exchange protocol within the Veins[2] vehicular networking simulation framework [23].

### A. *Driver Model*

The car-following models of SUMO are primarily designed for medium to large scale simulations, but can be used to reproduce drivers' behavior when approaching an intersection.

Of course, they have different characteristics and generate different mobility patterns, which, however, might not be always realistic on a local scale. We therefore compared the Krauss and the IDM models with the real world measurements shown

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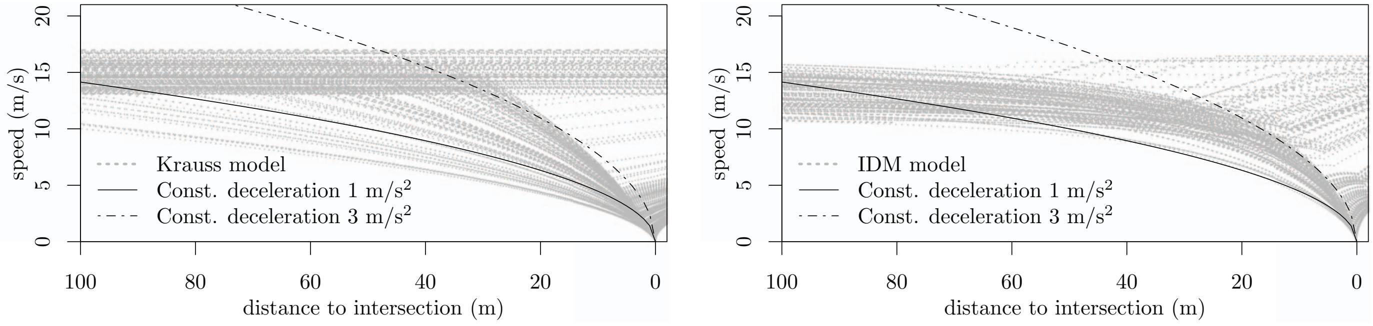
[1] These simple sanity checks are needed in simulations to avoid 'pathologic' situations that do not happen in reality, like a car entering an intersection at a speed so low as to engage it for minutes as the driver model in the simulator mandates to cross it at constant speed.

[2] http://veins.car2x.org/



(a) Krauss (b) IDM

Fig. 3. Different braking behaviors for Krauss and IDM car following models.

in [11, Fig. 4], by plotting the speed of the cars as a function of the distance to the intersection. For better readability, we added two theoretical curves showing the dynamics for constant deceleration values of $1\,\mathrm{m/s}^2$ and $3\,\mathrm{m/s}^2$.

The results show that, with the Krauss model, the cars approach the intersection at a constant speed and, at a certain point, suddenly start to slow down (cf. Fig. 3a). Moreover, cars with the right of way do not decelerate at all, as shown in the upper part of the plot. When comparing this behavior with the real-world measurements, we can conclude that Krauss, i.e., the default car following model used by SUMO, does not reproduce realistic behavior when approaching an intersection.

IDM shows very different behavior (cf. Fig. 3b): vehicles start to smoothly decelerate far from the intersection and then increase the deceleration rate as they move towards it. In addition, the plot shows that even drivers with the right of way decelerate somewhat and, if the intersection is free, re-accelerate to reach the desired speed. Since the pattern generated by IDM better resembles the measurements in [11], we used the IDM in our simulations.

### B. Crash-Enabled Road Traffic Simulator

To be able to simulate the behavior of drivers during an intersection approach that results in a crash, we had to enable SUMO to support collisions. We decided to modify SUMO in a way that we expect to be close to reality and human behavior: we enabled selected vehicles to ignore traffic rules. The adaptation of SUMO ensures that traffic offending vehicles continue driving towards the intersection as if they assumed they had the right of way. We checked the behavior of these traffic offending vehicles and found that they behave as expected. The other cars' behavior is not affected, i.e., their drivers' model ignores that some cars may not abide to rules. This may not cover all possible real behaviors and situations, but it is sufficient to study how CAMs disseminated by beacons impact predictability of possible crashes.

### C. Crash Detection in Network Simulator

We developed a crash detection module within the network simulation part of the Veins simulation framework, which governs simulation execution. This module reads precise vehicle dimensions from the road traffic simulation, as well as position and speed information. It can then detect collisions by checking for intersecting outlines similar to a *red and blue line segments* intersection problem, for which algorithms that run in $\mathcal{O}(n \log n)$ time have been proposed [24]. Because of this approach, the module can be extended in future work to also estimate the severity of crashes based on the relative speed and the point of contact. We also implemented a detector for 'almost crashed' situations by extending the outer shape of the cars with a safety boundary.

### D. Scenario Setup

We simulated a typical suburban X intersection where two roads cross each other without a traffic light. We only considered pair of cars that cross the intersection without turning. This reduces the possible different scenarios to four (buildings are not equal on the four corners, so cars coming from the different roads give rise to different propagation scenarios). Fig. 1 shows the precise geometry of the intersection, showing the lane width $w_{\text{lane}} = 3.15\,\mathrm{m}$ and how it relates to the position of parked cars: Austrian law mandates a minimum distance of $5\,\mathrm{m}$ to the intersection. We add an additional $1.5\,\mathrm{m}$ to account for the fact that vehicles will not have their antennas placed at the very back or front of the car, but somewhere on the roof. The resulting $6.5\,\mathrm{m}$ represent a reasonably favourable case, allowing to illustrate the benefits of relaying when using parked cars. Fig. 4 shows a perspective view of the intersection and illustrates how vision and radio signals get obstructed by buildings, which are placed according to OpenStreetMap geodata.

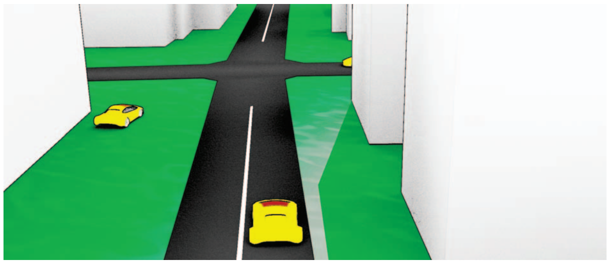
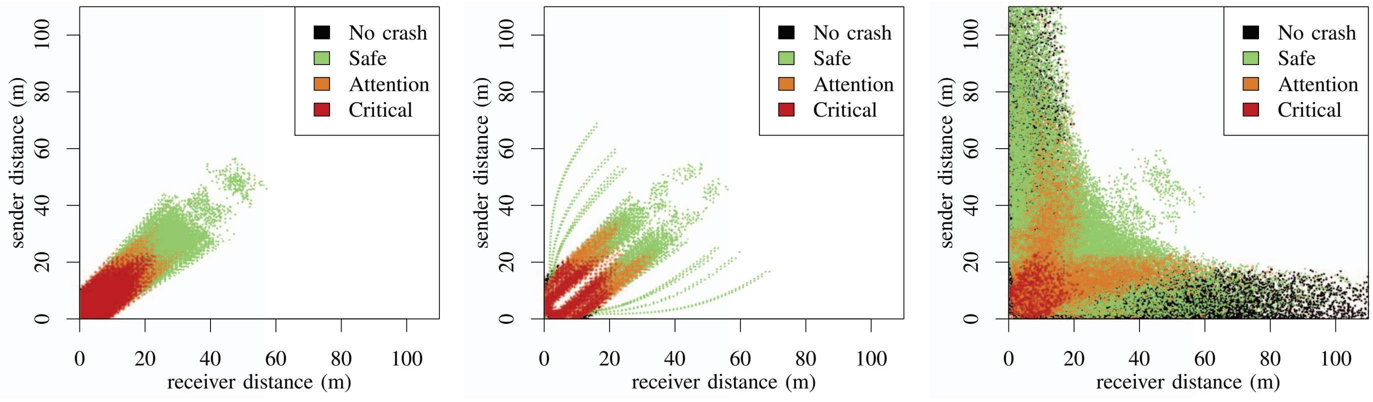


Fig. 4. Perspective view of the simulated X intersection.



(a) Crashed situations

(b) Almost crashed situations

(c) No crashed situations

Fig. 5. Classification of received beacon based on the sender and receiver distance from the intersection subdivided by intersect situations.

We randomly selected $50\,\%$ of the vehicles to ignore traffic rules to increase the rate of dangerous situations. To simulate different intersection approaches we let the cars enter the simulation at the same distance from the intersection and at the same time, but randomly distribute their initial speeds. In addition, we varied the IDM parameters maximum speed, desired deceleration, and maximum acceleration per vehicle according to Table I, in order to resemble different driver behaviors during the intersection approach. To better isolate the vehicles' behavior, we ensured that only two vehicles approach the intersection at the same time and can influence each other. The distributions of maximum speed, desired deceleration, and maximum acceleration are summarized in Table I. For each parameter set (different beacon interval and choice of relaying) we simulated 5000 different intersection approaches.

For simulating 'crashed', 'almost crashed', and 'not crashed' situations, we used our modified SUMO version for generating the vehicles' mobility. IVC was simulated using OMNeT++ and the MiXiM framework [25] with an IEEE 802.11p Model [26] and a model for realistic radio shadowing by buildings [27]. Relevant parameters of the models are summarized in Table I.

| Parameter | Value |
|---|---|
| Building wall attenuation $\beta$ | $9\,\mathrm{dB}$ |
| Building internal attenuation $\gamma$ | $0.4\,\mathrm{dB/m}$ |
| Frequency | $5.89\,\mathrm{GHz}$ |
| Channel width | $10\,\mathrm{MHz}$ |
| Tx rate | $18\,\mathrm{Mbit/s}$ |
| Tx power | $20\,\mathrm{mW}$ |
| Sensitivity | $-94\,\mathrm{dBm}$ |
| $\mathrm{CW}_{\mathrm{min}}$, $\mathrm{CW}_{\mathrm{max}}$ | 3, 7 |
| AIFSN | 2 |
| Maximum speed | $\sim\mathcal{N}(13.89, 2.92)\,\mathrm{m/s}$ [12, Tab. IV] |
| Maximum acceleration | $2.1\,\mathrm{m/s^2}$ |
| Desired deceleration | $\sim\mathcal{N}(3.47, 2.76)\,\mathrm{m/s^2}$ [12, Tab. IV] |

TABLE I
PHY, MAC, AND IDM PARAMETERS.

## V. INVESTIGATION OF WARNING MESSAGES

In the following, we show selected results from the extensive set of simulations we described. For each intersection crossing (two vehicles driving toward the intersection and leaving the intersection area – or crashing), we observed the final outcome at the intersection: Out of all simulated intersection approaches $3.7\,\%$ resulted in a crash, $1.6\,\%$ in almost crashes, and $94.7\,\%$ in no crash. During the approach, we classify the received beacons into warning levels using the classification presented in Section III. Note that we do not influence the behavior of the vehicles, as our key focus is on assessing the possibilities arising from the use of beaconing based approaches. To treat the vehicles' behavior as truly unknown, we decided to use $a_{\text{acc}} = 2.5\,\mathrm{m/s^2}$ and $a_{\text{dec}} = -5\,\mathrm{m/s^2}$ as conservative parameters for calculating the intervals $\mathcal{I}_1$ and $\mathcal{I}_2$[3]. We first validate our severity classification based on the X intersection scenario without relaying also investigating the impact of the beacon interval. We conclude this section with an analysis of the advantage of message relaying using a parked vehicle.

### A. *Validation of Risk Classification*

For understanding the impact of the classification, we plotted in Fig. 5 the class of all received beacons by sender and receiver distance. To validate the intended behavior of the classification, we split by the situation at the intersection (not crashed, almost crashed, crashed). For better readability, we draw on the plots first the NO-CRASH points, followed by SAFE, ATTENTION, and CRITICAL.

Fig. 5a shows all beacons that have been received while approaching the intersection for those cases where the two vehicles finally crashed at the intersection. It can be seen that beacons get classified as SAFE until a distance of approximately $30\,\mathrm{m}$, i.e., no action by the safety system is needed. Furthermore, we see that most of the beacons received closer than $30\,\mathrm{m}$ to the intersection are classified

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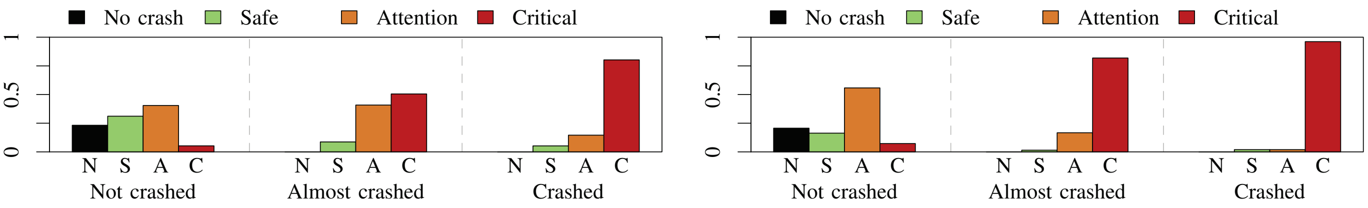
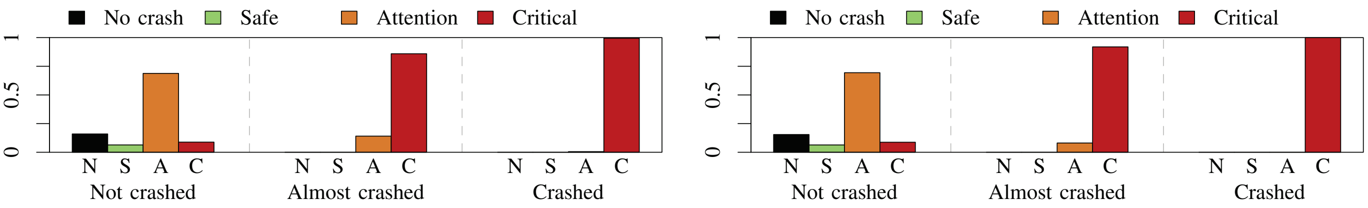
[3] We also performed the same set of simulations with a much higher deceleration rate of $a_{\text{dec}} = -7.5\,\mathrm{m/s^2}$. Aside from shorter distances at which an approach is classified as critical, the results are similar and are not shown.



(a) Beacon interval 1.0 s

(b) Beacon interval 0.5 s



(c) Beacon interval 0.1 s

(d) Beacon interval 0.04 s

Fig. 6. Worst case classification of beacons during single intersection approaches.

as ATTENTION. This boundary is not sharp, because we are also taking situations into account in which the vehicles have different speeds at their position. Finally, all beacons received closer than approximately 20 m are classified as CRITICAL. No beacon at all gets classified as NO-CRASH.

Fig. 5b summarizes all intersection approaches where a crash has almost occurred, i.e., taking the 1 m safety guard into consideration. It is obvious that most of the real 'crashed' situations are located on the diagonal and 'almost crashed' situations are close to the diagonal but directly not on it. This fact becomes even more clear when having a look at the CRITICAL class. No beacon on the diagonal is classified as such until vehicles get very close to the intersection.

Finally, Fig. 5c depicts all other intersection approaches. Here, the effect of the building shadowing model can be noticed: We can see partial communication possibilities when both cars are roughly 50 m away from the intersection. Vehicles can communicate more frequently when at least one of the two is close to the intersection (as shown by the two sets of beacons close to the axis, but further away than 50 m) and nearly never when they are both far from the crossing. More interestingly from the point of classification, we see that, although the amount of data underlying this plot is huge, only a very small portion of beacons is classified as ATTENTION and even less as CRITICAL. Additionally, a huge number of beacons get categorized as NO-CRASH, but they are not that visible in the plot because more critical messages are plotted on top of less critical ones.

### B. Influence of the Beacon Interval

So far, we investigated the classification on a per-beacon basis, i.e., how each beacon is categorized depending on the distance and speed at which it has been sent and received. For understanding the impact of different beacon intervals, we now concentrate on how each intersection approach as a whole gets classified and present two different perspectives or possible event classification. Fig. 6 shows the 'worst' categorization that each vehicle has assigned to at least one of the beacons received during the intersection approach. Results are shown for different beaconing intervals, again split by the situation at the intersection.

Let us first concentrate on the intersection approaches which resulted in a crash. It can be seen that the lower the beacon interval is, the better the worst case classification gets. For a beacon interval of 1.0 s more than 20 % of cars never classify the situation as CRITICAL. Reducing the beacon to 0.5 s, the fraction of misclassification already drops to 5 %, while reducing the interval to 0.1 s and 0.04 s quickly guarantees a 100 % correct classification rate. The same observations hold for the 'almost crashed' approaches.

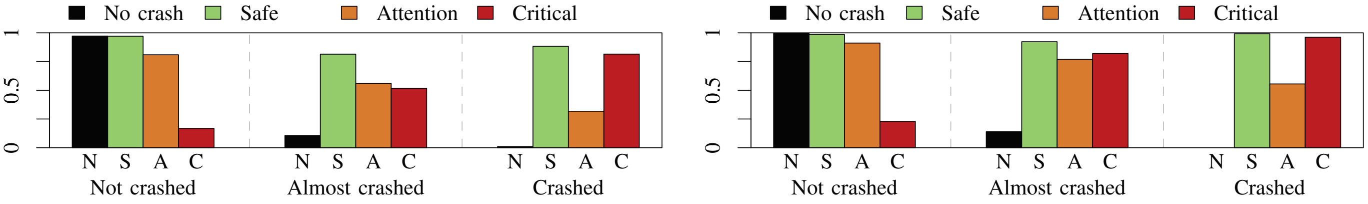
Using a beacon interval of 1.0 s the delay between two consecutive beacons is too large to correctly identify some of the dangerous situations. This fact demonstrates the need of beacon intervals lower than 0.5 s for any kind of VANET intersection application.

In no crash intersection approaches, we see that independently of the beacon interval only a marginal proportion of beacons is classified as CRITICAL; however, the majority of situations have at least once been identified as ATTENTION, which is a level of false positives probably too high.

A different perspective of the classification is shown in Fig. 7. For each warning level (NO-CRASH, SAFE, ATTENTION, and CRITICAL), we plot the percentage of approaches during which the level was triggered at least once.

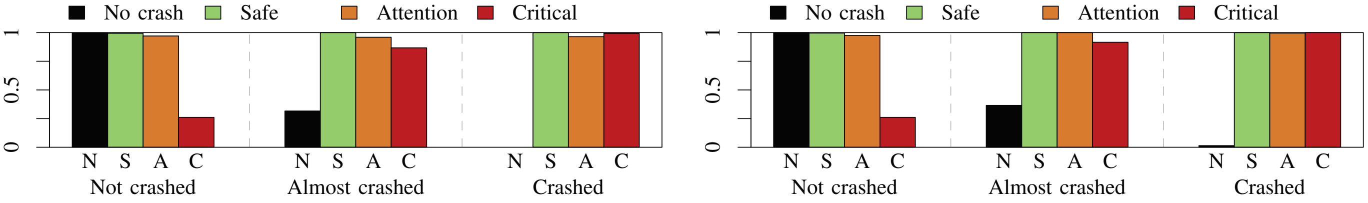
The majority of approaches trigger all warning levels, showing that beacons were received at different points of the approach. Two notable exceptions are very few recorded instances of CRITICAL in approaches that did not end in a collision and, vice versa, of NO-CRASH in approaches that did result in one.

Focusing on Fig. 7a, which shows results recorded for a beacon interval of 1 s, it is clear that the levels of awareness arisen is hardly acceptable. While none of the approaches that ultimately ended in a collision were ever misclassified as NO-



(a) Single hop, Beacon interval 1 s

(b) Single hop, Beacon interval 0.5 s



(c) Single hop, Beacon interval 0.1 s

(d) Single hop, Beacon interval 0.04 s

Fig. 7. Rate of approaches during which a certain warning level was triggered. Plotted for all investigated beacon intervals.

CRASH, more than 10 % never triggered SAFE (approaching vehicle detected, both vehicles can still stop before entering the intersection). It was only much later that either ATTENTION (approaching vehicle detected and only one of the vehicles can still stop before entering the intersection) or CRITICAL (neither can stop) was suddenly triggered. Even more interesting is that in less than 30 % of approaches ATTENTION was triggered: this means that a warning arrives only when it is really difficult to avoid the crash, as the two vehicles must act with coordination, one braking and the other accelerating.

### *C. Impact of Relaying*

As described before, we use a vehicle parked close to the intersection as a relay. The full derivation of an optimal relaying protocol is beyond the scope of this paper. In the context of the small scale scenarios considered in this investigation it suffices to configure parking vehicles to relay all beacon messages.

As shown in Fig. 8, enabling relaying by parked vehicles leads to 100 % of the vehicles receiving messages also during the time window when messages are still classified as SAFE. With beacons spaces 1 s apart, however, even the relay cannot help closing the gap between SAFE and CRITICAL. Results with smaller beacons interval (not shown for lack of space) confirm that beaconing with intervals smaller than 0.1 s and relay lead to smooth transitions between SAFE and CRITICAL beacon classifications. The use of relays clearly increases cooperative awareness of all vehicles. This observation is in line with findings presented in [17].

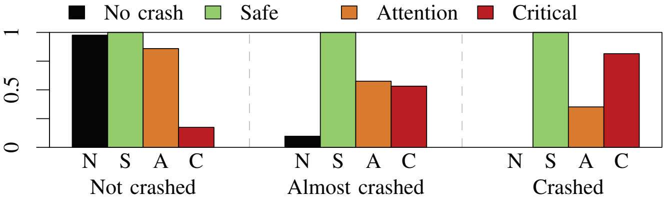


Fig. 8. Rate of approaches during which a certain warning level was triggered for relaying with a beacon interval of 1 s.

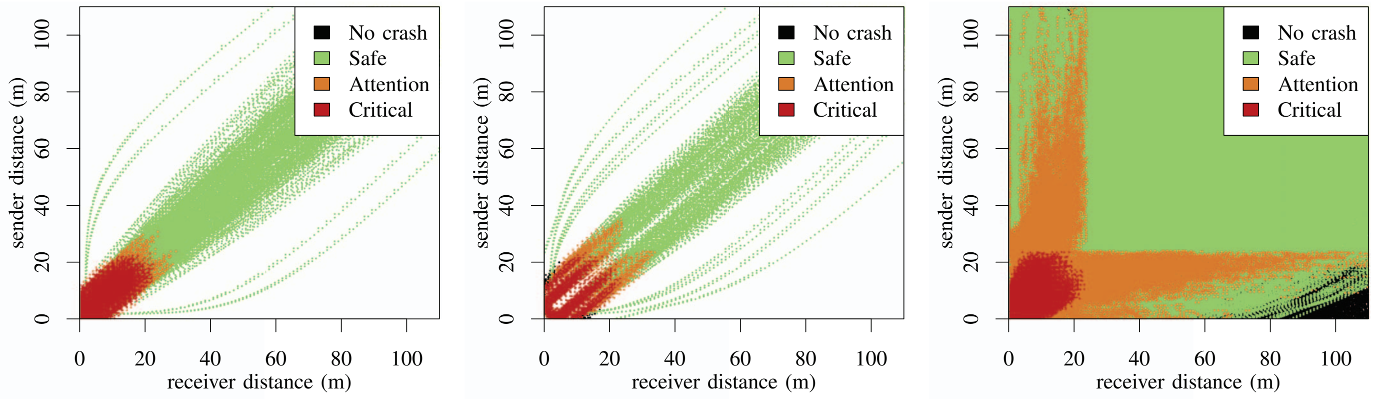
The detailed study of relaying as well as the sensitivity to the beaconing interval and proposals for dynamic beacon rate adaptation is a very promising future line of research.

Relaying can thus become a very important factor for ICWS since it enables the vehicles to trace the movements of others much earlier than they could do otherwise. Fig. 9 shows the classification of every received beacon based on the received and own trajectory when a relaying car is parked at the intersection. We see that in 'crashed' and 'almost crashed' situations the single approaches can get traced much further away. Naturally, we receive beacons at any combination of sender/receiver distance also for 'not crashed' situations and the majority gets classified as SAFE. With this early additional information, future ICWS might be able to predict really dangerous situations quite well and, hopefully, avoid false positive warnings in most cases.

## VI. CONCLUSION

This paper has presented and made available to the community an integrated mobility and networking simulator, which empowers the study of collisions and collision avoidance techniques at road intersections.

Based on this simulation tool, we have investigated some fundamental properties of beacon-based warning messages in a realistic X intersection including buildings derived from suburban Innsbruck. These preliminary results give two different and somewhat contradicting indications: on the one hand, especially when beacons can be relayed, e.g., by parked cars, they are efficiently received and can be the base for early warning or collision avoidance systems; on the other hand, a simple classification of potentially dangerous situations lead to a fairly high false warning rate, which can be annoying to drivers. However, we have only studied a simple classification in the absence of effective warning to drivers, so that further studies and better motion prediction models can surely lead



(a) Crashed situations

(b) Almost crashed situations

(c) Not crashed situations

Fig. 9. Classification of every received beacon including relayed beacons based on the received and own trajectory; subdivided by the resulting intersection situation.

to effective early warning systems and also lay the ground for automatic collision avoidance systems. To our knowledge this work, for the first time, puts together the simulation of mobility, propagation with obstructions, protocols, and the evaluation of safety, leveraging simple yet effective models of vehicles' dynamics together with detailed packet level simulations.

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