Fairness Kills Safety: A Comparative Study for Intersection Assistance Applications

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***Abstract*—We study the ability of Inter-Vehicle Communication (IVC) solutions to handle real-time requirements in safety scenarios using beaconing as a communication primitive. One of the envisioned safety applications is intersection assistance. The objective of such applications is to either warn the driver or even to act autonomously if other approaching vehicles endanger the vehicle. Fairness, combined with aggressive channel access for low-latency safety messages, has been one of the main research line according to which state of the art congestion control mechanisms have been developed. We show that these solutions are not able to sufficiently support intersection assistance applications. Specifically, we show that current approaches fail exactly due to their fairness postulation. We propose a new situation-aware solution to this fairness dilemma by allowing temporary exceptions for vehicles in dangerous situations. We show the applicability for two state of the art congestion control mechanisms, namely ETSI Transmit Rate Control (TRC) and Dynamic Beaconing (DynB). Our investigation also reveals important research objectives for future IVC protocols, namely how much reactivity and situation-awareness is needed in the highly dynamic environment of vehicular networks.**

I. Introduction

A major achievement in Inter-Vehicle Communication (IVC) research [1] was the standardization of physical layer as well as medium access mechanisms for Dedicated Short-Range Communication (DSRC) in the IEEE 802.11p standard [2]. Beaconing based protocols including the ETSI ITS-G5 Decentralized Congestion Control (DCC) standard build on top of this standard, and researchers are investigating beacon-based safety applications on top of this technology [3]–[6].

Safety applications are diverse and range from rear-end collision avoidance to complex situations like overtaking or intersection coordination. We concentrate on intersection assistance applications as a major portion of road accidents happen at intersections. The focus of this work is on communications for intersection collision prevention.

In this research line, Le et al. [7] investigated the busy time fraction of DSRC for intersection assistance applications. They used a fixed unit-disk communication range, which leaves open questions regarding channel utilization. A detailed study on communication requirements for crash avoidance applications has been published by Haas and Hu [8]. They changed collision-free vehicle traces by artificially injecting collisions with constant velocity to evaluate their protocol for crash mitigation. However, simplifying assumptions like not considering low speed collisions ($< 7\,\mathrm{m/s}$) limit its contribution for intersection safety applications. In a previous work [9], we investigated intersection applications with safety metrics and also considered shadowing effects of Non Line of Sight (NLOS) communication. We compared static beaconing approaches and showed the necessity for high beacon rates of at least 2 Hz, which is also the minimum for current automated intersection collision avoidance systems [10]. In this paper, we investigate the applicability of dynamic beaconing approaches.

ETSI has proposed the use of Cooperative Awareness Messages (CAMs) as a basis for all envisioned safety applications, similar to the concept of Basic Safety Messages (BSMs). The terms CAM and beacon are used interchangeably in this paper. Recent studies [4]–[6] have also shown that static beaconing may congest the channel. Thus, vehicular networks strongly need channel congestion control, which can be achieved by different mechanisms: transmit power control, encoding (bit rate), and transmit rate control. The current ETSI ITS G5 DCC standard uses all three techniques [3]. Regarding safety applications, it has been shown that even in slowly changing environments it is advantageous to use a fixed transmit power level which is dependent on the vehicle density [5]. Since intersection assistance applications have to deal with a very challenging and rapidly changing NLOS wireless channel, the vehicle density is hard to predict. Therefore, we assume for the rest of the paper that the highest allowed transmission power and a robust encoding, i.e., a low bitrate, are used. The remaining possibility is to adapt the transmit rate.

We rely on two competitive approaches for rate adaptation, the ETSI ITS G5 DCC standard and in particular its Transmit Rate Control (TRC) mechanism, as well as the very reactive protocol Dynamic Beaconing (DynB) [4]. Both approaches succeed in their main objective: keeping the channel use and packet collision probability below a given threshold. Further, they also work towards giving fair access chances to all nodes. TRC and DynB also support safety applications but still provide the same service for all vehicles without being able to take situation specific constraints into account.

One immediately emerging idea to tackle this problem might be to use higher-priority Access Categories (AC) for the purpose

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of prioritizing CAMs. Yet, this would improve the situation for safety applications only slightly, because CAMs would still be subject to rate reduction by congestion control mechanisms. We claim that for safety applications this approach is not sufficient as it might result in situations where two endangered vehicles are not able to exchange sufficient information for their safety applications.

Other proposals include ideas to outright disable congestion control mechanisms for safety messages. This mechanism can be beneficial for event triggered safety messages, however, it is inapplicable to safety applications that are continuously operated, as is the case for intersection assistance applications.

In this paper, we propose a *situation-based rate adaptation* scheme that allows temporary exceptions for endangered vehicles to use more than the equal fair share of the channel.

Our key contributions can be summarized as follows:

- Based on a study of current congestion control methods in intersection scenarios, we propose a novel *situation-based rate adaptation* (Section III).
- We study the feasibility and implications on safety applications of the proposal for two different congestion control mechanisms, namely TRC and DynB (Section V).
- We conclude the paper identifying important research directions for future congestion control mechanisms (Section VI).

II. Fundamentals

In the following, we briefly describe the two information dissemination protocols TRC and DynB; we outline how intersection collisions are simulated, and introduce the intersection collision probability $\mathcal{P}_C$, which can be used to estimate how "dangerous" a situation is.

A. Transmit Rate Control

The TRC algorithm, which is part of the ETSI ITS-G5 DCC standard [3], adapts the beacon interval I based on the congestion level of the wireless channel. The congestion is estimated by sampling the channel busy ratio b_t, i.e., the ratio of time where the channel is sensed busy; b_t is computed over a time window T_m and used by TRC to switch between states (that reflect the current congestion level) and adjust the beacon interval.

Within TRC, state transitions to a more relaxed state, i.e., a state with shorter I, are triggered if all observations of the busy ratio are smaller than b_min for a period of T_down. Similarly, transitions to more restricted states are triggered if all observations exceeded b_max for T_up: T_up and T_down are time windows that allow for different adaptation speeds towards more restricted and more relaxed states.

B. Dynamic Beaconing

In certain situations, TRC is not able to adapt to the channel conditions rapidly enough. The reason is that the adaptation is delayed by the time windows T_up and T_down that are used to avoid state oscillations. DynB [4] acts more aggressively by continuously adapting the beacon interval I. DynB sets a desired beacon interval I_des that is used as long as the channel busy ratio b_t does not exceed a desired level b_des. If b_t rises above this level, I is adapted to keep the channel at b_des, where b_des is set to a congestion level that balances throughput and the number of collisions. Since the channel load is determined by I and the number of hosts competing for channel access, DynB also has to take the number of neighbors N, i.e., vehicles in communication range, into account and computes I as $I = I_\text{des}\,(1 + rN)$ with $r = b_t/b_\text{des} - 1$ clipped to the interval $[0, 1]$.

C. Modeling Intersection Approaches

In the previous works [9], [11], we simulated intersection crashes by randomly selecting vehicles that disregard traffic rules. To evaluate communication aspects of intersection assistance applications, we used the Veins simulation framework [12] which bidirectionally couples the road traffic simulator SUMO and the network simulator OMNeT++. By checking for collisions of vehicles, intersection approaches can be classified in three classes: Crash, Near Crash, and No Crash. Near Crash refers to situations where the vehicles violated their safety boundary of 0.4 m, but did not crash.

To analyze intersection assistance applications in an exhaustive manner, we implemented an intersection approach model that is parameterized by the aggressiveness and discipline of the driver as proposed in [13]. This allows the simulation of arbitrary intersection approaches: Crash situations with different speeds and acceleration/deceleration behaviors (via disabling right-of-way rules in SUMO) can thus be analyzed. A wider range of intersection collision situations can be simulated, but most of all, being able to pick random driver behaviors that result in a Crash or Near Crash, we are able to simulate almost only "dangerous" situations, speeding up the evaluation. When studying the effects of crowded IVC channels, the simulation time becomes a limiting factor.

We only focus on vehicles approaching the intersection and crossing it without turning, and we guarantee that only two vehicles at a time are approaching the intersection for the sake of results interpretation, and we do not modify the behavior of vehicles based on communications. The key parameters for simulating the vehicle dynamics are summarized in Table I.

D. Intersection Collision Probability

To be able to decide whether a vehicle approaching an intersection is in a dangerous situation, adequate metrics are needed. We rely on an *intersection collision probability*, which

TABLE I
Road traffic simulation parameters.

Parameter	Value
Maximum speed v_max [14, Tab. IV]	~$N(13.89, 2.92)$ m/s
Crossing speed v_cross	~$U(3, 12)$m/s
Maximum acceleration a_max	2.1 m/s^2
Desired deceleration a_des [14, Tab. IV]	~$N(3.47, 2.76)$ m/s^2
Maximum deceleration a_min [15]	9.55 m/s^2
Driver Aggression potential	~$U(10, 90)$%
Driver Discipline	~$U(10, 90)$%
Safety boundary for Near Crash	0.4 m

provides a suitable measure given an arbitrary driver behavior model [11]. The idea is that a vehicle can calculate the collision probability with a possible crash candidate based on its own position and speed every time it receives a beacon message (with position and speed) from the other vehicle.

More formally, two potentially colliding vehicles A and B have a distance d_A and d_B from the intercept of their trajectories, a current speed v_A, v_B, and maximum deceleration a_{min} and acceleration a_{max}. The collision probability $\mathcal{P}_C$ can be calculated by considering all possible future trajectories with constant acceleration of both vehicles by integrating over the interval $[a_{\text{min}}, a_{\text{max}}]$:

$$\mathcal{P}_C = \int_{a_{\text{min}}}^{a_{\text{max}}} p(a_B) \int_{a_{\text{min}}}^{a_{\text{max}}} p(a_A)\,\text{coll}\left(\begin{bmatrix} a_A \\ v_A \\ d_A \end{bmatrix}, \begin{bmatrix} a_B \\ v_B \\ d_B \end{bmatrix} \right) \mathrm{d}a_A \, \mathrm{d}a_B. \tag{1}$$

The key element of this calculation is the function coll (), which uses distance, speed and acceleration of both vehicles as input to determine whether two given trajectories will result in a crash or not; returning 0 for NO CRASH and 1 for CRASH. The likelihood of single trajectories are weighted by the acceleration probability distributions $p(a_A)$ and $p(a_B)$ and the overall collision probability can be calculated.

Two different types of distributions for $p(a)$ have been proposed and validated in [11]: a *uniform* distribution for validation and easy computation purposes and a *triangular* distribution resembling more realistic driver behavior. In this work, we use the *triangular* distribution, because the calculated collision probability better reflects a realistic driver behavior. In addition to the acceleration limits (a_{min} and a_{max}), the triangular distribution needs the current acceleration of the vehicle (a_{cur}). Using a_{min} as lower limit, a_{cur} as mode and a_{max} as upper limit, the probability of a given acceleration between a_{min} and a_{max} can be calculated.

III. SITUATION-BASED RATE ADAPTATION

To circumvent communication blackout periods in critical situations at intersections, as they might occur with current congestion control protocols, we propose to use a *situation-based rate adaptation*. This rate adaptation makes use of the intersection collision probability and can be added to any congestion control mechanism.

Let's start with a closer view on the collision probability in realistic scenarios. Figure 1 shows the evolution of the collision probability for intersection approaches that finally resulted in a CRASH. To get a better understanding of the evolution, we used the *time to crash* on the x-axis. The time to crash has been post-calculated for received CAMs when a crash happened. It can be seen that the collision probability during an intersection approach does not rise linearly in time.

To understand the evolution of the intersection collision probability, Figure 2 plots the change of the collision probability (step size) compared to the preceding CAM as a function of the collision probability for a fixed beacon rate of 5 Hz. The step

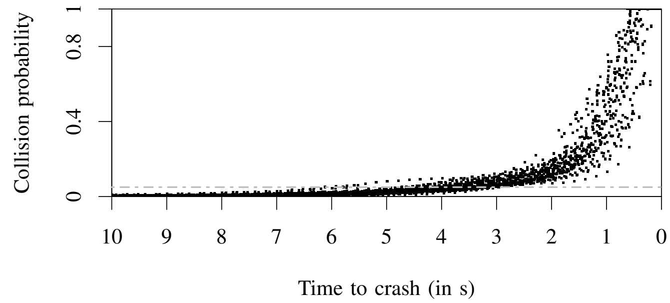

Fig. 1. Evolution of the collision probability for various intersection approaches which finally resulted in a CRASH for a beacon rate of 5 Hz.

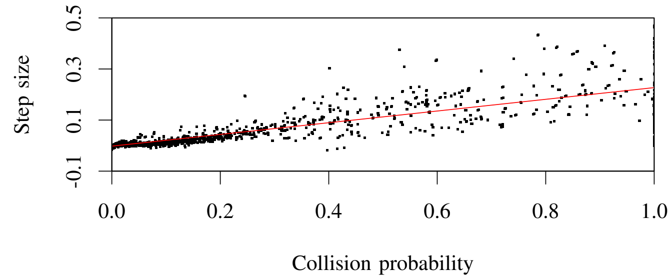

Fig. 2. Relationship of the change of the collision probability *step size* to the preceding CAM (plotted on the y-axis) and the collision probability (on the x-axis) for a beacon rate of 5 Hz and CRASH approaches.

size is dependent on the collision probability, which explains why, and how the evolution of the collision probability in Figure 1 is non linear. The red line in Figure 2 shows that there is a linear correlation between the step size and the collision probability, albeit with a large dispersion. Therefore, we suggest to use a *linear adaptation* of the information dissemination rate to compensate this effect.

This novel adaptation algorithm can be used in conjunction with any other congestion control mechanism and it overrides the information dissemination rate when a certain threshold $\mathcal{P}_{\text{th}}$ on the collision probability is exceeded. When no CAMs are received within the last beacon interval, each vehicle computes a *"self collision probability"* $\mathcal{P}_{\text{self}}$ assuming there is a vehicle driving at the same speed and having the same distance to the potential collision point.

In detail, the situation-based rate adaptation works as follows (we denote the minimum and maximum beacon rate by r_{min} and r_{max}, respectively):

1) When a vehicle receives a CAM, it calculates the current collision probability ($\mathcal{P}_{\text{cur}}$) based on its own current data and the data contained in the CAM.
2) If the current intersection collision probability $\mathcal{P}_{\text{cur}}$ exceeds the threshold $\mathcal{P}_{\text{th}}$, the current CAM dissemination rate (r_{ccm}) is adapted accordingly. The adapted rate is set to the maximum between the current dissemination rate (as computed by DynB or TRC), the minimum admissible rate, and the situation-based adapted rate:

$$r_{\text{adapted}} = \max(r_{\text{ccm}}, r_{\text{min}}, \mathcal{P}_{\text{cur}}\, r_{\text{max}}); \tag{2}$$

TABLE II
GENERAL NETWORK AND CONGESTION CONTROL PROTOCOL PARAMETERS

	Parameter	Value
PHY & MAC	Path loss model	Free space ($\alpha = 2.0$)
	PHY model	IEEE 802.11p
	MAC model	IEEE 1609.4 single channel (CCH)
	Frequency	5.89 GHz
	Bitrate	6 Mbit/s (QPSK R = 1/2)
	Access category	AC_VO
	MSDU size	193 B
	Transmit power	30 dBm
TRC	I_{min}, I_{def}, I_{max}	0.04 s, 0.5 s, 1 s
	b_{min}, b_{max}	0.15, 0.40
	T_{M}, T_{DCC}, T_{up}, T_{down}	1 s, 1 s, 1 s, 5 s
DynB	I_{des}	0.04 s
	b_{des}	0.25
	Adaptation r_{min} ,r_{max}	5 Hz, 100 Hz

3) When no CAM has been received during the last beacon interval, the rate gets adapted based on the *self collision probability* by substituting $\mathcal{P}_{\text{cur}}$ with $\mathcal{P}_{\text{self}}$ in Equation (2).
4) When $\mathcal{P}_{\text{cur}} < \mathcal{P}_{\text{th}}$, the current dissemination rate of the congestion control mechanism r_{ccm} is used.

For intersection assistance applications it is of the utmost importance to have reliable and continuous communications for a certain time before the potential crash. In Figure 1, it can be seen that 5 s before the potential crash, most of the approaches did not yet exceed a threshold of 5 % (indicated by the dashed grey line). For this reason, we set the threshold $\mathcal{P}_{\text{th}}$ to 5 % to evaluate the effects of our new adaptation scheme.

IV. SIMULATION MODEL AND SETUP

To analyze the effectiveness of the situation-based rate adaptation, we used the Veins simulation framework[1] mentioned before. We summarize the used PHY and MAC models and their parameters as well as the TRC and DynB configuration in Table II. According to the ETSI recommendation, we modified the queueing mechanism of the MAC to omit transmissions of outdated information so that, if a new CAM is generated before the previous one is sent, the old CAM is substituted with the new one.

A. Scenario Description

In the scenario we consider all vehicles in the vicinity of the intersection hear and hence interfere with each other (*single interference domain*) as shown in Figure 3. More precisely, we assume that there are no obstacles (e.g., buildings) in the Line of Sight (LOS) of any pair of vehicles and hence no shadowing effects need to be considered, and the freespace path loss model is adopted. The aim is to show important baseline properties of the situation-based rate adaptation: shadowing, fading and more complex NLOS situation would simply make results interpretation more cumbersome. Even if there is plain electromagnetic LOS drivers might still be unable to see other cars, and in any case dangerous situation arise also from distraction and other reasons, not only from blind crossings. Background traffic is generated by 15, 20, or 25 static sources placed in each road leading to the intersection at an average distance of 50m from the intersection center. In total we have 60, 80, or 100 equivalent interfering vehicles, but they do not interact with the cars under analysis from the road traffic point of view. Each simulation has been repeated using TRC and DynB with and without situation-based rate adaptation.

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

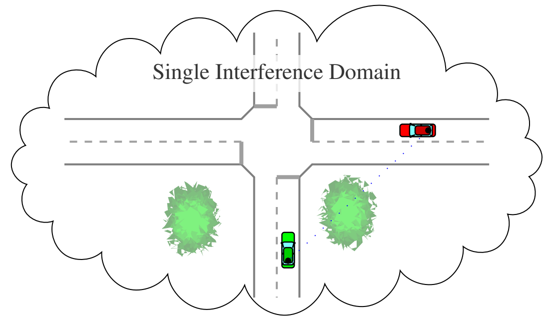

Fig. 3. Schematic overview of the considered scenario showing two approaching and communicating vehicles, that do not see each other yet. Vehicles causing network congestion are not shown.

B. Metrics

To evaluate IVC communication strategies for safety, usual network metrics like channel load, collisions, and update delay are not sufficient [11]. Therefore, we perform an update delay analysis which is specific for vehicular safety applications and takes the time to crash into account. Using a sequence number we can detect dropped and missed CAMs. All plots in the evaluation show only data points of intersection approaches that resulted in a CRASH (175 out of 250 simulated).

V. EVALUATION

A. Feasibility of Situation-Based Rate Adaptation

In Section III, we have proposed a linear adaptation of the information dissemination rate with the collision probability. To validate our proposed solution, we plot the change of the collision probability (*step size*) to the preceding beacon when our adaptation is in place (Figure 4). It can be seen that the situation-based rate adaptation successfully keeps the change

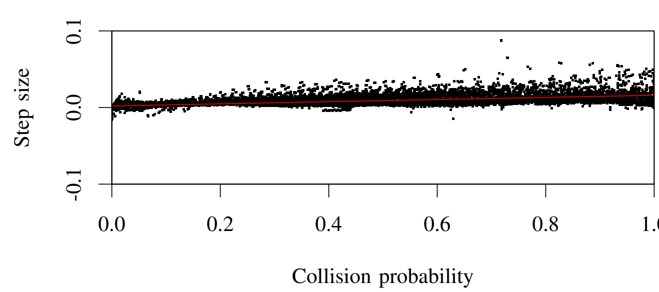

Fig. 4. The change of the collision probability *step size* to the preceding beacon (plotted on the y-axis) can be reasonable small and within constant range if the information dissemination rate is correctly adapted.

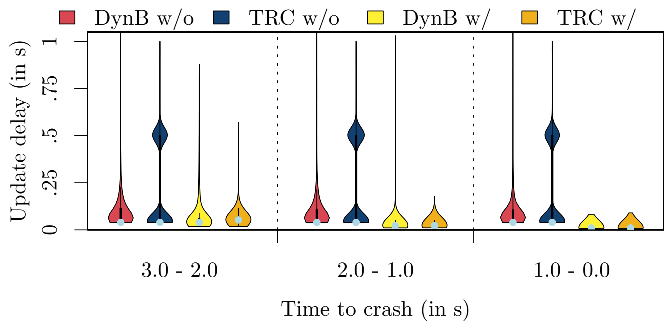

Fig. 5. Violin plot comparing DynB and TRC without and with adaptation, 60 vehicles causing background traffic.

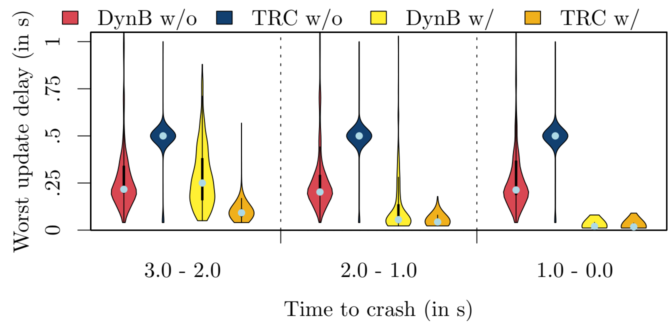

Fig. 6. Violin plot comparing the worst case update delay per bin for DynB and TRC without and with adaptation, 60 vehicles causing background traffic.

of the intersection collision probability in a small range during the overall intersection approach. Moreover, the red line, which shows the trend by using linear regression, is almost horizontal and very close to zero.

B. Initial Network Analysis

Let's now have a look at the general network performance using our adaptation scheme. Figure 5 plots the distribution of all update delays in three bins of 1 s each. We use violin plots, which not only show the 1st and 3rd quartile (by the thick black line) and the median (shown by a light blue dot), but also give insights on the distribution itself. The width of the violin is determined by a kernel density estimation and hence reflects the density of data points.

When looking at DynB and TRC without adaptation, we notice that the shape of the violin is almost identical in all three time to crash bins. For DynB the update delay is lower than 150 ms for more than 75 % of vehicles. One problem of DynB is evident by looking at the long tail, showing update delays greater than 1 s. Since DynB is designed to very aggressively adapt to a desired channel usage, long intervals can be calculated, leading to long update delays which are not acceptable for safety applications. Although TRC is able to provide the lowest possible update delay around 40 ms for half of the vehicles, a non marginal amount (25 %) is experiencing an update delay greater than 0.5 s.

Both congestion control mechanisms would be able to provide frequent updates (within 500 ms) for some endangered vehicles, but not for all. The situation gets worse when more vehicles compete for the channel usage (vehicle densities 80 and 100; data not shown). For example, when 100 vehicles want to access the same channel, DynB is still able to keep the update delay lower than 0.2 s for 75 % of messages, but for TRC more than 50 % of all CAMs have an update delay greater than 0.5 s.

When considering DynB and TRC with our novel adaptation system in place (cf. Figure 5), we find that the adaptation provides benefits to both protocols. However, when comparing the tails of the violins it can be seen that TRC is able to adapt faster to the dedicated small update delays. This is more evident in the second bin: DynB has still a very long tail. In the timespan shortly before the crash (bin from 0 s to 1 s) both protocols are equally successful.

To understand why the situation-based rate adaptation works slightly better for TRC than for DynB, we need to look at the two congestion control mechanisms in detail. As explained before, DynB always opts for the desired channel busy ratio which in our case has been set to 25 %. Since DynB is very reactive and hence aggressive in using all the available channel capacity it might happen that although a vehicle has a very low beacon interval (in our case adjusted by the situation-based rate adaptation) CAM transmissions get deferred due to channel occupation of other vehicles. On the other hand TRC adapts the beacon interval much slower, because it uses fixed time windows (> 1 s) to monitor the channel and different thresholds for state transitions. Therefore, the channel load fluctuates (cf. [4]) and hence the adaptation is more likely to hit a timespan where it is possible to transmit a CAM.

C. Implications on Safety

The initial network analysis focused on the distribution of the update delay. To study the implication on safety, we now present a different view on the update delays in the different time to crash bins by showing the distribution of the worst case update delay in each bin per vehicle.

Figure 6 shows the distribution of the worst case update delay using the same bins as before. The first difference can be seen for DynB without adaptation, which shows the median for this worst case update delay distribution around 0.2 s. For the TRC distribution, the median is above 0.5 s and, since there is no black box visible, more than 75 % of vehicles experience a worst case update delay greater 0.5 s. Obviously, the tails of DynB and TRC without adaptation remain, because they are part of this worst case update delay distribution. Looking at the worst case update delay distribution of the protocols w/ adaptation it can clearly be noticed how the adaptation works during CRASH intersection approaches. Figure 6 also clearly shows that the adaptation with DynB works way slower than with TRC (visible in bin 3 s to 2 s where DynB has a far-ranging distribution of worst case update delays, with the median still around 0.25 s).

To assess the safety of the vehicles, Figure 7 shows an eCDF of the timespan that vehicles spent in an unsafe state during their intersection approach for the last three seconds (time to crash < 3 s). We define a vehicle to be in an unsafe state

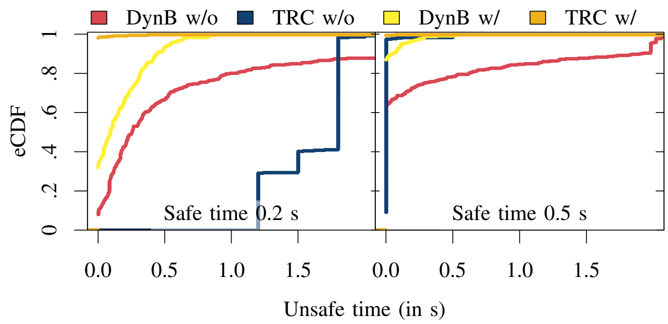

Fig. 7. eCDF showing the timespan that vehicles spent in an unsafe state, because of not receiving an update within the safe time, 60 vehicles experiment.

whenever it has not received an update for a specific pre-defined *safe time* t_{safe}. In our evaluation, we used $t_{\text{safe}} = \{0.5\,\text{s}, 0.2\,\text{s}\}$. The first value accounts for a reasonable update frequency of 2 Hz, which is needed for the automated collision avoidance controller designed in [10]. The second one is more restrictive, because it accounts for the reaction time of a human.

Let's first study the protocol behavior for $t_{\text{safe}} = 0.5\,\text{s}$ (Figure 7, right). Our finding that DynB without adaptation is not able to satisfy the strict update requirements of an automated collision avoidance controller of 2 Hz can be confirmed. TRC without adaptation is able to provide an update almost every 0.5 s for 95 % of vehicles. Moreover, the figure shows that TRC with adaptation allows 99 % of vehicles to get reliable updates every 0.5 s. For DynB with adaptation, more than 85 % of vehicles are always safe; the remaining portion experiences larger update delays only more than 1 s before the crash (cf. Figure 6).

The advantage of our situation-based rate adaptation becomes even more visible for $t_{\text{safe}} = 0.2\,\text{s}$ (Figure 7, left). For DynB without adaptation it can be noticed that for the majority of vehicles it is working better than TRC without adaptation, but DynB with adaptation leaves way more vehicles in an unsafe state than TRC with adaptation. Finally, it can be seen that TRC with situation-based rate adaptation is also able to provide updates every 0.2 s for more than 98 % of vehicles. In detail, vehicles using TRC with adaptation spend time in an unsafe state only 2 s before a crash would happen.

VI. Conclusion

This paper clearly points out that current envisioned congestion control mechanisms for IVC will not be able to support vehicular safety applications in specific scenarios. The reason is rooted in their fairness postulation, which does not take into account the *situation* of different cars in relation to safety. We propose a *situation-based rate adaptation*, which allows vehicles to make use of temporary exceptions of congestion control restrictions. Endangered vehicles can communicate at their necessary information dissemination rate, because non endangered vehicles will compensate the additional channel load by sticking to congestion control restrictions. The presented simulation results confirm that both the protocols (DynB and TRC) using this adaptation are able to provide updates within real-time requirements and hence help to improve situation awareness. Moreover, we believe that the situation-based rate adaptation is feasible not only for the intersection approach use case, but also for many other safety use cases which have a demand for frequent CAM updates.

Future work will concentrate on urban scenarios which are very challenging due to radio shadowing effects of buildings and hence need to be investigated separately. Finally this paper has revealed that reactivity and aggressiveness of congestion control mechanisms have a non negligible impact on vehicular safety applications.

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